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Hydrogeological characterization of karst aquifers in Switzerland using a pragmatic approach

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by

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"Hydrogeological characterization of karst aquifers in Switzerland using a pragmatic approach"

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Foreword

This dissertation has been performed in the frame of the Swisskarst project, part of the National Research Program 61 (Jan. 2010 - Dec. 2013) related to the "Sustainable Water Management in Switzerland". The project was supported by the Swiss National Research Foundation. Objectives of the project were to establish and improve a pragmatic approach (KARSYS) to document the hydrological functioning of karst systems over the territory in order to provide a support to improve their management. This covers a large range of fields such as water supply, civil engineering, renewable energies, natural hazards, etc.

The Swisskarst project started in early 2010. A first PhD student was engaged but he left the position in April 2010. A second student has been engaged but she also left in April 2011. In total these two PhD students used up 11 months of salary and provided only a very restricted number of useful ideas and work for the project. Arnauld Malard was finaly committed in June 2011 and a request for additional financial was submitted in October 2011 in order to complete the financing of this third PhD-student. Then the project really started only about one year later the beginning of the NRP61.

The Swisskarst project has received further support from federal offices, cantons and communities which bring their respective expectations. All along these four years, the approach has been applied on the following cantons: Vaud, Bern, St-Gall, Fribourg and punctually Neuchâtel, Jura, Schwyz, Graubünden but also for private companies (i.e. CSD, BG ingénieur conseil, Buchs & Plumey, e-dric, SEFA…). Thanks to various collaborations with institutions abroad, the approach was also applied in Slovenia (2012), in Spain (2013) and later in Ireland and France. Over these 4 years, the KARSYS approach has been expanded on nearly 1/3 of the Swiss territory and more than hundred karst systems have been documented.

ISSKA - SISKA

The **Swiss Institute for Speleology and Karst Studies** is active on various karst-related fields: fundamental and applied scientific research (geology, hydrogeology, cave climate, speleology, and paleontology), teaching, protection of the karst heritage, safety measures, and national speleological documentation. The institute has been launched in 1999 as a non-profitable foundation - two years after the 12th International Congress of Speleology.

The office is located at La Chaux-de-Fonds (NE).

SISKA mainly works for cantonal authorities, communities, water authorities, engineers and consulting firms. It frequently collaborates with universities, high-schools and geological private companies, in Switzerland but also abroad.

The staff entails 11 permanent collaborators (hydrogeologist, geologist, biologist, administration and graphic designer) and temporary collaborators: trainees, voluntaries from the Civil Service, etc.

Further information about SISKA can be found at www.isska.ch

Abstract / Résumé

[EN] Recent studies reveal that karst aquifers represent a significant part of the Swiss groundwater reserve (120 km^3) and resource (8.4 km^3/year), although they only extend over 20% of the territory. On the one hand, high infiltration rates and large permeabilities of karstified rocks make karst aquifers highly interesting for water management. On the other hand, karst groundwater flow-systems are characterized by a highly heterogeneous structure including quick- and slow-flow components (conduit network, phreatic and epikarst storage) which lead to important hydrodynamic variabilities and complex flow dynamics which cannot be solved by the mean of standard hydrogeological tools. Finally, karst aquifers are also highly vulnerable to contamination and require specific attention for protection. Consequently, in spite of interesting groundwater resources, karst aquifers are often disregarded, flow-dynamics are poorly known and groundwater management is far from being optimal.

These are the reasons which motivated SISKA to submit the Swisskarst project as part of the Swiss National Research Program 61 dedicated to sustainable water management in Switzerland (Jan. 2010 – Dec. 2013). The motivation of the Swisskarst project was to develop a 3D conceptualization approach (KARSYS) for improving the hydrogeological characterization of karst aquifers. This dissertation is directly related to the Swisskarst project and to the KARSYS approach.

All along the project, the existing form of the KARSYS approach has been tested on various sites in Switzerland and abroad in order (i) to test the applicability on real sites, (ii) to formalize methodological steps and (iii) to improve standard operations. Compared to the initial form of KARSYS (as published in 2013), semi-automatized procedures have been developed for generating conduit network and for delineating the systems catchment over the ground surface. Applications of KARSYS to numerous case studies showed that the approach reveals extremely efficient for documenting epigenic karst aquifers where karst processes are in equilibrium with hydrological base level, where contrasts of lithologies make it possible to identify karstified rocks from non-karstified rocks and where phreatic zones are of moderate extension or compartmentalized into several distinct units. For pure confined aquifers or where lithological contrasts make difficult to distinguish karstified from non-karstified rocks, KARSYS remains applicable but less fruitful. Main limitations in the applicability of KARSYS concern the precision of geological data and hydrological indications regarding karst springs (activity, mean discharge, etc.).

As KARSYS is a conceptual approach, numerical approaches of simulation have been developed as extensions. Two types of simulation models have been designed for groundwater recharge: one for alpine regions where recharge is dominated by relief-contrasts, snow and glacier melts and one other for low-land regions where recharge are dominated by vegetation and soils/epikarst processes. Applications of these models make it possible to distinguish all the components of the recharge processes (precipitation, RET, etc., with the exception of the condensation) in the different compartments of the aquifers (storage in soils, epikarst, low permeable volumes, etc.). In addition to these recharge model, a hydraulic model for

simulating flows in the conduit network has been developed. This model uses the generated conduit network and the simulated recharge as inputs to reproduce the discharge for each outlets of the flow-system. Applications of these models with a constant interaction with the 3D conceptual model of the karst aquifers make it possible to infer additional properties of flow-systems (perched conduits, thresholds, etc.). These models may now address various issues in karst hydrology (storage, impacts of construction, flood hazards, etc.).

Another extension has been developed in the form of guidelines for mapping hydrogeological information resulting from the application of KARSYS. These guidelines promote three types of karst hydrogeological maps depending on the scale and on the issues: the karst groundwater map, the karst aquifer map and the karst flow-system map.

Finally, this project was also the opportunity to address general questions on karst groundwater at Swiss scale: the annual recharge, the minimal low-flow storage and the seasonal storage and the expected evolution of groundwater resources with the climate changes. These works made it possible to provide insights, key-values or recommendations regarding the current dynamics of karst aquifers and their expected evolution in the coming decades. They will contribute to support decision regarding future strategies for karst groundwater management.

Approaches and extensions which have been developed in this dissertation contribute to improve knowledge on karst aquifers in the scope of improving the sustainable management of groundwater in Switzerland.

Key words: karst hydrology, karst hydraulic, conceptual model, conduits generation, flow simulation

[FR] Des études récentes révèlent que les aquifères karstiques représentent une part importante des réserves en eau souterraine de la suisse (120 km^3) et des ressources renouvelables (8,4 km^3/an), bien qu'ils ne s'étendent que sur 20% du territoire. D'une part, les taux d'infiltration élevés et les grandes perméabilités des roches karstifiées rendent les aquifères karstiques très intéressants pour la gestion de l'eau. D'autre part, les systèmes d'écoulement karstiques sont caractérisés par une structure très hétérogène à composantes d'écoulement rapides et lentes (réseau de conduits, stockage phréatique et épikarst) qui conduisent à d'importantes variations hydrodynamiques et à des dynamiques d'écoulement complexes qui ne peuvent être résolues à l'aide d'outils hydrogéologiques standard. Enfin, les aquifères karstiques sont également très vulnérables à la contamination et nécessitent une attention particulière pour leur protection. Par conséquent, malgré des ressources en eaux souterraines intéressantes, les aquifères karstiques sont souvent ignorés, la dynamique de l'écoulement est mal connue et la gestion des eaux souterraines est loin d'être optimale.

C'est pour ces raisons que l'ISSKA a décidé de présenter le projet Swisskarst dans le cadre du Programme National Suisse de Recherche 61 consacré à la gestion durable de l'eau en Suisse (janvier 2010 - décembre 2013). La motivation du projet Swisskarst était de développer une approche conceptuelle 3D (KARSYS) pour améliorer la caractérisation hydrogéologique des aquifères karstiques. Cette thèse est directement liée au projet Swisskarst et à l'approche KARSYS.

Tout au long du projet, la forme existante de l'approche KARSYS a été testée sur différents sites en Suisse et à l'étranger afin (i) de tester l'applicabilité sur des sites réels, (ii) de formaliser les étapes méthodologiques et (iii) d'améliorer les opérations standards. Par rapport à la forme initiale de KARSYS (telle que publiée en 2013), des procédures semi-automatisées ont été développées pour générer un réseau de conduits et pour délimiter les bassins d'alimentation en surface. Les applications de KARSYS à de nombreuses études de cas ont montré que l'approche se révèle extrêmement efficace pour documenter les aquifères karstiques épigéniques où les processus karstiques sont en équilibre avec le niveau de base hydrologique, où les contrastes des lithologies permettent d'identifier les roches karstifiées à partir de roches non karstifiées et où les zones phréatiques sont d'extension modérée ou compartimentées en plusieurs unités distinctes. En ce qui concerne les aquifères purement confinés ou lorsque les contrastes lithologiques rendent difficile la distinction entre les roches karstifiées et les roches non karstifiées, l’approche KARSYS reste applicable mais moins performante. Les principales limites à l'applicabilité de KARSYS concernent la précision des données géologiques et des indications hydrologiques concernant les sources karstiques (activité, débit moyen, etc.).

Comme KARSYS est une approche conceptuelle, des approches numériques de simulation ont été développées en tant qu'extensions. Deux types de modèles de simulation ont été conçus pour la recharge des eaux souterraines : l'un pour les régions alpines où la recharge est dominée par les contrastes de relief, la fonte des neiges et des glaciers et l'autre pour les régions basses où la recharge est dominée par la végétation et les processus sol/épikarst. Les applications de ces modèles permettent de distinguer toutes les composantes des processus de recharge (précipitations, RET, etc., à l'exception de la condensation) dans les différents compartiments des aquifères (stockage dans les sols, épikarst, volumes faiblement perméables, etc.). En plus de ces modèles de recharge, un modèle hydraulique de simulation des débits dans le réseau de conduits a été développé. Ce modèle utilise le réseau de conduits généré et la recharge simulée comme entrées pour reproduire la décharge à chaque exutoire du système d'écoulement. Les applications de ces modèles en interaction constante avec le modèle conceptuel 3D permettent de déduire des propriétés supplémentaires des systèmes d'écoulement (conduits perchés, seuils, etc.). Ces modèles peuvent maintenant aborder diverses questions relatives à l'hydrologie karstique (stockage, impacts de la construction, risques d'inondation, etc.).

Une autre extension a été développée sous la forme de lignes directrices pour la cartographie de l'information hydrogéologique résultant de l'application de KARSYS. Ces lignes directrices favorisent trois types de cartes hydrogéologiques karstiques selon l'échelle et les enjeux : la carte des eaux souterraines karstiques, la carte des aquifères karstiques et la carte du système d'écoulement karstique.

Enfin, ce projet a également été l'occasion d'aborder des questions générales sur les eaux souterraines des aquifères karstiques à l'échelle suisse : la recharge annuelle, le stockage minimal à faible débit et le stockage saisonnier et l'évolution attendue des ressources en eaux souterraines avec les changements climatiques. Ces travaux ont permis de fournir des aperçus, des valeurs clés ou des recommandations concernant la dynamique actuelle des eaux souterraines et leur évolution prévue dans les décennies à venir. Ils contribueront à appuyer les décisions concernant les stratégies futures de gestion des eaux souterraines karstiques.

Les approches et extensions développées dans cette thèse contribuent à améliorer les connaissances sur les aquifères karstiques dans la perspective d’une gestion durable des ressources.

Mots clefs : hydrologie karstique, hydraulique karstique, modèle conceptuel, génération de réseaux de conduits, simulation d’écoulement

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1. *Introduction*

1.1. Generalities and background

1.1.1. The Swisskarst project

This thesis has been realized within the frame of the Swisskarst[1] project (January 2010 – December 2013) which was part of the National Research Program 61[2] ("Sustainable Water Management"). The program was funded by the Swiss National Funds[3] which supported 16 interdisciplinary and transdisciplinary projects.

Details of the activities which have been carried out along the Swisskarst pojects are placed in Appendix 10.1. Results of the project have been integrated to the final reports of the NRP 61 as a synthesis of karst groundwater knowledge over the territory and its evolution ("Teilsynthese", Björnsen Gurung and Stählli [2014]).

1.1.2. General issues related to karst environments

Even though karst environment is relatively widespread over the world (Ford and Williams [2007]), it is always considered as rather unpredictable and specific. It is seen as difficult to understand and to manage, and the development of agriculture, activities, settlements and infrastructures tends to be reduced due to surface-water scarcity and to thin or even absence of soils. However, because one part of the population lives on karst, this media is used and management strategies have to be developed all over the World in order to insure (i) a sufficient availability in water resources and (ii) a sustainable land-use.

Karst environments are often seen as dual.

On the one hand, karst offers significant resources for water supply (Bakalowicz [2005a]; Ravbar [2003]) or energy. Streams are often absent at land surface but karst aquifers often represent interesting groundwater resources due to the high porosity and the significant annual recharge rates. With the exception of young volcanic aquifers which also develop high permeabilities (Charlier et al. [2011]), karst aquifers rank among the most productive aquifers.

On the other hand civil engineering construction projects have to face specific problems in karst (Jeannin et al. [2010a]; Milanović [2004]; Parise et al. [2008]), and a series of natural hazards are associated to karst, such as inundations, instabilities, sinkholes collapses, etc. (Bonacci et al. [2006]; Delle Rose et al. [2004]; Lastennet and Mudry [1995]; Parise [2009]; Waltham et al. [2010], etc.).

[1] www.swisskarst.ch
[2] www.nrp61.ch
[3] www.snf.ch

Otherwise, due to rather direct connections between land-surface and the aquifer, karst groundwater is also sensitive to contamination, which may lead to a degradation of the available water resources.

Nowadays, due to the increasing pressure on the environment, concrete problems occur. Stakeholders and managers become thus progressively interested for the promotion and the management of karst environment and its resources.

1.1.3. **Main characteristics of karst in Switzerland**

1.1.3.1. Existing documentation

Karstified rocks in Switzerland outcrop over nearly 20% of the territory, mainly in the Jura Mountains, in the Prealps and in the Helvetic Alps, but also in the Austroalpine domain.

Karst aquifers mainly develop in the Jurassic and Cretaceous limestone beds in western Switzerland (Jura and Helvetic Alps) but also in the Triassic dolomite which may be encountered in eastern parts of Switzerland (Austroalpine domain). The Figure 1—1 provides more details in the distribution of the carbonate formations - potentially karstified over the territory.

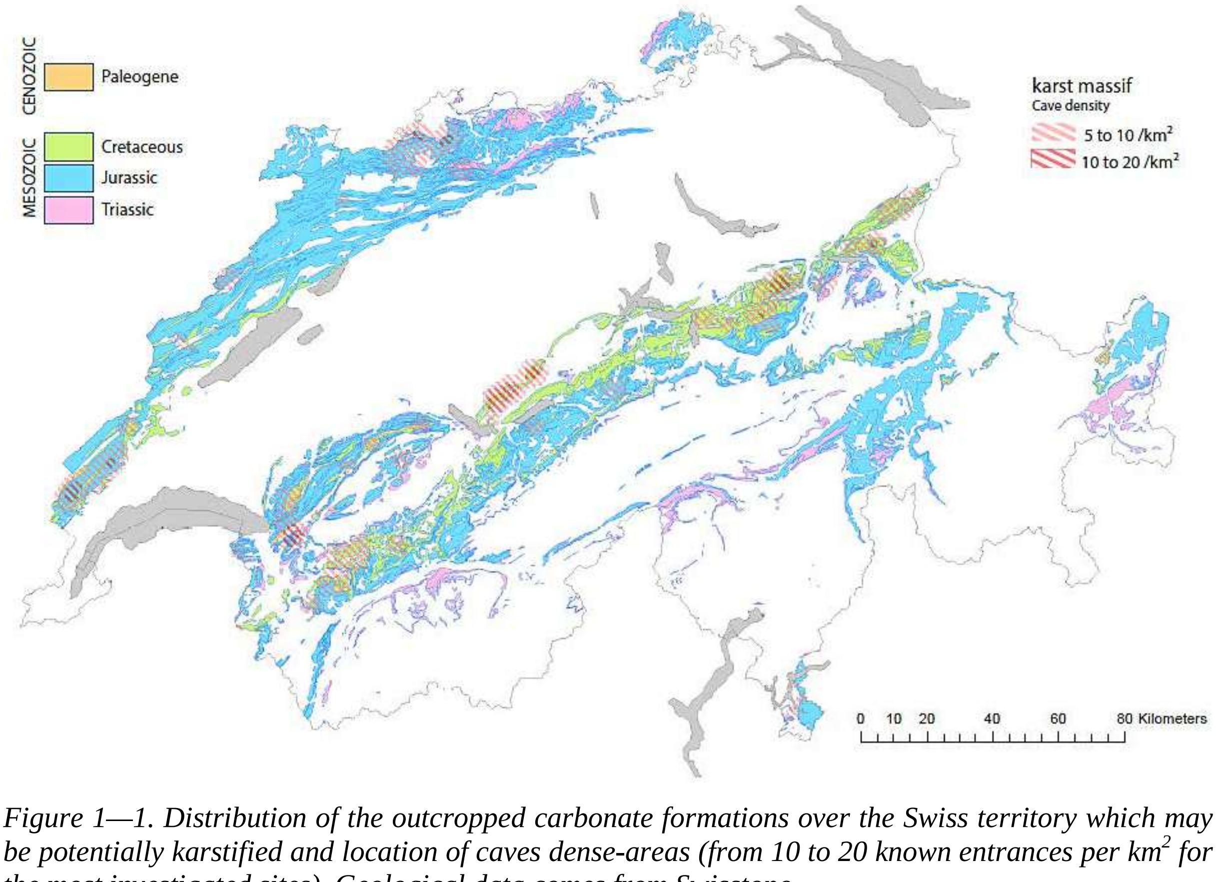


Figure 1—1. Distribution of the outcropped carbonate formations over the Swiss territory which may be potentially karstified and location of caves dense-areas (from 10 to 20 known entrances per km^2 for the most investigated sites). Geological data comes from Swisstopo.

Some karst areas in Switzerland are really famous as they enclose well developed cave networks such as the Siebenhengste cave system in the Helvetic Alps of Interlaken (Häuselmann [2002]), the Hoelloch-cave in the Helvetic Alps of Schwyz (Bögli [1970]; Wildberger [1986]), the Vallorbe cave in the Jura mountains (Aubert [1977]) or the Milandre cave in the tabular Jura (Jeannin [1995]). These areas have been studied by diverse universities or independent cavers. A review of the main karst areas and caves of Switzerland has been published by Wildberger and Preiswerk [1997]. This volume provides the most complete overview concerning karst areas and caves in Switzerland until now; however regional and local hydrogeological functioning are not addressed, limiting the reading to cavers or people interested by karst from a morphological or heritage point of view.

Some karst regions of Switzerland have been also documented and described from an hydrogeological point of view, whether through the publishing of caves inventories in the following cantons; Neuchâtel (Gigon [1976]), Jura (Gigon and Wenger [1986]), Basel (Bitterli [1996]), Vaud (Audétat et al. [2002]; Deriaz et al. [2007]), Bern (Bitterli and Häuselmann [2009]), etc. or through local studies performed by students in the frame of their hydrogeological courses or thesis: Jeannin [1996]; Kovács and Jeannin [2003]; Luetscher and Perrin [2005]; Rieben [2000], etc. or by cavers in the frame of their exploration works (Bitterli [1985]; Dickert et al. [2012]; Jeannin and Beuret [1995]; Wildberger and Niederberger [2006], etc.). These works usually include relevant hydrological data and observations on the karst aquifer functioning which may have been used to set up hydrological models.

In addition, semi-official maps for karst morphology and groundwater management do exist for some Swiss regions; Bernese Oberland (Wildberger [1979]), Neuchâtel (Kiraly [1973a]), Ajoie (Grétillat [1992]), Alvier, Alpstein and Churfirsten (canton St-Gallen, Leibundgut and Attinger [1988]; Leibundgut and Rieg [1995]), Fribourg (Müller and Plancherel [1982]), etc. These documents are of great interest as they support nowadays most of the decisions regarding groundwater resources at the local (communities) or regional (cantons) scales. However these document are heterogeneous in quality and details and poorly describe the functioning of karst aquifers (cf. Figure 1—2). The available documentation only covers 1/4 to 1/3 of karst territories in Switzerland.

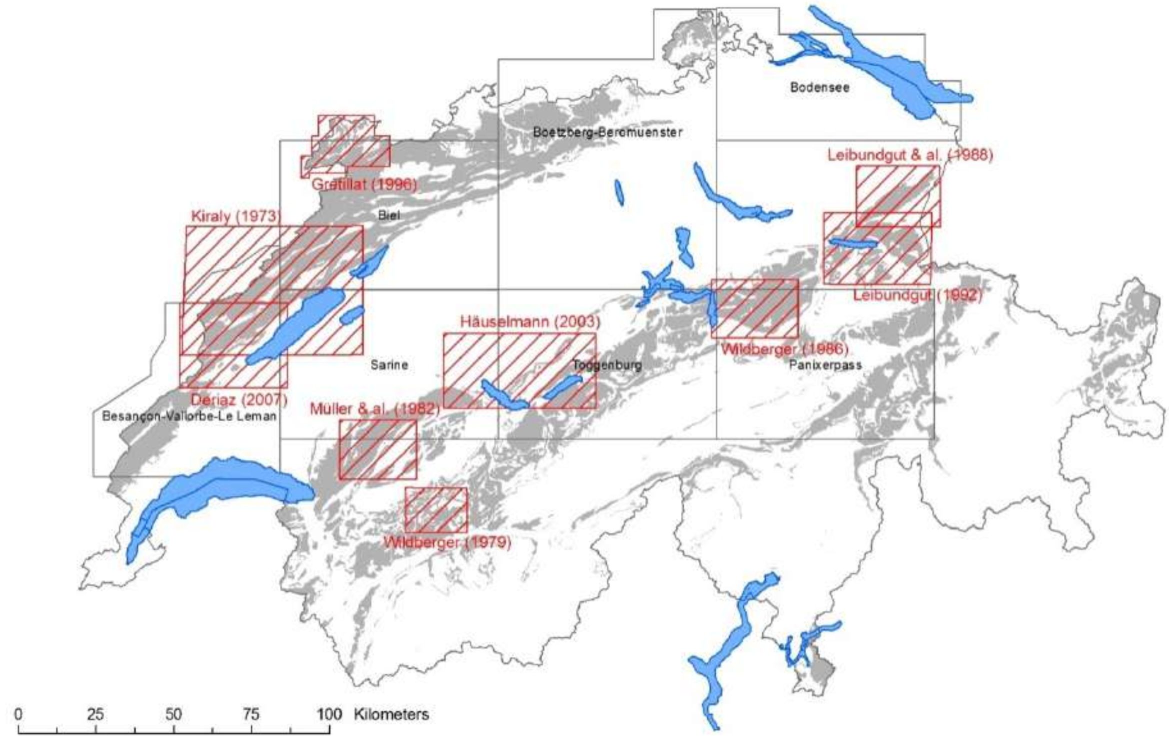


Figure 1—2. Swiss documented areas from a karst-hydrogeological or morphological point of view prior to the Swisskarst project. Black breakdowns refer to Swiss official hydrogeological maps (1/100'000, Swisstopo)

Karst areas are often described from a geomorphological point of view and completed with partial hydrogeological (aquifer properties, catchment boundaries, etc.) or hydrological (flow connection, outlets, etc.) aspects. Therefore these karst "hydrogeological" maps remain accessible only to persons who have a minimum knowledge in both karst and hydrogeology, restricting the scope of the information. As a matter of fact, existing karst hydrogeological maps remain (i) rooted to the areas where they have been established and (ii) depending on concepts and principles assumed by their authors. They are hardly comparable and most of them cannot be extended to another area without changing concepts and mapping principles.

1.1.3.2. Karst environments in Switzerland

Karst environments in Switzerland range from high alpine massifs to low-elevated plateaus in northern Jura. The Figure 1—3 shows a synthetic sketch of the main types of karst environments.

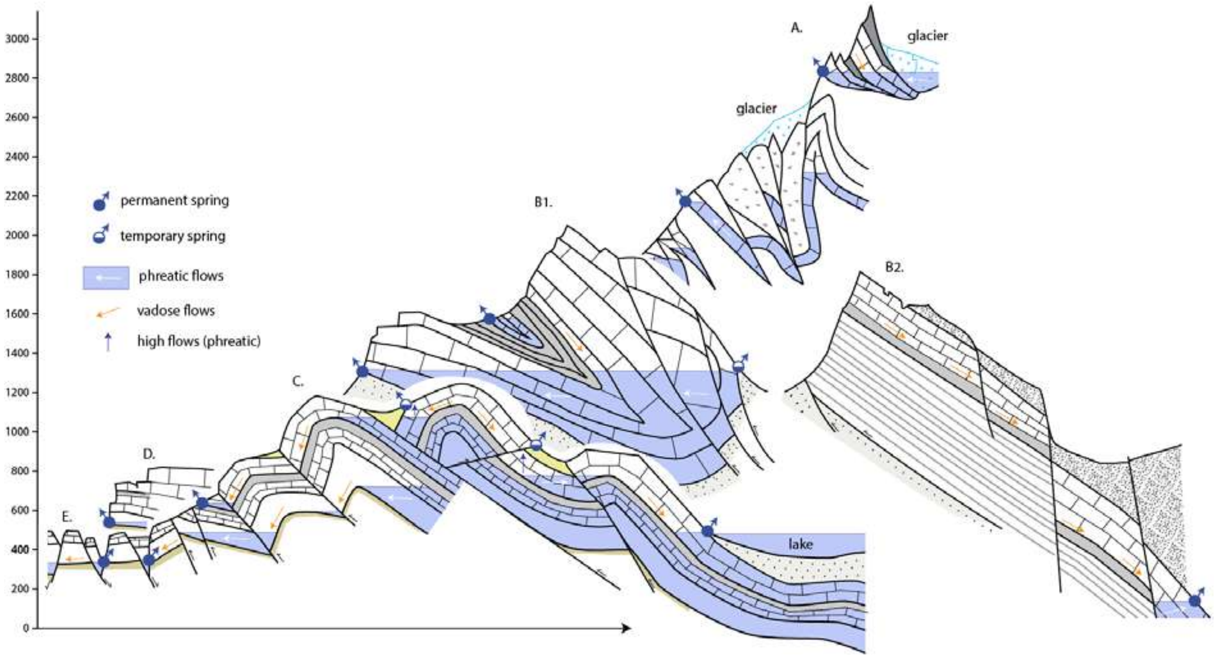


Figure 1—3. Schematic sketch of various karst environments in Switzerland

Five to six typical karst environments in Switzerland may be described, depending on the elevation and on the geological context.

- **Alpine karst massifs** (A., B., C. in figure) refer to mountainous areas where karst genesis results (or has been influenced) by glaciations (see recent work ISSKA [2017] for additional information). Alpine karst massifs of high elevation (type A.) are partially fed by glaciers melting. Large springs – with significant discharge rates - may emerge above 2’000 m a.s.l. (ex: the Wyssbachhöhle spring in the Bernese high mountains). Such environments may be encountered in central Switzerland, in Wallis (ex: the Sarine and the Sionne springs) and in Graubunden. Such elevated karst systems are usually of modest extension (a few square kilometers) and highly compartmentalized due to the multiple thrusting slivers. Alpine karst massifs of mid-elevation (type B.) refer to massifs which are not fed by glaciers melting anymore. These are often of a large thickness and may present a huge saturated zone (for instance case B1, see in the Prealps "fribourgeoises" or canton St Gallen) or a large unsaturated zone (for instance case B2, see the Siebenhengste in Bernese Oberland). Basal springs emerge in the bottom of the valleys (at least ~500-600 m of elevation) but perennial springs may be active up to 1’500 m a.s.l. Due to a lower compartmentalization, flow-systems may be of larger extension (i.e. exceeding 50 km^2). Jurassian karst massifs of folded environments (type C.) are also of Alpine type as their formation results was influenced by glaciers. These are often characterized by large saturated zones in syncline and monocline structures and unsaturated zones in anticlines. Due to thick interbedded clay layers, these aquifers may form perched compartments. Flow-systems may be of large extension (more than 100 km^2). Examples of such aquifers may be encountered in cantons Vaud (ex: the Orbe karst system), Neuchâtel (ex: the Areuse karst system) and in Bernese Jura (ex: Dou spring).
- **Plateau karst massifs** (D., E.) refer to karst environments of lower elevation which were not been influenced by glaciers. Two types may be distinguished in Switzerland. The Jurassian karst plateau (type D.) is characterized by no apparent tectonic structures (thrusts or horst-grabens) which may compartmentalize the aquifers. Aquifers are characterized by thick unsaturated zones and a large

phreatic zone. Examples of these aquifers may be observed all along the Doubs river (cantons Neuchâtel, Bern, Jura). Karst environments of low-elevated tabular plateaus (type E.) are observed in northern Switzerland (north of Jura, Basel, Aarau and Schaffhausen) where the land-level uplift rate is low and where no Quaternary glaciers did modify the base level. As they are close to the Rhine graben, these are marked by distensive conditions. These aquifers are often characterized by large and shallow saturated zones. Most of them are capped by recent deposits and karst features are not well visible. With the exception of a few flow-systems (see Beuchire-Creugenat for instance), most of the flow-systems are usually of moderate extension (2-20 km^2) due to the high density of valleys.

1.1.3.3. Karst groundwater resources

Due to the high precipitation amount in an alpine context as well as the existence of numerous lakes, Switzerland is known as the water tower of occidental Europa - giving birth to major rivers as the Rhine, the Rhône and the Danube. A recent synthesis from the Swiss Federal Office for the Environment (Sinreich et al. [2012]) estimated that national groundwater reserves are comparable to water storage in Swiss lakes (~150 km^3). Karstified (or at least carbonated) formations lying in the Jura, the Prealps and in some parts of the Alps thereby represent the most significant groundwater storage. Considering a maximal depth of 1000 m and assuming 2% of efficient rock porosity, it was established that karst groundwater represents nearly 120 km^3 - in other words 80% - of Swiss groundwater reserves. The significance of karst in Switzerland and implications for various domains of the society is further analyzed in §. 3. Annual recharge and groundwater resources are further analyzed in §. 7.

1.2. Problem summary

In Switzerland as in many other countries, karst environments remain poorly documented. Excepting local sites that are monitored and studied by cavers or universities, available data and information remain vague. Even the delineation of karst/non-karst regions is not fixed, leading to difficulties in land and water management.

Although karst specific problems are well known, only few dedicated approaches or methods have been developed so far to improve groundwater and environmental management in the field. Karst is mainly considered as an academic topic and problems are addressed in an academic way, rather than being included into applied development. As a consequence, karst areas are often not managed or managed with an inappropriate or a non-optimized manner.

A sustainable water management in Switzerland requires karst media to be considered as a significant part of the global groundwater resources and addressed in an appropriate way.

With the exception of the work of Wildberger and Preiswerk [1997], there is no other documentation of karst areas at the scale of Switzerland. Even a database which gathers karst springs did not exist before the beginning of the project. Many data did exist but were not gathered and formalized.

1.3. Objectives of the thesis

This thesis is closely related to the tasks which have been performed within the frame of the Swisskarst project. As the project involved the participation of several collaborators who worked on the documentation of karst aquifers in Switzerland, regional aspects of the project will not be presented here.

The main goal of this thesis was to develop and to improve a systematic and pragmatic approach for documenting karst hydrogeology. The approach must take into consideration the specific aspects of karst hydrology and must be applicable in the field for the sustainable management of groundwater and the environment. The approach was first and mainly developed for Switzerland, but it was also tested in other contexts abroad.

As objectives of the thesis were closely related to the objectives of the Swisskarst project, they have been defined and refined along with the development of various concepts and their applications. The thesis does not intend to present all results of the Swisskarst project; it is focused on conceptual and methodological aspects. The main result is the development of the KARSYS approach which was formalized and expanded along the course of the project. The development of KARSYS is presented based on selected case-studies and thematic cases that have been studied all along the project.

The development of a new approach required to identify, analyze and criticize usual approaches considering their relevance to address pragmatic issues in karst environment. This implied (i) a discussion of concepts, methods and tools usually applied in karst hydrogeology regarding the functioning principles of the systems, (ii) an inventory and understanding of practices for addressing practical issues in karst media and (iii) the formulation of “standards” (i.e. descriptors, principles, mechanisms, etc.). A strong review was essential for the design and the improvement of KARSYS in order to provide intelligible and usable results (or outputs) for management processes.

In details, the thesis adressed three main work-packages forming a logical and consistent way to improve the documentation of the karst aquifers:

i. To improve the applicability of the KARSYS approach; this implied (i) to better formalize the different steps of the approach, (ii) to better characterize its applicability and its limitations, and (iii) to provide validation criteria in order to discuss the reliability of the results. It should be kept in mind that main concepts and first guidelines of the KARSYS approach already existed before the thesis started but the formalization of all steps, the optimization of all application processes (in GIS and 3D-software) were not developed;
ii. To develop extensions compatible with the standard approach in order to address questions related to (i) conduits generation, (ii) catchment delineation, (iii) hydrogeological mapping, (iv) recharge and (v) hydraulic simulations;
iii. To forecast – at least from a qualitative point of view – expected changes in groundwater quantity (recharge, discharge) and quality for the mid-term future (2085) according to probable climate scenarios.

1.4. Structure of the chapters

This dissertation covers a large spectrum of karst-related aspects: 3D, hydrology, hydraulics, mapping, etc. This required a redefinition / reprecision of notions and terms commonly used in karst hydrology in order to be consistent all the way through KARSYS approach and its related extensions. This is the reason why most chapters start from the basics and are a bit longer than in usual dissertations in hydrogeology.

The Figure 1—4 presents the logical structure of the ideas developed in this thesis. The figure may be seen as the guiding thread of the dissertation; each box referring to a chapter.

The **Introduction** mainly explains the objectives and the structure of the dissertation. It includes some general background on karst environments in Switzerland. **Chapter 2** describes general characteristics of karst aquifers and of flow-systems based on a literature review. The chapter defines concepts, terms and principles that are used in the dissertation. This was a requisite work for the establishment of a systematic approach.

Chapter 3 presents the main practical issues related to karst environments in Switzerland (water supply, natural hazards, civil engineering, etc.), and users concerned with these issues. Users’ expectations for the management of this singular media are listed. This chapter is essential for introducing requirements for a pragmatic and systematic approach.

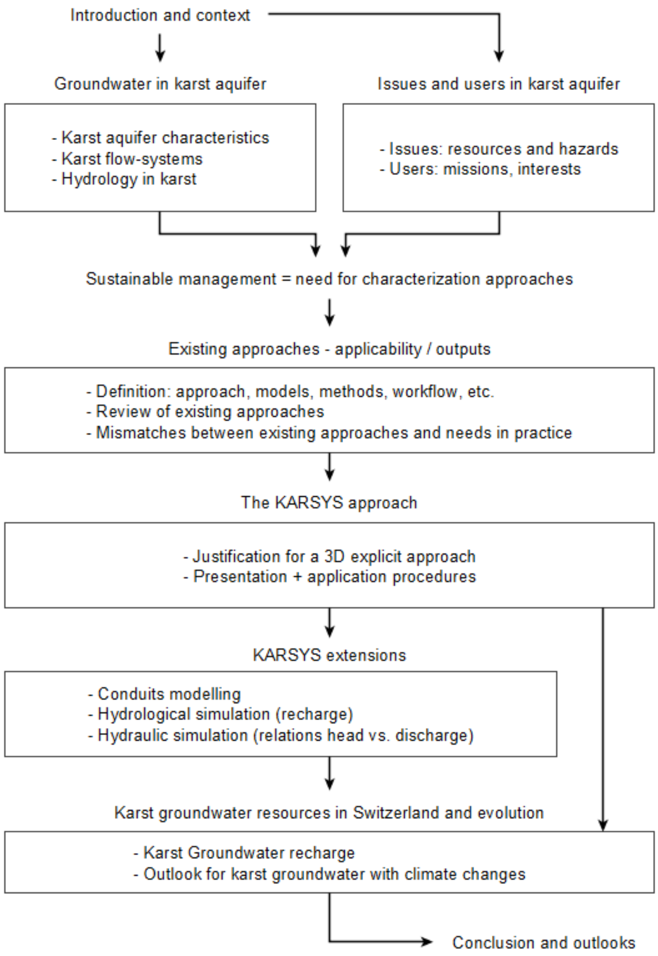


Figure 1—4. Objectives and guiding thread of the dissertation; each block refers to chapters that are developed hereafter

Chapter 4 is a review of the most popular characterization approaches in karst which have been developed to infer aquifer properties: conduit network modeling, mapping groundwater resources, hydrological simulation tools, etc. Concepts and workflow used for the aquifer characterization are described. It appears that even if most of these approaches provide significant and consistent properties of karst aquifers, rare are those which can be systematically applied within a formal pathway leading to explicitly describe the characteristics of the aquifer(s) and the flow-system(s). Most approaches are restricted to particular types of karst aquifers; they also often require a significant amount of expensive and time-consuming investigations resulting only to a partial understanding on the aquifer dynamics and structure. The absence of conceptual models and of formal steps for most of these approaches makes it difficult to apply them, to compare them and to discuss the inferred properties. The mismatch between these existing approaches and the user's requirements is then discussed in order to point out pragmatic aspects that the users are looking for.

Chapters 2, 3 and 4 do not explicitely refer to KARSYS. However, they are indispensable for elaborating concepts and principles of KARSYS and its extensions. Terms, concepts, and objectives of KARSYS are based on this analysis. Readers who are already experienced with these concepts may directly jump to Chapter 5.

Chapter 5 presents the original form of the KARSYS approach (called KARSYS "Original 3D"), including general concepts and formal steps. As several aspects of the KARSYS approach were developed and published before the thesis started, the emphasis is put on the improvement of the formulation, technical aspects, conditions for application (context, data, resolution), validation processes, advantages and limitations of the approach.

Chapter 6 presents three extensions to KARSYS which have been developed in the frame of this thesis. The first extension deals with the generation of a karst conduit network based on a KARSYS 3D model. The generator has been applied on the Beuchire-Creugenat karst system (Ajoie, JU), providing a consistent drainage conduit network over the whole catchment of the system. As the process of conduits generation is semi-automatized, it can be applied to other systems in a reproducible way. The second extension makes it possible to perform hydrological and hydraulic simulations of flow-systems by using outputs of the KARSYS approach (recharge areas, conduits geometry, etc.). Two types of simulation programs are used; semi-distributed models for assessing the recharge over the catchment area and pipe-flow models which make it possible to simulate the flow hydraulics within the conduit network generated in the previous step. Application of these simulation programs to the outputs of the KARSYS approach on the Beuchire-Creugenat karst system provides relevant results as well as new insights on the system functioning (thresholds activation, by-pass conduits, overflow, etc.) for high-flow conditions. The combination of KARSYS with these extensions is useful to assess construction, natural hazards, and water resources in karst.

Chapter 7 focuses mainly on the assessment of annual resources in Switzerland and on the evolution of karst environments and groundwater resources according to climate changes. Results are important for issues such as water supply, geothermal heat and hydropower potential.

The **Conclusion** is divided into two parts. The first part recaps the main improvements and developments which have been added to the KARSYS approach. The second part recaps findings and key-values of the actual dynamics and of the expected evolution of Swiss karst groundwater within the frame of climate changes. Outlooks are given at the end of the conclusion.

2. *Groundwater in karst*

Groundwater in karst may be seen in two ways: the **aquifer** and the **karst flow-system**. The aquifer is defined as groundwater reservoir while the karst flow-system refers to groundwater drainage. A karst aquifer may be divided into several flow-systems, and a flow-system may develop in several aquifers.

Due to fast dissolution processes and to high transport capacities of dissolved materials karst flow-systems permanently develop and improve the aquifers drainage according to given hydrological conditions (boundaries, flux conditions and base level). Properties of the aquifer (geometry, equivalent porosity or permeability, saturated and unsaturated zonation, etc.) constantly evolve over the time; progressively or suddenly through cataclysmic events.

2.1. Karst aquifer

2.1.1. Definition

Among the many definitions of the term "karst aquifer", one of the most relevant was introduced by Ford and Williams [1989]; *"[karst] aquifers are defined as rock formations [soluble rocks] that store (**storage**), transmit (**drainage**) and yield economically significant amount of water (**production**). They may be confined, unconfined and/or perched. […] a karst aquifer can be envisaged as an open system with a boundary defined by the catchment limits and with input, throughput and output flows, mechanisms and controls"*. Hydraulic boundaries of an aquifer are set in place by (i) impervious formations or structural constraints and (ii) by the ground surface that fixes the hydraulic base level.

The term "**karstification**" refers to physic and chemical mechanisms affecting all types of soluble rocks (mainly carbonate rocks but also other soluble sedimentary indurated formations such as gypsum, salt, etc.). Chemical dissolution and corrosion processes lead to the enlargement of preexisting rock weaknesses (faults, bedding plans, etc.) and increase the porosity and the permeability of most soluble rocks. Without karstification, most of the carbonate formations could not be considered as aquifer, or else as a mediocre aquifer as the primary porosity of the limestone is low.

As the karstification degree of the rocks evolves through the time, most of the authors considered two opposite poles: (i) **low-karstified aquifers**, in which porous and fissure permeabilities govern groundwater flow, and (ii) **karstified aquifers**, in which karst conduits govern groundwater flow. For instance, Shuster and White [1971] defined two types of karst aquifers: "**conduit flow**" and "**diffuse flow**". The term "Conduit flow" refers to carbonate aquifers in which well-developed conduit networks control most of groundwater flow. At the opposite, "Diffuse flow" refers to carbonate aquifers which do not present a high degree of karstification, at least an insufficient density of conduits to control the major part of groundwater flow. Marsaud [1996] refined the typology of the karst aquifers by introducing the **1^st^-order non-functional karst aquifers** (= diffuse flow) and the **1st-order functional karst aquifers** (= conduit flow). In practice, the author found eight different nuances of aquifer types depending on (i) the degree of the karstification, (ii) the aquifer boundaries conditions and (iii) the hydraulic potential. *De facto*, characterizing the karstification degree of an aquifer is still complex.

According to the classification proposed by Ford and Williams [1989] (fig. 1.2), karst aquifers range from **epigenic** karst (resulting from meteoric waters) to **hypogenic** karst (resulting from the rise of deep crustal waters and gas). In between, **hydrothermal** karst aquifers could be seen as a combination of epigenic and hypogenic processes of karstification.

The evolution of karst aquifers is dominated by the meteoric dissolution in the **epigenic** (idem as **hypergenic** or **telogenic**) zone and by the dissolution from deep thermal water and acids (CO_2 degassing) in the **hypogenic** zone (Palmer [1991]). Another definition of hypogenic karst is provided by Klimchouk [2007] who considers that hypogenic speleogenesis is not restricted to a specific geochemical process. The author demonstrates that hypogenic formation processes are related to the source of the fluid and to the type of the flow system. This is supported by the observation of a lot of hypogenic karst systems in various parts of the world which show similar patterns in morphologies and formation contexts. These similar patterns indicate that hypogenic karst forms by ascending transverse flows in confined or semi-confined deep-seated zones due to vertical contrasts in permeability.

2.1.2. **Distribution**

Carbonate rocks outcrop in all continents. Groundwater from carbonate rocks provides 20 to 25% of drinking water across the world and up to 80 - or even 100% - in many regions (e.g. around the Mediterranean sea). The distribution of carbonate outcrops and carbonate overlaid formations is displayed Figure 2—1 (copyright Auckland University). This map shows the locations where karst aquifers may be expected.

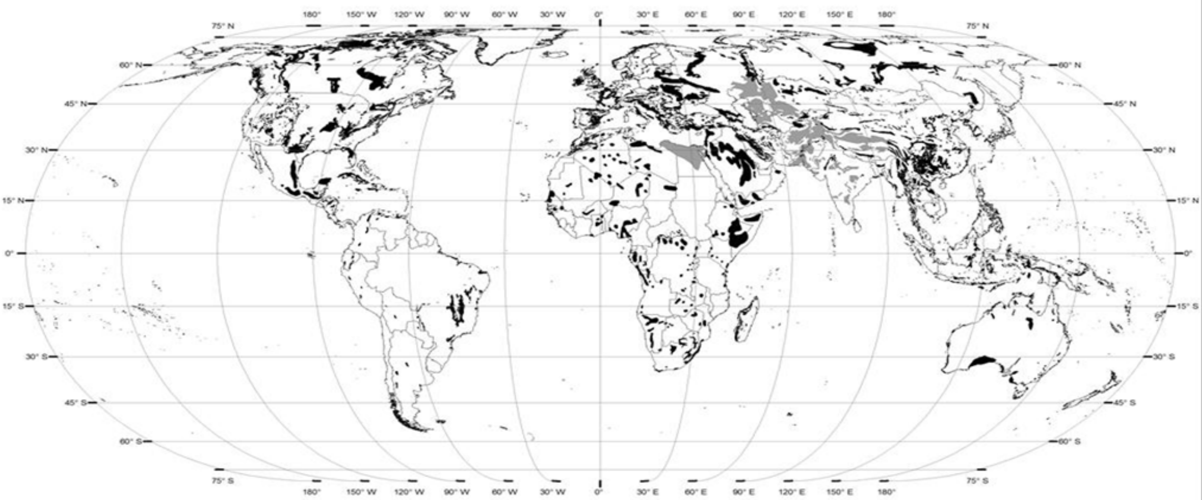


Figure 2—1. Distribution of carbonate rocks over the World (SGGES, University of Auckland, New Zealand); numerous populated and « arid » zones (Mediterranean, Persian Gulf, Central America, etc.) are located in karst area. Two types of aquifers are here distinguished; (i) outcropping carbonate rocks (black) and (ii) “deep” or overlaid carbonate rocks (grey). Most of these carbonate rocks are supposed to be karstified.

Regarding the evolution of the karstification with the depth; the epigenic karstification is supposed to decrease while the hypogenic one is assumed to increase. In both case, the maximal depth reached by the karstification is usually not well known and difficult to establish.

It is known in several places of the Earth that carbonate formations from marine deposits may reach a depth of several kilometers - until 8 km as mentioned by Wenzhi et al. [2014]. Milanović [1981] wrote that voids or karst conduits have been found deeper than 1’500 m below the sea level in the Dinaric karst. In other places of the world, voids or conduits have been intersected up to 4 km below the sea level in carbonate formations (case in minor Asia, TOTAL, personal communication). Significant voids were also observed at a depth exceeding 5 km in recent exploratory boreholes crossing Paleozoic carbonates in China (Wenzhi et al. [2014]). Nevertheless, the origin of these karst conduits (buried epigenic or hypogenic) is not further described. Different authors (Loucks [1999]; Xingping et al. [2009]) demonstrated that below the buried depth of 1’500 - 1’700 m, a large proportion of karst conduits may collapse under the overlaying formation pressure. However, depending on the rocks type and on the geometry / organization of the conduits, karst conduits may be potentially still preserved until a depth of 6 km (Xingping et al. [2009]). Obviously, such deep karstification is also nowadays a privileged target for oil and gas exploration in ultra-deep zones (i.e. deeper than 4’500 m).

2.1.3. **Characteristics**

2.1.3.1. Vertical structure

Karst aquifers display a specific vertical structuration. Depending on their evolution and their geometry, epigenic karst aquifers are usually segmented into: soil / epikarst, unsaturated (vadose) zone, saturated (phreatic) zone and epiphreatic zone (Figure 2—2).

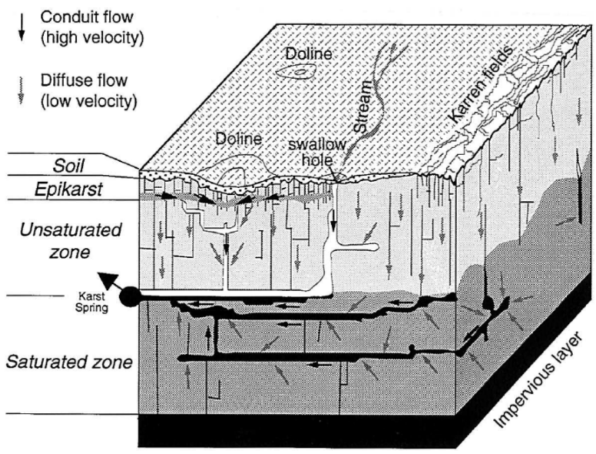


Figure 2—2. Schematic vertical structuration of epigenic karst aquifers (from Doerfliger [1997]). From top to bottom, karst aquifers are sub-divided into four main zones: Soil, Epikarst, Unsaturated zone and the saturated (phreatic zone). The unsaturated zone may be divided in two zones: the vadose which never floods and the epiphreatic zone which periodically floods

2.1.3.1.1. Soils

Soils in karst are made by an aggregate of clay resulting from limestone decalcification, silt, sand and pebbles, organic matter, etc. Soils are rather thin in karst terranes compared to other geological environment; usually, it does not exceed 50 cm to 1 m if it lies directly on limestone but it may show strong irregularities depending on the topography and on the presence of concentrated infiltration features. The permeability of the soils is heterogeneous; it is considered as higher at the top of the soil and it decreases with the depth. Two main zones may be described (see Figure 2—3):

- The **upper soil** (US) is characterized by a high relative porosity and a high relative permeability. Water fluxes are drained vertically through irregularly-distributed interstices;
- The **lower soil** (LS) is characterized by a lower porosity and a lower permeability. This zone develops at the contact with the upper epikarst. Water fluxes are still mainly vertical but horizontal flows may be

observed. Depending on the soil accumulation, small perched groundwater bodies may develop – at least for wet climatic conditions. Lateral circulations driving water to open by-pass shafts do exist but they do not exceed a few meters. Water infiltrating into soil feeds the underneath epikarst by seepage.

As soils are not always present or as they may be scattered by to enlarged cracks, infiltration water may directly by-passes the soil and flows to the epikarst.

2.1.3.1.2. Epikarst

The **epikarst** develops below the soil. Its usual thickness ranges between 1 and 10 m (Williams [1985]; Williams [2008a]). The epikarst may be divided in three zones (see Figure 2—3):

- The **upper epikarst zone** (UE) is characterized by an intermediate relative permeability. Water fluxes are mainly vertical through cracks and enlarged fissures;
- The **intermediate epikarst zone** (IE) is characterized by a relative high permeability due to the presence of small and interlaced conduits. Water fluxes are both vertical and pseudo horizontal as the water may move toward epikarst shafts that by-pass the lower epikarst zone;
- The **lower epikarst zone** (LE) is characterized by a low relative permeability which makes it possible the development of a permanent "epikarstic" groundwater body (Schwartz et al. [2013]). During recharge events, the rise of the groundwater table activates the intermediate conduit network and forces water to lateral displacement toward open shafts (Perrin et al. [2003]).

The drainage network of the epikarst collects water and feeds the "epikarst-shaft zone" (see Filipponi et al. [2012]). This zone develops vertically below epikarst for a few dozens of meters. It entails a high density of vertical shafts converging to the vadose zone.

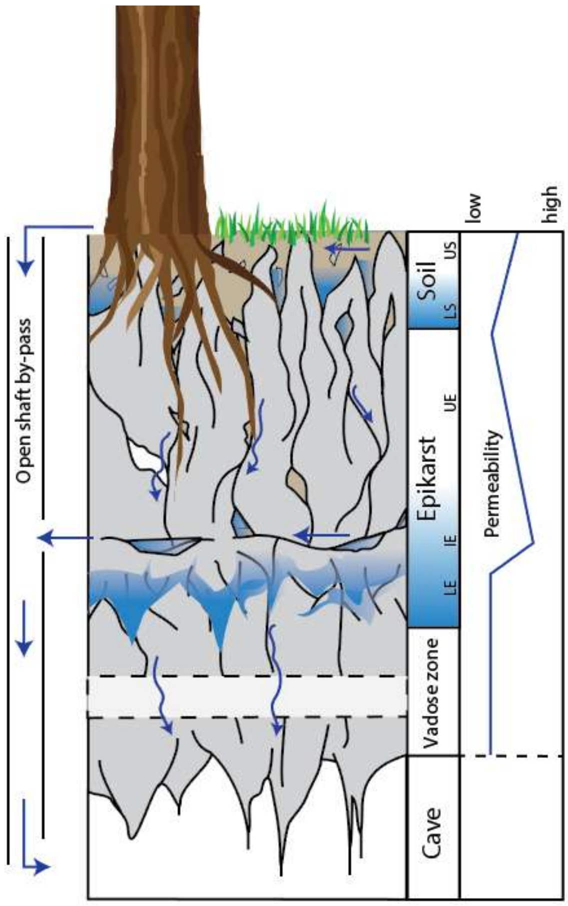


Figure 2—3. Schematic profile of the soil and of the epikarst in karst terrane

Soil and epikarst may be locally by-passed by vertical open shafts where surface water directly penetrates and flow toward the unsaturated zone (Perrin et al. [2003]). However, this observation is valid for a minor percentage of the infiltrated water. Mohrlok and Sauter [1999] observed on a site in Swabian Alps that 10% of the water infiltrating through the epikarst flows rapidly via the epikarst shafts toward the lower aquifer zone. The remaining 90% slowly percolates through the less permeable volumes of the epikarst toward the lower zones. This observation is also supported by Emblanch et al. [2003]. Working on Fontaine de Vaucluse (France), authors found that 80% to 90% of the infiltrating water is stored within the unsaturated zone (i.e. soil + epikarst + the 1’500 m thick vadose zone) and is slowly released downward. In this case, authors expect that most of groundwater stores in the epikarst zone.

Working on the Milandre test site (Swiss Jura), Savoy [2007] also attested that a major part of the infiltrated water stores in the soil and epikarst zones. Author wrote that for a large flood, only 20 to 30% of freshwater directly contributes to the peak discharge measured at the spring.

At the opposite, Smart and Friedrich [1987] found that 77% of the infiltrated water through the epikarst flows rapidly downward via the epikarst shafts. Only 23% of the water slowly percolates downward via seepage.

Differences in infiltration from a site to another mainly depend on the repartition of soil cover and of outcropping karst features that enhance direct infiltration.

2.1.3.1.3. Unsaturated (vadose) zone

The **vadose or unsaturated zone** of a karst aquifer acts as a transition zone between the epikarst and the lower (epi)phreatic zone. Due to high hydraulic conductivities, the unsaturated zone in karst aquifers may be of great thickness (up to 2’000 m). This is a typical feature of the karst aquifers compared to other aquifer types. However, the unsaturated zone may be thin in shallow aquifers or even absent in confined zones.

The bottom of the vadose zone may be formed either by the flooded part of the aquifer (the phreatic zone) or by an impervious basement. Indeed, while the epikarst and the saturated zone are expected to be always present in outcropping karst aquifers, the presence of a phreatic zone (favorable to groundwater storage) depends on the geometry of the aquifer (see in Ford and Williams [2007]; Mijatovic [1993]).

2.1.3.1.4. Phreatic (or saturated) zone

The phreatic zone refers to the part of the karst aquifer which is **permanently flooded**. It may be assimilated to the karst aquifer volume that extends below the basal karst spring(s). In this zone, groundwater stores in conduits and in the fissured and matrix parts of the aquifer surrounding the conduits. The groundwater flooding the conduits/fissures parts of the aquifer is assumed to be hydraulically “well” connected; this entity could be designed as “karst groundwater body”. As for other aquifer types, karst groundwater bodies can be unconfined or confined.

2.1.3.1.5. Epiphreatic zone

The epiphreatic zone lies at the transition between the permanently unsaturated and saturated zones of the aquifers. This zone is defined as the part of the unsaturated zone which is temporarily flooded for high-flow conditions.

2.1.3.2. Porosity

The porosity refers to the volume of voids in rock, divided by the total volume of the rock. Several classifications have been proposed for porosity in carbonate and karst aquifers (Worthington and Ford [2009]). A review of these classifications is given in Appendix 10.2, each one having been developed for specific applications. It should be first mentioned that most of these classifications do not discretize the aquifer according to its vertical structuration; the authors usually focused on the phreatic and epiphreatic zones.

Basically, three types of porosities do exist in carbonate rocks: the **primary porosity** depends on lithologies and diagenetic processes, the **secondary porosity** (or fissures porosity) depends on the tectonic contexts and the **tertiary porosity** depends on the karstification (voids enlargement by dissolution). Values for these different porosities in carbonate rocks have been listed in Appendix 10.2 Table 10—1. Depending on rocks, the primary porosity ranges between a few percent up to **30%**. The secondary porosity is about **0.1** or **0.2%** max and the porosity resulting from conduits or voids enlargement ranges between **0.01** to **0.5 %** max.

From the hydrogeological point of view, the most relevant indicator to assess the storage capacity of an aquifer is the **"effective porosity"**. It refers to the amount of interconnected pores in the aquifer (i.e. the groundwater yield by gravity) and values are expressed in percentage of interconnected (effective) voids compared to the total aquifer volume (voids + rocks). As for the other types of aquifers, this value is lower than total porosity. The more the voids-size decreases (reducing the interconnectivity), the more the deviation increases between effective porosity and total porosity. Various values of effective porosity in karst aquifers have been found in the literature. These have been reported in the Table 2—1.

Authors	**Massif**	**Values (%)**
Tripet [1972]	Jurassic limestone, Swiss folded Jura	0.3 to 0.6
Torbarov [1976]	Jurassic limestone, Dinaric karst	1.2 to 1.5
Milanović [1981]	Jurassic limestone, Dinaric karst	1.4 to 3.5
Burger and Pasquier [1984]	Jurassic limestone, Swiss folded Jura	0.2 to 0.4
Bonacci [1995]	Limestone, Dinaric karst, Croatia	0.11
Jeannin and Grasso [1997]	Jurassic limestone, Swiss tabular Jura	0.7
Worthington [1999]	Paleozoic limestone, Kentucky	0.06 to 0.09
Kiraly [2003]	Jurassic limestone, Swiss folded Jura	0.4 to 1
Worthington and Ford [2009]	Paleozoic dolostone, Ontario	0.01 to 0.1

Table 2—1. Values of effective porosity at the scale of a karst aquifer (review from literature)

The above-listed values of effective porosities in well-documented karst aquifers are about **0.1 to 1%** excepting for Dinaric karst where the effective porosity obviously exceeds 1%. Bonacci [1987] already listed different values from karst aquifers in various regions of the world (p. 47). The author proposes a median value for the effective porosity of about 1.6%; which may be seen slightly overestimated compared to values listed in the here-above table.

In reality, the development of the effective porosity is controlled by the distribution of the aquifers' vertical zones. As karst aquifers show a vertical zonation: soil, epikarst, vadose and saturated zones, and some privileged level and features for conduits development, a unique value reflecting the effective porosity of the aquifer is not relevant. Effective porosity in the epikarst zone is much higher than in the lower vadose zones (Mangin [1986]; Smart and Friedrich [1987]; Williams [2008a]). In the phreatic zone, the effective porosity is higher close to the interface with the vadose zone. It then decreases with the depth in the initial inception zone.

With regard to the values given in the previous Table 2—1 and the Table 10—1 (Appendix 10.2), values of effective porosity for the different karst zones may be proposed (Figure 2—4). These are still indicative and should be taken with caution.

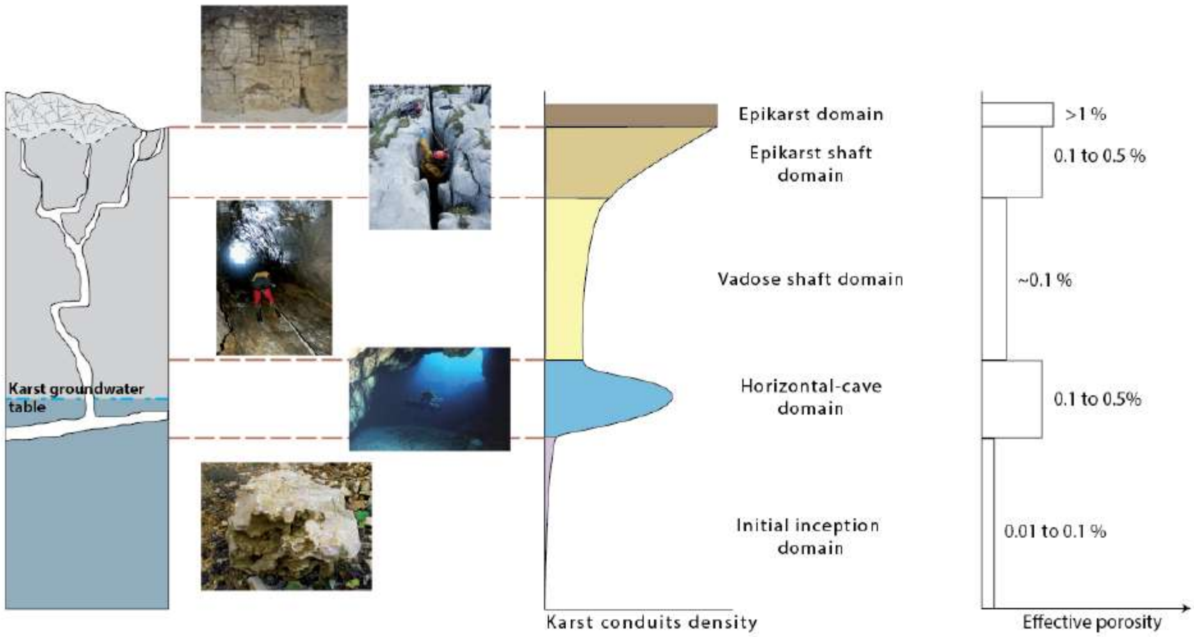


Figure 2—4. Vertical zones in a karst aquifer and associated ranges of effective porosity (completed from Filipponi et al. [2012])

2.1.3.3. Permeability

As the porosity, the permeability (ķ) is a characteristic parameter in hydrogeological science. It describes the ability of the water to flow through the ore space of rocks. ķ is usually expressed in m^2. Darcy introduced the hydraulic conductivity (K in m/s) as another expression of the permeability. In the Darcy's law (Equation 2—1), flows direction is guided by the hydraulic gradient while flow-rates depend on the hydraulic conductivity. This equation is valid as far as the hydrogeological media is considered as homogeneous and as far as flows are laminar (i.e. as far as the Reynolds dimensionless Number (Re) is lower than 2'300, see Reynolds [1883]).

$$\vec{\mathrm{q}} = -K.\vec{\nabla}H$$

Equation 2—1. Common expression of the Darcy's law formula; $\vec{q}$ refers to the flow velocity (LT-1), K is the hydraulic conductivity (LT-1), H is the hydraulic head (L)

Depending on the homogeneity of the materials which form the aquifer and on structural disturbances: faults, thrusts which may create weaknesses and then preferential flow-paths, the permeability's field may be seen (or not) as homogeneous at the scale of the flow-systems. Notion of permeability then requires to define hydrogeological units for which values of permeability may be associated.

In karst aquifers, it has been demonstrated by Kiraly [1975] that the measured hydraulic conductivity of carbonate rocks depends on the scale of the observation. Between metric observations and kilometric observations, hydraulic conductivities may vary for 3 orders of magnitude. Such enlarged permeabilities at large scale results from the conduit network.

Then, application of the permeability concept in karst aquifer usually requires to define two fields of permeability: a weak permeability for the matrix (i.e. the low permeability volume) and a large permeability for the conduits' zones. This practice is however not optimal as the low permeability volumes and the conduit network are heterogeneous medias and as conduit's flows are turbulent (i.e. Re > 4'000). In theory, the Darcy's law cannot apply correctly.

Therefore, the concept of permeability in karst is meaningless as it does not bring a signification of the real physical processes. Hydraulic laws (see next sections) are more adapted to the real physical processes and most parameters may be observed and measured in the field.

2.2. Karst flow-system

It appears essential to promote a clear and consistent definition of a **karst system** as the following chapters are dedicated to the hydrological and hydraulic description and simulation of these systems.

Various definitions of a karst system have been proposed in the literature: i.e. Kiraly [1970]; Mangin [1975], and Soulios [1985]. Definitions vary according to (i) the considered conceptual model and (ii) the methods of characterization. In the frame of this dissertation and in accordance with the KARSYS approach, a karst system will be considered as a **flow-system** (as defined by Tóth [1963]) draining one or several aquifers and exclusively or partially feeding one major karst spring (or a group of springs). A karst flow-system is usually formed by: a **recharge zone** (the catchment area), a **drainage zone** and a **discharge zone** (the springs zone) - these zones being further detailed hereafter – and it is defined for low- and high-flow conditions.

2.2.1. Recharge zone

2.2.1.1. Catchment area

The concept of **catchment area** is a basic element used in hydrology and was extended to hydrogeology. This is defined in hydrology as the piece of land feeding a given location of a stream (or river). Assuming that most of precipitation water runs off at land-surface towards streams and rivers, the delineation is usually based on topographic shape and can thus be obtained anywhere quickly and efficiently. However this procedure is not correct if the ground is highly permeable and pierced by conduits, as in karst environments. As mentioned by White, 2003; ["*The total area of the groundwater basin, including surface catchments of allogenic streams, is easily determined once the underground divides of the groundwater basin have been established*"].

The catchment area of a karst flow-system may then be defined as pieces of land-surface where at least one part of the precipitated water (i.e. a significant percentage) reaches the system output (spring or group of springs). This delineation may include pervious surfaces, where the water directly infiltrates (**autogenic zones**) and impervious ones (**allogenic zones**) from which runoff is discharged to autogenic zones where it infiltrates. A third surface, considered as "semi-pervious", may also be introduced. This corresponds to parts of the catchment where the water may form a surface stream, which may partially infiltrate, feeding the karst aquifer by leakage along the stream banks or through concentrated swallow holes (see Malard et al. [2015a] for further description).

In karst, tracing tests evidenced that water infiltrating at one location of the ground surface often reaches two or several karst systems. Such phenomenon in hydrology is called "**diffluence**" and is very frequent in the saturated zone of karst aquifers as the hydraulic gradient may considerably evolves in space and time leading to changes in the flow direction. The splitting of one conduit into two downstream ones is sometimes observed in caves and is a good explanation for such diffluence.

These observations tend to indicate that boundaries of a karst system - especially those in the saturated zones - are supposed to constantly change depending on the hydrological conditions. Thus for a given flow-system, the catchment area rarely has a fixed delineation. The extension of the recharge zone may significantly fluctuate. This induces that parts of a karst catchment area may belong to two or several adjacent karst systems…

Delineation principles of basin units and system catchment area are further explained in §. 6.1.

2.2.1.2. Surface drainage

The organization of **surface drainage** depends on the autogenic or allogenic nature of the catchment (Ford and Williams [2007]). Due to a high and quick infiltration capacity, outcropping karstified formations (i.e. autogenic areas) usually present a notably deficit of surface drainage compared to other geological environments under comparable climate. With the exception of small streams due to local imperviousness (for instance thin layer of marls), surface drainage features are scarce; they do not usually exceed a few hundreds of meters before being captured by the underground drainage. By contrast, the drainage network develops underground and its organization increases with depth, as the flow converges towards the system outlet(s).

Regarding allogenic areas, the geological nature of the zones is favorable to the concentration (convergence) of runoff forming surface streams which sinks through localized horizons to the underground drainage zone.

In some areas, under temperate climate, this absence of drainage features is used as an indicator for karst area (see Komac and Urbanc [2012]) or to assess the intrinsic groundwater vulnerability (see Vlaicu and Munteanu [2008]).

The concept of **drainage density** has been introduced by Horton [1945]. Regarding a hydrologic basin, the drainage density index is defined as the total length of perennial streams [km] divided by the basin area [km^2]. Schneider [1961] indicates that neither the selected scale nor the size of the basin induce a significantly change in the value of the drainage density for a considered area. Horton [1945] also defines the "critical distance" which refers to the minimal distance of **hyporheic** runoff to initiate a stream head at the surface of the catchment. This value depends on the infiltration rate, the slope of the catchment, the rainfall regime and the erosional sensitivity of the soil (Gregory and Walling [1968]).

Indications on perennial streams on maps should be carefully considered as they may reflect other factors than the infiltration solely. Furthermore, on most topographic maps, streams have been inferred from the period of the survey, or from the presence of a stream bed. These observation do not always reflect the conditions of a "**perennial stream**" – which is a great limitation over most of these maps, especially at local scale (i.e. 1/25'000 or higher). Besides the infiltration capacity of the geological formation, the distribution of perennial streams depends on:

- **The elevation:** rainfalls usually increase with the elevation leading to the initiation of more stream-heads.
- **The topography:** as the convexity of the flanks tends to increase with the elevation, the number of streams logically increases per surface unit. These decrease as the flanks progressively become concave (see typical cases for flanks of large volcanoes, or large detritic foot-slopes).
- **The local rainfall regime:** the trend is that the higher the rainfall regime, the higher streams density (flank exposure, etc.).
- **The presence of surrounding glaciers** (Gremaud et al. [2009]).
- **Anthropic changes of the hydrographic stream network,** especially in karst areas: e.g. pavement of stream-beds with concrete (see Trebišnjica river, Milanović [2004]), rivers bed sealing, etc.

As these parameters may disturb the relationship between the drainage density and the infiltration capacity of the geological formation, they have to be independently taken into consideration.

Even if the drainage density reflects a concrete hydrological process, existing data - mostly "frozen" topographic maps that are not related to specific hydrological conditions – are often not sufficient to systematically assess the drainage density of an area. Consequently, the drainage density index may be an indicator for identifying areas of high infiltration rate (i.e. karst) but it is not an exclusive one.

2.2.2. Drainage zone

The **drainage zone** (matrix, fissures and conduit network) refers to the structures which transmit the flows through the karst flow-system. This entails (i) flows through the matrix (i.e. the low permeability volumes of the aquifer), (ii) flows through the fissures network and (iii) flows through the networks of "**active**" karst conduits which develop for one part in the unsaturated zones and for the other part in the phreatic zone. "Active" means that conduits are permanently or temporary drained by groundwater. Active conduits are opposed to "**fossil**" conduits, which have been abandoned by the flows and remain dry all the time.

Ford and Williams [2007] (Table 2—2) introduced the **karst hydrographic zones** in order to distinguish the different components of the drainage zone through the flow-system. These zones are further described in the next sections.

1.	Unsaturated (vadose) zone*	1a. Soil
		1b. Epikarst (subcutaneous) zone
		1c. Free-draining percolation (transmission) zone
2.	Intermittently saturated zone*	Epiphreatic zone (zone of fluctuation of water table)
3.	Saturated (phreatic) zone*	3a. Shallow phreatic zone
		3b. Deep phreatic (bathyphreatic) zone
		3c. Stagnant phreatic zone

*Table 2—2. Description of the karst hydrographic zones which form the karst flow-system (from Ford and Williams [2007], p 107); * refers to zones that may be traversed by conduits (permanently flooded in zone 3). It should be kept in mind that lower horizons of soils and epikarst zones may also be partially saturated.*

An illustration of the drainage zones and the associated flows is given by the following Figure 2—5 for a typical epigenic karst flow-system.

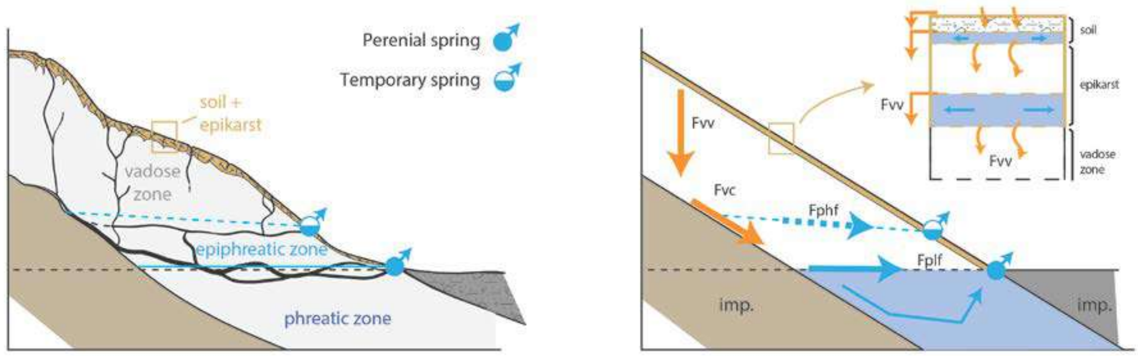


*Figure 2—5. Schematic cross-section of a karst flow-system (alpine or jurassian environment); imp.: aquifer basement, **Fvv**: vertical vadose flows, **Fvc**: basement-controlled vadose flows, **Fplf**: phreatic low-flows, **Fphf**: epiphreatic flows (figure from Malard [2013]).*

Regarding the Figure 2—5, flow conditions differ from a zone to another one. In the vadose zone, where the hydraulic gradient is vertical, water flows (**Fvv**) is unsaturated and almost vertically until reaching the top of the aquifer basement (**imp.**). At the contact with the impervious basement, flow (**Fvc**) is controlled by the topography of the basement until it reaches the phreatic zone. In the phreatic zone, the hydraulic gradient is controlled by the elevation of the spring or the elevation of an underground threshold, and by hydraulic conductivities. Therefore, flow (**Fplf**) is mainly horizontal – or nearly horizontal. Under high-flow conditions, the hydraulic head significantly increases within the system due to head-losses in conduits. The groundwater table raises leading to the generation of the epiphreatic flows (**Fphf**) which may activate upper passages and overflow springs. This mechanism may induce a strong modification of the hydrodynamics as new conduits may be activated leading to a reinforcement of the downstream discharge rate or diffluences toward adjacent flow-systems.

Drainage zones and their respective efficiency are evaluated as "**drainage capacity**". This notion has been introduced in surface hydrology but may be extended to karst hydrology. In karst aquifers, the drainage capacity is defined as the **flow-system discharge for a given hydraulic head**. Higher is the value of the drainage capacity, more efficient is the flow-system to transfer flows from the recharge areas to the discharge points. In surface hydrology, main parameters that control the drainage capacity are:

- The **density of the drains** (channels, streams, etc.) which is the cumulated length of the drains per surface unit (cf. Horton [1945]);
- The **distribution of the drains**: for a same density, a homogenous spacing of the drains will contribute to a larger drainage capacity than an anarchic spacing;
- The **organization of the drains**: a nested and ramified organization of the drains which progressively connect from upstream to downstream is a criteria of efficiency;
- The **caliber** (or equivalent diameter) and the **connectivity** of the drains must also fit with the usual high-flows of the system.

These parameters may be extended to karst hydrology as drains and channels are replaced by the conduit network. The main difference with surface hydrology concerns the **pressure** in the karst conduits due to the rise of hydraulic heads.

A deficit or an undersized of the here-above parameters lead to reduce the **drainage capacity** of the system which may be not able to easily transfer the recharge for large flows (Zhou [2007]). For high-flows, head-losses in conduits induce an abrupt rise of the **hydraulic gradient** in the system (up to several hundred of meters in alpine karst) and upper overflow zones activate. This considerably decreases the infiltration of more water. Surface streams may form in karst valleys (fed from runoff and temporary outlets) and become progressively significant; some of them may discharge several cubic meters per second (see Beuchire-Creugenat karst system, §. 6.3).

2.2.2.1. The unsaturated vadose zone

2.2.2.1.1. Subsurface drainage (soil and epikarst)

Subsurface drainage includes drainage through the soil and the epikarst.

In karst environments, water penetrates through the soil in two manners: infiltration through **diffuse interstices** (soils pores) and infiltration through **concentrated point features** (dolines, swallow holes or large open cracks). As soils in karst terranes are usually thin and highly permeable, they present a reduced storage capacity in comparison to other geological environments where soils are thicker and less permeable.

Water flowing through the epikarst zone usually presents two components: a **fast transfer component** and a **slow transfer component**. This indicates that the epikarst displays privileged flow-paths and slower ones, which correspond to the filling and emptying (i.e. overflowing) of local groundwater reservoirs.

The epikarst usually forms perched groundwater **reservoirs** with a relative significant storage capacity which contribute to feed the system over a long period after the recharge passed (see storage in § 2.3.2). A part of the water infiltrating through the soil and the epikarst quickly reaches the unsaturated zone of the aquifer and flows downward to the phreatic zone while another part is stored longer in the epikarst and may still contribute to the evapotranspiration.

In the Milandre test site - which is characterized by a significant diffuse recharge processes - Perrin et al. [2003] observed that soils and epikarst act as efficient storage and **mixing zones** which release groundwater to the vadose drains. Depending on recharge intensity, observations also indicate that the storage capacity of soil/epikarst may be exceeded for high-recharge periods; in that case, the excess of infiltrated groundwater may quickly by-pass the soil reservoir and/or the epikarst reservoir and flow through the vadose zone. In this view, the storage capacity of the unsaturated zone is mainly represented by the tandem soil/epikarst.

When the water penetrates the lower part of the epikarst, the hydraulic gradient increases and it forces water to lateral displacements through epikarst conduits. Water then circulates on a pseudo horizontal axe following a **ponds / thresholds functioning** which depends on the distribution of local hydraulic gradients. Migrations of the water usually do not exceed few dozens of meters (60 m for Friederich and Smart [1981]) except Zhou [2007] which observes displacement exceeding several hundreds of meters… before moving downward into the **epikarst shaft zone** via fractures or shafts.

These observations indicate that there is at least a **shaft each 30-50 m** in order to allow the discharge of the upstream corresponding catchment. This estimation is consistent with the observations made by Perrin et al. [2003] on the Milandre test site. Compiling other observations, Filipponi et al. [2012] estimate that a shaft should exist each **30 to 100 m in the epikarst shaft zone** (i.e. 1 to 10 shaft(s) pro 100 m^2).

2.2.2.1.2. The vadose free-draining zone

As illustrated in Figure 2—5, the vadose zone of the aquifer may be distinguished in two drainage zones: (i) the **vertical drainage zone** (Fvv) and (ii) the **down-dip controlled zone** (Fvc).

Drainage structures (shafts) in the vadose zone are mainly vertical leading to a rapid transfer of the groundwater from the epikarst to the aquifer basement. Filipponi et al. [2012] estimate that density of vertical conduits in this zone ranges between **25 to 100 shafts pro square kilometer** for the upper parts and decrease with the depth (see also Tscherfinger [2010]). This has been also evidenced by Barbel-Périneau [2013] who observe that flows inlets in a gallery penetrating into a karst plateau are divided by two between 0-200 and 200-400 m depth (2-3 shafts to less than 1.5 per 100 m of gallery) and re-divided by two between 200-400 and the deeper zone of the gallery (less than 1.5 to less than 0.5 shafts per 100 m of gallery).

Bottrell and Atkinson [1992] and later, Tooth and Fairchild [2003] or Garry et al. [2008] evidenced three flow components in the unsaturated zone, mostly reflecting storage processes in the epikarst. These are (i) a fast through-flow with a short residence time (a few days), (ii) an intermediate component (2 to 4 months) and (iii) a delayed and attenuated component (up to 6 months). Each component presents a specific hydrochemical signature in Total Organic Carbon (TOC), Magnesium (Mg^{2+}), pCO_2 and Calcite Saturation-Index or in Mg/Ca and Sr/Ca ratios. Flow components of very low residence time are characterized by low Mg^{2+} and high TOC concentrations while components of longer residence time have typical high Mg^{2+} concentrations and low TOC concentrations. The intermediate component shows low Mg^{2+} and TOC concentration. All intermediates do exist showing the possible mixing of the water flowing through the unsaturated zone.

Water in the vadose zone mainly transits through vertical fissures and enlarged free-air conduits. Under usual conditions and - excepting a few punctual passages which remain narrow or which could be partially collapsed - vadose drainage is usually not flooded. This indicates that the drainage capacity is sufficiently high compared to recharge. Palmer [1991] observed that vadose streams may develop independently from each other for great distances without joining.

Depending on the location and the extension of the phreatic zone, flows reach (i) the top of the phreatic zone or (ii) the top of the aquiclude unit. In the latter case, the base of vadose shafts will initiate an **underground stream** (Fvc) which will converge towards the phreatic parts of the aquifer, mainly guided by the slope of the basement and possibly influenced by the orientation and the extension of existing faults (Grillot and Drogue [1977]). As for surface hydrology, streams will organize as a branched-conduit network in order to collect water and to guide it toward phreatic zones.

Among other equations, flow in vadose conduits can be approached by applying the Manning-Strickler formula (Equation 2—2) which considers **losses by friction** along rough walls of karst channels (Manning's n coefficient).

$$Q = \mathrm{V.A} = \frac{1}{n}.AR^{\frac{2}{3}}.\sqrt{S})$$

Equation 2—2. Expression of the Manning Strickler formula; Q is the flow rate (m^3/s), V the flow velocity (m/s), A the flow area (m^2), n the Manning's roughness coefficient, R the hydraulic radius (m) and S the Channel (or conduit) slope (-).

The Manning's roughness coefficient (n) in conduits is usually assessed at 0.05 (see Jeannin [2001] for phreatic conduits). This value is not expected to change too much from case to case as all karst conduits are sculptured by similar dissolution processes. It is higher than values usually considered for rocks channels (n=0.035 Peterson and Wicks [2006], or n=0,03 ODOT [2011]) because cave conduits include not only small-scale discontinuities (cm-dm), but also pools, niches and curves (m-scale) which are usually not present in manufactured pipes or hand-made channels.

2.2.2.2. The saturated (phreatic) zone

According to the thickness of the phreatic zone, two zones may be defined: the **shallow phreatic zone** and the **deep phreatic zone** – also designed as **bathyphreatic zone** by Ford and Williams [2007], see Table 2—2 or **inception zone** by Filipponi et al. [2009]). In the phreatic zone, networks usually develop a hierarchized **interlacing** of conduits towards the main permanent outlet(s) of the flow-system. Observations show that most of the phreatic conduits develop close to the elevation of the base level that prevails during the karstification phase.

Under low-flow conditions (i.e. periods without significant recharge), due the high density, and the relative high **hydraulic conductivity** of the conduits, the **hydraulic gradient** in the phreatic zone is low and groundwater flows almost **horizontally**. Measurements of low-flow hydraulic gradients in the phreatic zone have been collected in the literature; mainly in the thesis of Worthington [1991a] (p. 113). Additional measurements were found in other papers and are listed in the Table 2—3.

Flow-system	Value (or range)	References
Lobos / La Galiana karst system, Spain	0.065%	Rosales et al. [2011]
Northwestern Yucatan peninsula	0.000005 to 0.00001%	Marín and Perry [1994]
Gargano aquifer, Italy	0.06% to 0.1%	Maggiore and Mongelli [1991]
Unconfined aquifer, Western Mount Vermion, Greece	0.02 to 0.05%	Marinos [2001]
Solana-Onteniente-Volcadores karst aquifer, Spain	0.1%	Ruiz-Constán et al. [2014]
Maligne Aquifer, Alberta	0.006%	Worthington [1991b]
Gravel-Leck Beck Head aquifer, UK	<0.1%	Waltham [1983] (in Worthington [1991b])
Stoke Lane aquifer, UK	<0.2%	Atkinson [1977] (in Worthington [1991b])
Luire-Bournillon-Arbois karst system, France	0.13%	Delannoy and Maire [1984] (in Worthington [1991b])
Apulia aquifer, Italia	0.03 to 1%	Grassi and Tadolini [1985] (in Worthington [1991b])
Hölloch karst system, Central Swizerland	<0.08%	Bögli [1980] (in Worthington [1991b])
W. Balcony Mountains aquifers, Hungary	0.08 to 0.65%	Erdélyi and Gálfi [1988] (in Worthington [1991b])
Tiemcen aquifer, Algeria	0.03	Collignon [1987] (in Worthington [1991b])
Trebeciano-Timavo aquifer, Slovenia	<0.046	Belloni et al. [1972] (in Worthington [1991b])
Gunung Sewu karst system, Indonesia	0.28 to 0.5%	Waltham and Brook [1980] (in Worthington [1991b])
Niangziguan aquifer, China	0.09 to 1.3%	Chen and Bian [1988] (in Worthington [1991b])
Friars Hole karst system, USA	0.2%	Worthington [1984] (in Worthington [1991b])
Elk River karst system, WV, USA	0.06%	Medville and Storage [1986] (in Worthington [1991b])
The Portal karst system, WV, USA	0.03	Medville, pers. Com (in Worthington [1991b])
Florida karst aquifer, USA	0.02 to 0.1%	Stringfield [1966] (in Worthington [1991b])
Mill Hole-Green R. Mammoth Cave, KY, USA	0.0095	Quinlan et al. [1983] (in Worthington [1991b])
Yucatan karst aquifer, Mexico	0.002%	Back and Hanshaw [1970] (in Worthington [1991b])

Table 2—3. Hydraulic gradient values measured in the phreatic zone for low-flow conditions in various karst flow-systems (literature review)

Values of Table 2—3 refer to values collected in the literature as well as those already collected by Worthington [1991a]. These show that, under low-flow conditions, and for a non-interrupted phreatic zone, the hydraulic gradient in the flooded conduit network is always low (a few ‰). This observation applies to most flow-systems.

Worthington [1991a] indicates that values exceeding 1‰ (i.e. 1 m/km) probably reflect a **perched water** table, without direct hydraulic relation with the downstream measurement point. In case where continuity of the aquifer is disrupted by faults that may **compartmentalize** the phreatic zone in distinct cascading blocks, the drainage in the aquifer is a succession of free and pressure flows (see Figure 5—7). However, each phreatic compartment is supposed to present a low hydraulic gradient.

The statement of a generalized low hydraulic gradient in the phreatic conduits makes possible to postulate that, knowing (i) the location (resp. the spring elevation) of the hydraulic base level of the flow-system and (ii) the location of existing hydraulic barriers in the aquifer, it may be possible to assess the extension of the phreatic zone under low-flow conditions. This assumes a low-amplitude gradient (usually 0.1%, even null) as considered in most studies (e.g. Shennan et al. [2014]).

A few exceptions do exist as locally, **hydraulic obstacles** in the phreatic zone may significantly increase the hydraulic gradient upstream (i.e. conduit shrinkage or partial obstruction). These may persist for a while until being dissolved or by-passed; it is merely a question of time. In case of **immature** karst systems, where the outlets recently dropped due to a rapid lowering of the base level, the hydraulic gradient in the phreatic zone may also remain “high” for a while until the conduit network adapts to these new settings (see for instance the Brunnmühle-Wasserhooliloch karst system (CH), Jeannin et al. [2015a]). Observations in similar contexts (e.g. karst flow-systems resulting from several phases of karstification) show that epiphreatic conduits are usually bigger than those in the actual phreatic zone. Epiphreatic conduits significantly contribute to the drainage capacity of the flow-system – and they even may discharge more water than permanent outlets for an hydrological cycle (see Aubonne-Toleure (Perrin and Luetscher [2008]), Beuchire-Creugenat (Malard et al. [2015a]), Brunnmühle-Wasserhooliloch (Jeannin et al. [2015a]), etc.).

Water in the phreatic zone mainly transits though the conduit and the fracture network. In the fracture network, water transits with respect to Poiseuille’s equation for **laminar** flows (cf. Equation 2—3) while in the conduit network, water transits with respect to Darcy-Weisbach’s equation as flows become **turbulent** (cf. Equation 2—4). As conduits are by several orders of magnitude bigger than fractures; they have a much larger drainage capacity compared to fractures. The hydraulic response is first discharged by the conduit network while fissured and fractured networks display a delayed response and of lower amplitude. During low-flow conditions, water is discharged from the “**low permeability volumes** of the aquifer” (including fissures and matrix porosity) towards the conduit network and supports base-flow.

$$Q_i = -\frac{b^3}{12\mu}\left(\frac{dp}{dx} - \rho g\right)$$

Equation 2—3. Cubic law of the Hagen-Poiseuille formula used for laminar flows in 2D planes (fracture network); ***Q_i*** *is the discharge,* ***b*** *is the fracture aperture,* ***μ*** *is the kinematic viscosity,* ***dp/dx*** *is the head-loss along the x axis,* ***ρ*** *is the fluid density and* ***g*** *is the gravitational acceleration.*

$$\frac{\partial H}{\partial x} = -\mu \cdot \frac{q^2}{2gd}$$

Equation 2—4. Common expression of the Darcy-Weisbach formula; ***q*** *is the mean flow velocity,* ***μ*** *is the friction coefficient,* ***d*** *is the conduit diameter,* ***x*** *is the flow length along the flow path.*

These two equations are close related; the Hagen-Poiseuille formula for circular conduits (not the cubic law) may be recovered by substituting the friction factor in the Darcy-Weisbach formula.

2.2.2.3. Intermittently saturated (epiphreatic) zone

The epiphreatic zone only forms for high-flows conditions. Under such conditions, head-losses along the phreatic conduits induce a more or less pronounced **rising of hydraulic heads** in the conduits flooding the lower part of the unsaturated zone. Hydraulic heads usually rise by 20 to 50 m in the conduit network, but larger values up to 350 m (Hölloch cave, Helvetic Alps, Switzerland) or 460 m (Luire, Vercors, France) can be observed under extreme event of recharge. However, these are not general observations as low values (a few meters) can also be observed in very mature karst systems (e.g. Mammoth Cave).

In this zone, groundwater flows may pass through an upper conduits system and/or they partially flood the vertical vadose conduits.

Over the ground surface, the rise of the hydraulic head may activate existing **overflow springs**, for which discharge rates may frequently become larger than those of the perennial springs.

The activation of upper conduits system or overflow springs contributes to decrease (significantly or not) the rise of the hydraulic head within the aquifer because new passages are used to drain water and global head-losses decrease. Figure 2—6 gives a schematic overview of various scenarios of the rise of the hydraulic gradient within the aquifer under high-flow conditions and the associated hydrographs in the downstream river and respective springs.

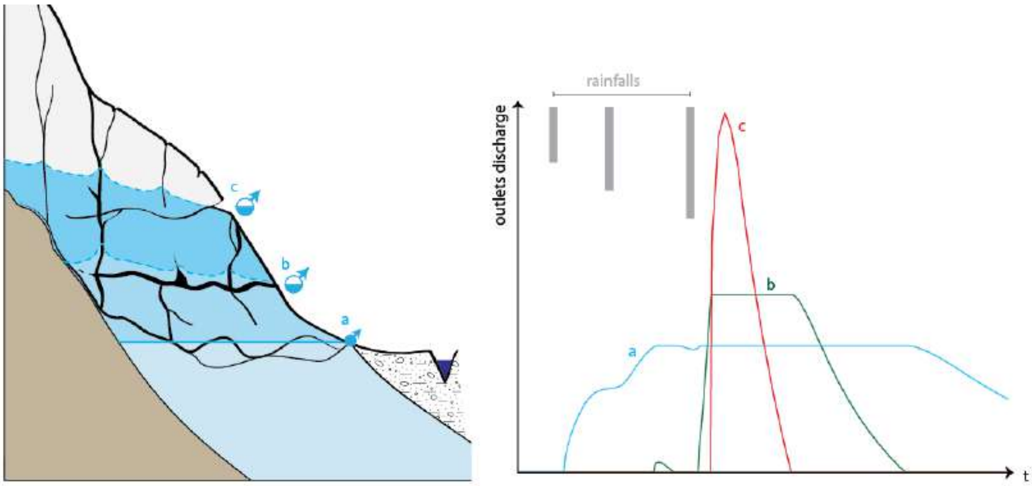


Figure 2—6. Schematic profile of the epiphreatic zone of a karst aquifer (left) and corresponding hydrographs (right). Recharge intensity, interconnection, elevation, volume and discharge capacity of the epiphreatic conduits are the main controlling factors of the hydraulic gradient evolution. While the hydraulic gradient rises and floods the epiphreatic zone (left), one part of the coming water is successively drained by overflow conduits, leading to a multi-component signal at the respective springs (right), while the other part may be stored and later released (figure from Malard et al. [2014a])

The Table 2—4 present some values of hydraulic gradients that have been measured in various karst flow-systems over the world for high-flow conditions. Most of these values were already inventoried and presented by Worthington [1991a]. Values show that high-flow hydraulic values may exceed several percent! Values collected by Worthington [1991a] range from 0.15 to more than 4.6%! These recorded values show that the evolution of the high-flow hydraulic gradients significantly vary from a system to another, and they even may be extremely variable for a same system. The rise of the hydraulic gradient in the conduit network depends on three parameters at least:

- The intensity of the recharge event;
- The drainage capacity of phreatic conduits (connectivity, equivalent diameters of the conduits, etc.) which control the drainage head-losses;
- The presence of conduits in the epiphreatic zone (e.g. by-pass conduits, filling chambers);
- The existence of temporary overflow springs;
- The presence of local constrictions (collapses, sediments, etc.).

Flow-system	Value (or range)	References
Lobos - La Galiana karst system, Spain	0.25%	Rosales et al. [2011]
Zhaidi karst aquifer, China	0.96 – 5.32%	Yi et al. [2014]
Beuchire / Creugenat karst system	0.7%	Vouillamoz et al. [2013]
Maligne Aquifer, Alberta	2.5%	Worthington [1991b]
Luire-Bournillon-Arbois karst system, France	2.6%	Delannoy and Maire [1984] (in Worthington [1991b])
Vaucluse karst aquifers, southern France	<0.28	Courbon and Chabert [1986] (in Worthington [1991b])
Hölloch karst system, Central Swizerland	4.6%	Bögli [1980] (in Worthington [1991b])
Jordtulla karst aquifers, Norway	0.15%	Lauritzen et al. [1985] (in Worthington [1991b])
Trebeciano-Timavo aquifer, Slovenia	0.38	Belloni et al. [1972] (in Worthington [1991b])
Friars Hole karst system, USA	<0.3%	Worthington [1984] (in Worthington [1991b])
Elk River karst system, WV, USA	0.5%	Medville and Storage [1986] (in Worthington [1991b])
Mill Hole-Green R. Mammoth Cave, KY, USA	0.28%	Quinlan et al. [1983] (in Worthington [1991b])

Table 2—4. Measured values of ***high-flow*** *hydraulic gradients in the phreatic zone for various karst aquifers (literature review); most of them have been obtained by linear extrapolation between two observation points.*

As a consequence, unlike the low-flow hydraulic gradient, it is almost impossible to generalize standard values of high-flow hydraulic gradients within a massif without knowing the properties of the conduit network.

Due to the rise of the hydraulic heads in the conduit network, interactions between two or more flow-systems draining the same aquifer or distinct aquifers might become possible (Bonacci [2001]; Taylor and Greene [2008], etc.). Through various observations, evidences for **diffluence** and their mechanisms have been demonstrated by several authors through:

- The observation of multiple output points of a tracer injected at one single location (Goldscheider et al. [2008]; Gosporadič and Habič [1976]; Luetscher and Perrin [2005]; Maurin and Zötl [1964]; Meus [1988], etc.);
- Direct observations in caves where underground vadose stream may divert, even for low-flows (Cabras et al. [2008]; Häuselmann [2003]; Wacker and Jeannin [1984], or the example of "gouffre des Partages", Bigot [2012]). Active diffluences for low-flow conditions reveal a capture process from a lower developing karst system leading to a progressive reduction of the underground catchment (Phillips and Walls [2004]). Palmer [1986] mentioned that diffluence processes are frequent in vadose zones, but it should be mentioned that most of diffluent streams converge in the phreatic zone;
- Hydraulic correlation analyses for two supposed disconnected systems (Bonacci [1988]), e.g. (i) two or more monitored outlets, (ii) monitored outlets and water table records (in piezometers, caves or vauclusian springs) and (iii) two or more water table fluctuations records.

Such divergences are difficult to identify and to locate without establishing an explicit model of the aquifer or without analyzing the evolution of the hydraulic heads and/or by comparing the discharge rate of the systems outlets. However, they may be of great significance in the hydrological budget of the systems and should be considered explicitly for designing a hydrological or hydraulic simulation model.

2.2.1. Discharge zone

This refers to the zone where all or part of the water flowing through the aquifer returns to ground surface, at permanent or temporary **karst springs** or other types of **outlets**. Karst springs may be seen as the principal (and usual) discharge point for the groundwater flows (Mull et al. [1988]). They fix the downstream boundary for the flow-system. Springs almost systematically exist because of the concentrated fast-flow component which cannot completely discharge otherwise (for example through an adjacent porous / fissure aquifer), especially for high-flow conditions. This implies that for each permanent karst spring (= flowing all over the year) a proper flow-system could be assigned.

Several types of karst springs do exist and most of them have been described by Ford and Williams [2007] depending on the aquifer and on the configuration of the flow-system (Figure 2—7). Springs located at the lowest point where the aquifer outcrops and submarine springs are usually considered as **permanent**, while **overflow springs** act as temporary outlets of the system, discharging only during high-flow periods.

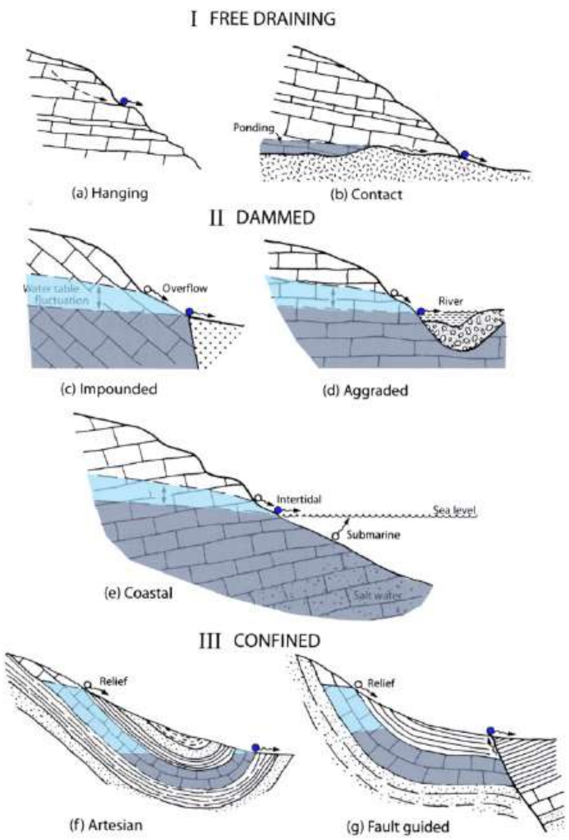


Figure 2—7. Karst springs are mainly of three types depending on the context of emergence: free draining springs, dammed springs and confined springs (figure from Ford and Williams [2007]). Whatever the context, if the epiphreatic zone shows significant fluctuations, one or several overflow spring(s) may exist upstream from the permanent one(s).

According to (i) the permanent karstification process of the aquifer and (ii) fluctuations of the base-level, the location of karst springs moves around the massif (Klimchouk et al. [2000]). Main permanent springs may be abandoned or may change for a temporary functioning due to the **base-level lowering** which provokes the incision (and activation) of a lower outlet. At the opposite, permanent springs may become **clogged** due to the rise of the base-level or be transformed into submarine springs. Because the position of the base-level is a direct boundary condition for karst hydraulics, karst systems–and by extension karst environment – must continuously adjust to changes occurring at land-surface. Human activities and settlement can strongly disturb (and resp. be strongly disturbed) by karst mechanisms: landslides, collapses, water flooding, dewatering, etc. Hydrological karst functioning is also sensitive to sudden changes after **cataclysmic** events (i.e. aquifer unclogging after a storm event, case of Vaison-La-Romaine in southern France, Lastennet and Mudry [1995]).

2.3. Hydrology

“**Hydrology**” is here defined as the functional relation linking precipitation to discharge and related components (recharge, flows, hydraulic head variations, etc.) while “**Hydrogeology**” is defined as processes and characteristics conditioning the water transfer from the recharge zone to the discharge zone (size of the system, infiltration characteristics, conduits organization, permeability, etc.).

2.3.1. Recharge

The **recharge** is defined as the sum of all the water components which contribute to the groundwater renewal of a flow-system. At the scale of a flow-system - whatever the context and for a defined period - the recharge may be assessed via the budget evaluation (or water balance) which could be expressed as follows:

$$\Delta S = P_{eq} - (Q_{out} + RET)$$

*Equation 2—5. Hydrological budget or (ground)water balance for a human non-influenced flow system; **ΔS** refers to changes in (ground)water storage, $\boldsymbol{P_{eq}}$ represents the equivalent precipitation, **RET** the real evapotranspiration, and $\boldsymbol{Q_{out}}$ is the water living the flow-system through the outlets.*

In karst environment, Q_{out} usually encompasses the sum of the surface streams (= Q_{str}, runoff over the catchment areas) and the karst outlets (= Q_k, permanent karst springs, overflow springs, underground overflows, etc.). Q_{out} may also include W, human withdrawals and E_x, the groundwater losses by exchanges to other adjacent (underneath) aquifers. C_k, the recharge by air condensation due to the ventilation of the aquifer should also be considered as a groundwater inflow component. The components of the karst groundwater recharge are schematically displayed in Figure 2—8.

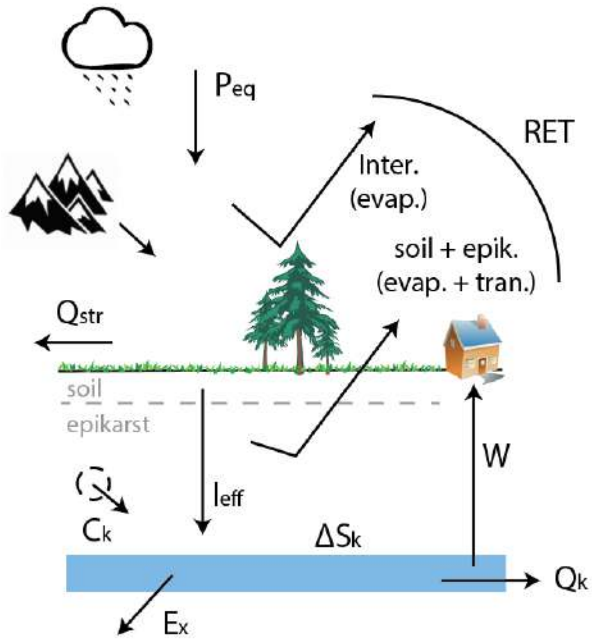


Figure 2—8. Schematic organization of the karst groundwater recharge components; each component is described here-after

Then, for karst groundwater recharge, the previous Equation 2—5 could be reformulated as follows:

$$\Delta S_k = P_{eq} + I_m + C_k - Q_k - Q_{str} - RET - E_X - W$$

*Equation 2—6. Hydrological budget for a karst flow-system; $\boldsymbol{\Delta S_k}$ refers to changes in karst groundwater storage, $\boldsymbol{P_{eq}}$ represents the equivalent precipitation, $\boldsymbol{I_m}$ is the water provided by glaciers melting, $\boldsymbol{C_k}$ is the inflow by underground air condensation, $\boldsymbol{Q_k}$, represents the karst outlets discharge, $\boldsymbol{Q_{str}}$ represents the losses by surface streams, **RET** is the real evapotranspiration, $\boldsymbol{E_x}$ represents the groundwater losses to other aquifers, and **W** reflects the eventual withdrawals for consumption.*

Two other notions may be introduced here as hydrological components of the flow-system: **groundwater resources** and **groundwater reserves** (Castany [1962]). The karst groundwater **reserve** is the volume of the saturated part of the aquifer under low-flow conditions multiplied by the known or assumed coefficient of effective porosity. Depending on the properties of the aquifer, groundwater reserves could reach a huge amount (i.e. in buried and well karstified aquifers) as well they could be neglected (i.e. shallow and juvenile karst aquifers). At the opposite, **resources** refer to the groundwater volume which is usually located within the upper part of the aquifer (epikarst and vadose zones). In the vadose zone, the resource volume corresponds to the oscillations of the epiphreatic zone from a few meters to dozens or hundreds of meters above the base-level of the aquifer (i.e. spring). Groundwater resources correspond to the annual water volume (m^3/year) discharged by the system. It can be approximated by the multiplication of the annual groundwater recharge by the size of the catchment area knowing that part(s) of the catchment may be diffluent.

Presence and significance of groundwater reserves mainly depend on the geometry of the aquifer while the groundwater resources depend on the recharge. Both also depend on the storage capacity.

2.3.1.1. Losses by surface runoff

The proportion of water losses by **surface runoff** in karst area compared to the proportion of infiltration is usually low and may even be neglected for most of the autogenic outcrops (see for instance Hess and White [2013] who wrote that there is no surface runoff in a **mature** karst aquifer). Another example is provided by Atkinson [1977] while working on the Carboniferous Limestone aquifer of the Mendi Hills in England. He evidenced that no surface runoff is generated over the catchment during recharge events.

This observation applies on most mature flow-system catchment – except locally where streams are indicated. Such streams are rare but some of them may develop and persist due to natural siltation of the riverbed (clogging of the interstices) or to artificial sealing. In that case, streams may collect a significant part of the runoff and export the water out of the catchment. For high-flow conditions, infiltrated water in the karst flow-system may lead to a saturation of the drainage capacity and to the rise of the hydraulic gradient above the surface. In that case, infiltration stops, groundwater overflows and temporary streams appear (see Maréchal et al. [2008]). Depending on the intensity and the duration of the event, these may represent significant water losses for the aquifers (up to 100%).

In less mature flow-system catchment, surface streams may also develop over the limestone and may drive water over relative long distance (see for instance Gremaud and Goldscheider [2010a] or Weber et al. [2012]) before it infiltrates.

Thus, consideration of runoff for the groundwater recharge evaluation is site-dependent. Potential streams driving water outside of the catchment boundaries and their associated regime should be identified and taken into consideration in the above recharge equation. In such conditions, the evapotranspiration is usually the limiting factor for the water to infiltrate into the aquifer.

2.3.1.2. PET and RET (potential and real evapotranspiration)

The concept of **PET** was introduced in hydrological models by Thornthwaite [1948]; it is defined as the reference **evaporation** + **transpiration** from soils/plants that occurs under adequate soil moisture supply at all times for given temperature and humidity conditions. PET strictly depends on climatic conditions. It can be measured on site or be computed by various models (Oudin [2004]). **RET** is defined as the **real evapotranspiration** which depends on the interception processes, the land-uses and the availability of the soil moisture. RET cannot be fully measured but estimated based on PET, on meteorological conditions, and on surface, soils and sub-soils properties.

After **equivalent precipitation** (i.e. the computed precipitation from rainfall, snow and snowmelt processes), RET is the second largest term to take into account for assessing groundwater recharge in karst area as runoff is usually of moderate significance. RET is obtained by the combination of the water loss by evaporation and transpiration from (i) the soil and sub-soil (E_v) and (ii) from the vegetation (T_R). RET is probably the most difficult parameter to assess properly. RET, E_V and T_R are expressed in millimeter per unit time – usually per year.

$$RET = E_V + T_R = \propto . \ PET, \qquad \propto \in [0; 1]$$

*Equation 2—7. **RET** is the sum of Evaporation (**E_V**) and Transpiration (**T_R**) and is part of **PET***

Evapotranspiration processes usually take place (i) above the soil, (ii) in the soil or (iii) in the first meters of the superficial aquifer(s) by evaporation and plants transpiration. Then infiltration becomes effective below the depth where the withdrawal from evapotranspiration is assumed to be negligible. In karst aquifer, the evapotranspiration may withdraw a significant part of the groundwater flowing through the epikarst, as proposed by Bakalowicz [2005b] or Williams [2008a]. Indeed, in numerous studies (Kiraly et al. [1995]; Perrin et al. [2003]) the assessment of the real evapotranspiration is related to the presence of a shallow aquifer where groundwater may be stored for a long time, and from which vegetation and evaporation can take water upwards to the atmosphere.

Main parameters controlling RET are:

- The vegetation type, the growth stage, the depth of the roots;
- The vegetation-cover over the catchment and its density;
- The net radiation (R_N) which is controlled by the solar radiation (R_S), the atmospheric radiation (R_A), and the terrestrial radiation (R_T). The net radiation may be expressed by the Equation 2—8.
- The relative aerial humidity (H_a), temperature (T_a) and the atmospheric pressure (P_a);
- The type of the soil, its moisture (H_s), its temperature (T_s) and its composition (porosity, permeability, thickness, etc.);
- The heat flux from the soil (G);
- The sunshine duration (SSD).

$$R_N = (R_s + R_A)(1 - \alpha) - R_T$$

*Equation 2—8. Net radiation formula; $\boldsymbol{R_S}$ is the solar radiation [W.m^{-2}], $\boldsymbol{R_A}$ is the atmospheric radiation [W.m^{-2}], $\boldsymbol{R_T}$ is the terrestrial radiation [W.m^{-2}] and $\boldsymbol{\alpha}$ is the value of Albedo [-]. The global radiation (**R**) often neglects the terrestrial radiation ($\boldsymbol{R_T}$).*

Several approaches and formulas do exist to assess PET depending on the context, the required time step and the available data (Thornthwaite [1944]; Turc [1961], Penman-McGuiness and Mustonen [1968]; Monteith [1965]; Priestley and Taylor [1972], etc.). Primault [1981] proposes a formula specific to the Swiss climatic conditions, valid between 250 and 1'800 m of elevation. The Haude method (Haude [1955]) requires a correction factor depending on the place where the formulae applies. Characteristics of these formulas - from simple ones to more complex ones - are listed in Table 2—5. They come from various sources of literature (Jeannin and Grasso [1995a]; Ward and Trimble [2003] and Oudin [2004]).

Authors	parameters	Time step	Context	Accuracy
Thornthwaite	K, T_a, I,	Monthly / 10 days	Central US, not applicable to arid and semi-arid regions	overestimate
Turc	R, T_a	Monthly / 10 days	Temperate climate	
Penman-Monteith	R_N, G, ra, ρ_A, rc, es, ea	Hourly / Daily		underestimate
Priestley and Taylo	R_N, G,	Daily		
Primault	H_A, SSD	Daily	Swiss Plateau (valid for 250-1'800 m of elevation	underestimate
McGuiness	T_a	Daily / Monthly	Temperate climate	
Haude	f_H, $p_{D,S}$, P_D, t	Daily	Humid climatic regions	

*Table 2—5. Various formulas to assess PET depending on the context, the available parameters and the computation time-step (literature review); $\boldsymbol{\rho_A}$ = air density [kg.m–^{3}], **ra** = (s.m–^{1}) aerodynamic resistance, **rc** (s m–1) canopy surface resistance, **es** (kPa) saturated vapor pressure, **ea** (kPa) real vapor pressure, **I** = monthly thermic index, $\boldsymbol{f_H}$ Haude factor (in mmPa^{-1}d^{-1}), $\boldsymbol{p_{D,S}}$ saturated vapor pressure (Pa), $\boldsymbol{P_D}$ current vapor pressure (Pa) and **t** the number of days for which the formulae applies.*

Most of these equations are expressed in various forms depending on the required time steps or accounting for local variability. In addition to these parameters, Thornthwaite and McGuiness formula also require indications on latitude and longitude of the catchment.

2.3.1.2.1. Interception

Water loss by evaporation during and after a rain (or snow) event over all types of surfaces is called **Interception**. In natural environments, interception processes depend on multiple factors such as: vegetation type, density, precipitation pattern, temperature, wind, solar radiation, etc. In urbanized areas, interception processes are controlled by the type and the shape of the urbanized forms and the presence of vegetation. Interception is of great importance in the hydrological budget as summarized by Carlyle-Moses and Gash [2011]; Gerrits [2010]; Herbst et al. [2008] or Kool et al. [2014]; it must be explicitly taken into account in groundwater recharge models as part of RET (see Figure 2—8 and Equation 2—5). As interception processes depend on the nature and the density of vegetation, seasonal variations are expected. For temperate climates, interception processes from the canopy are expected to be higher in summer than in winter. Two or three types of vegetation are usually described in the literature: **forests** (deciduous or coniferous trees), **cultivated lands** and **meadows** (or pastures). In addition, **urban areas** should also be mentioned as interception processes are significantly different from those in non-urbanized areas.

Horton [1919] was the first author who described interception processes. He suggested a series of equations to evaluate the annual interception for tree-covered surfaces depending on the nature of the trees. Gash [1979] established a first analytical model to assess the different components of the interception for a forested area. Since that time, abundant observations and measurements have been achieved. The **Gash model** is still utilized, and is continuously improved by researchers working on the field (Muzylo et al. [2009] or Zhang et al. [2011]). Models become complex (to establish and to calibrate) as they include details on the different components of interception (e.g. canopy storage capacity, trunk storage capacity, understory, stemflow, throughfall coefficient, etc.).

Basically, for each type of vegetation or areas, interception processes may be approached by reservoirs for which storage capacity evolves with the seasons - depending on the flowering / ripening stages. Stored water is lost by evaporation (part of RET) and overflows are supposed to pass through the soils (see Figure 2—9).

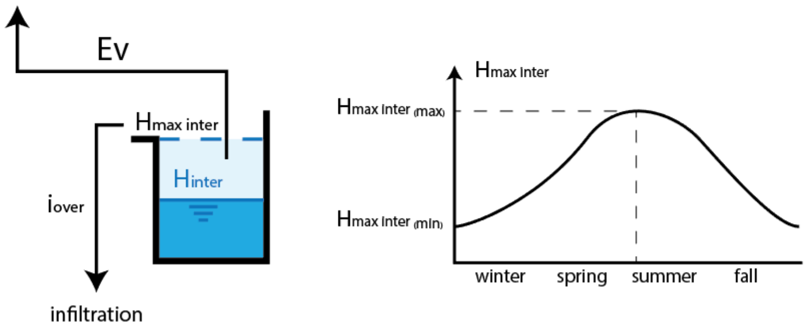


Figure 2—9. Structuration of interception reservoir; $\boldsymbol{H_{max\ inter}}$ *fixes the storage capacity which evolves with the seasons,* $\boldsymbol{H_{inter}}$ *is the stored water,* ***Ev*** *the losses by evaporation and* $\boldsymbol{i_{over}}$ *the part of water infiltrating through the soils.*

Such reservoirs may be declined for forests, cultivated lands, meadows, urban areas, etc. The challenge is to fix the seasonal variations for a given environment, as surprisingly only a few measurements do exist in the literature. Indeed, most published papers provide mean values for a hydrological cycle (see the synthesis by Zhang et al. [1999]) and only a few of them quantify the seasonal variability. Indeed, as indicated by different authors working in the field, monitoring and sampling devices with the aim to measure accurate values over a long period of time and for a large test site are extremely difficult to implement (Link et al. [2004]; Muzylo et al. [2009]). Furthermore, due (i) to meteorological factors and (ii) to the variety of vegetation that constitutes forests, meadows or cultivated lands, interception rates may be quite different; and for a same place they may also significantly differ from one year to another. In the following sections, interception processes are discussed according to the environments in order to fix orders of magnitude of storage capacity for the **interception reservoirs**.

2.3.1.2.1.1 Forest areas

In **forest areas**, interception is of two types: interception (resp. evaporation) by canopy and trunks and interception (resp. evaporation) from the forest floor (see Asadian and Weiler [2009]; Gerrits et al. [2010]; Herbst et al. [2008]; Levia et al. [2011], etc.). Globally, most authors estimate that **net canopy and trunks interception** ranges between 15 and 30% of the equivalent precipitation. Regarding a mixed deciduous forest in England, Herbst et al. [2008] found that annual interception by the trees (mainly oaks) is about 24.9% of the equivalent precipitation (respectively 192.2 mm and 773.1 mm). In a beech forest in Luxembourg, Gerrits et al. [2010] find that evaporation from intercepted water by the leaves is in average 5% of the rainfalls in winter when the leaves drop off and 18% in summer when leaves are developed. The author found that **interception from the forest floor** is more or less constant over the seasons, but a peak occurs in fall. This peak may be explained by the freshly fallen leaves which are curled when they just drop. This curled shape causes a bucket-like leave, with an enhanced water storage capacity. When time passes, the leaves become slowly more flat (especially after snow events, leaves are really flattened by the weight of the snow), and the interception globally decreases.

Still regarding seasonal variability, Specht and Specht [1989] observed that the coefficient of evaporation from the vegetation is multiplied by 2.5 between winter (when the leaves are off) and the summer boom of vegetation. Interception of the forest floor (understory) is less variable; it reaches 26% in winter and 36% in summer. In this view, a whole forest catchment may lose up to 50% of precipitation by interception… This value may appear somehow extreme under temperate climate but some other observations may attest of high interception. For example, in the elevated Jura Mountains, Tripet [1972] measured that the snow stock in forest area is half of those in pasture or non-vegetated area. This means that during wintertime, evaporation and sublimation of the intercepted water (resp. the snow) in forest areas may represent 50% of the equivalent (or gross) precipitation. Such high rates may be related to the nature of the forest, essentially composed by conifers (spruces, etc.). Indeed, other authors already observed that conifer forests present higher rates of evapotranspiration than deciduous forests (see by example Kędziora and Olejnik [2002]), particularly in winter and early spring seasons (ex. of northern Sweden, where interception losses by the conifers forests reaches 45% of the gross precipitation due to their persistent needles, Alavi et al. [2001]). Another example; in a German forest, Benecke and Van Der Ploeg [1975] demonstrated that annual evapotranspiration of spruce plantations exceeds those of beech plantations by about 100 mm, which is far from being negligible…

Regarding **storage capacity**, Link et al. [2004] estimate the canopy storage capacity for Douglas-fir-western hemlock ecosystem and found seasonal values of 3.0 mm in the spring and fall and up to 4.1 mm in the summer. Herbst et al. [2008] measured a storage capacity of 1.25 mm for a leafed canopy and 0.88 mm during the leafless period in a mixed deciduous forest in England. A very interesting contribution has been made by Gerrits et al. [2010] who measured the monthly evolution of the storage capacity for a beech forest (Figure 2—10); the average capacity evolves from 0.1 mm in February to 1.2 mm in June. However, within a same month, measurements show a large variability, especially in spring and summer (± 50 to 100% of the average value).

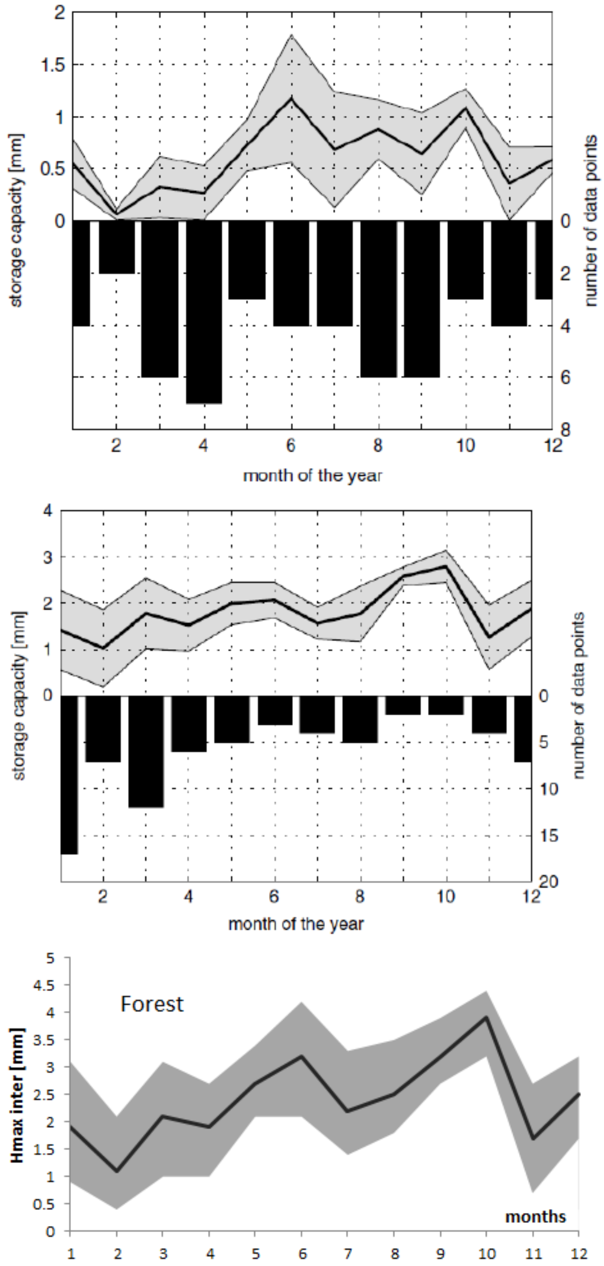


Figure 2—10. Seasonal evolution of the storage capacity for a beech forest (above: only the canopy, center: forest floor, below: canopy + forest floor) in Luxembourg (measurements from Gerrits et al. [2010]). Regarding the canopy, the storage capacity varies from 0.1 mm in February to 1.2 mm in June. As the falling season appears, the storage capacity (i.e. the interception power) significantly decreases. Regarding the forest floor, the maximum is reached in fall.

Finally, when looking at these values, we assume for **deciduous** forests that the **winter storage capacity is about 1 mm** (trunks + canopy when the leaves are off) and **in summer it may be about 2-3 mm**. For **coniferous** forests, the **winter storage capacity is of 2-3 mm**, while **in summer it may exceed 4 mm**. At least, in a **mixed forest**, the storage capacity may be considered about **2 mm in winter and 3 mm in summer**. This order of magnitude is also preconized by Breuer et al. [2003] for a deciduous forest (under temperate climate, the author found diverse values in the literature as 1.6 mm for a beech-wood or 0.6 to 2.7 mm for an oak-wood), while more extreme values may be used for dense coniferous woods (up to 9 mm!). Under European temperate climate, the authors found a mean value (annual) of 1.4 mm for deciduous forests and 1.8 mm for coniferous ones. Finally **in considering forest floor** (and/or understory forests) and canopy, the authors recommend **3.4 mm for deciduous forest and 3.8 mm for coniferous forest as annual average** as the storage capacity for understory is fixed at 2 mm.

2.3.1.2.1.2 Meadows and cultivated lands

In **cultivated lands**, the interception depends on the type of the **crops** (vine, cotton, maize, soy, Potato, Tomato, etc.) and their respective flowering / ripening stages and the crops rotations; a large spectrum of values do exist (i.e. Feddes [1987]). Olesen and Jensen [2013] propose a revised table of interception values for usual crops based on the synthesis of 51 studies dedicated on the topic in Europa but they are only available for an annual cycle. Dedicated studies demonstrated that short grass and crops intercept 20 to 48% of the rainfall during the growing season in average (Zhang et al. [1999]). Kędziora and Olejnik [2002] also observed that crops growing throughout the season (alfalfa or grass) show a higher amount of evaporated water than crops with shorter growing periods, such as wheat or sugar beet.

Regarding the global water balance, Kędziora and Olejnik [2002] found significant differences between forests and cultivated fields under continental climate in Poland. Over a hydrological year, surface runoff is about 10 mm in forest and 140 mm in cultivated fields, evaporation is 540 mm in forest and 420 mm in cultivated fields while infiltration is 470 mm in forest and 400 mm in fields. The presence of trees clearly increases interception and evaporation processes compared to cultivated fields. Conversely, the authors found that runoff is significantly higher in fields. However, in karst areas, local-scale runoff is expected to find some infiltration spot and to by-pass soil and possibly epikarst. In this view, infiltration may then become larger in fields areas than in forest. The same authors estimate that the maximum **evapotranspiration rate for a crop is about 0.35 mm/h** (early afternoon in June). This represents up to 5 mm of evapotranspiration per day in these conditions. For **meadows or pasture**, intensity of the interception is usually determined by using the **Leaf Area Index** (LAI) which informs on the density of the vegetation (the foliage). LAI is defined as the total one-sided area of leaves per unit ground surface; it may be obtained by aerial photography or spectral images. For a given vegetation, the evolution of the LAI fixes the percentage of the total rainfall which does not reach the soil (= evaporation coefficient "**k**"). The following Figure 2—11 shows an observed relation between the LAI and the evaporation coefficient k.

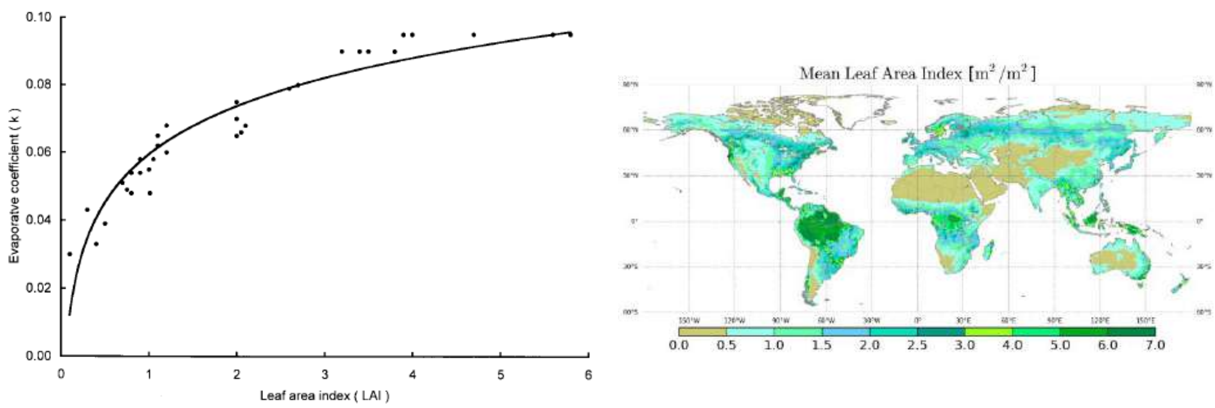


*Figure 2—11. Example of relation between the vegetation Leaf Area Index (**LAI**) and the coefficient of evaporation for temperate climate (*Specht and Specht [1989]*); the map provides an overview of the LAI mean distribution over the world.*

Regarding the graph, it appears that k follows a logarithmic curve as LAI increases. For given vegetation, evaporation coefficient may be multiplied by 5 as the LAI increases from 1 to 4. Most of the physical-based hydrologic models express the interception capacity by using the following (or similar) equation based on LAI:

$$Int_{max} = \alpha\ .\ \mathrm{LAI}\ \ [\mathrm{mm}]$$

*Equation 2—9. Example of formulation for the maximum interception capacity [mm], see Hydrological Model JAMS-J2000 (*Fink et al. [2007]*); Where α is the storage capacity per square meter of leaf area against the precipitation type (rain or snow) and **LAI** is the Leaf Area Index of the considered surface. The net precipitation occurs once the interception storage capacity is exceeded (= throughfall). The coefficient **α** is usually determined on the field.*

Regarding storage capacity, based on field experiments, Crouse et al. [1966] found an equivalent storage capacity of **1.3 mm for Californian meadows** that are exclusively composed of fat grass and exposed to dry, hot summers and rainy, mild winters. Based on synopsis of the literature, Breuer et al. [2003] proposes for European climate a mean storage capacity (annual average) of **1.5 mm for herbs, forbs and grasses (meadows) and of 2.9 mm for crops**. From this point of view, interception capacities for crops or meadows (pastures) environments are barely higher than for forests when only considering trunks and canopy.

2.3.1.2.1.3 Urban areas

In **urban areas**, Asadian and Weiler [2009] found that interception by vegetation is twice higher compared to natural environments (up to 98% of interception for a rainfall event of 26.3 mm) for a comparable cover of vegetation type (here coniferous). They suggest that the higher temperatures in urban areas and the open grown canopies of urban trees are the possible reasons for these differences. However, at larger scale, interception is usually lower in urban areas due to anthropic surfaces (pavements, concrete, asphalt, etc.). The storage capacity for interception reservoir in urban areas may reach **0.5 to maximum 1 mm** without significant evolution with the seasons.

2.3.1.2.2. Evapotranspiration from the soil / epikarst

In the review from Kool et al. [2014] about the partitioning between **strict evaporation** (from surface interception) and **(evapo)transpiration** (from soils and sub-soils), the authors wrote that evaporation from intercepted water globally accounts for 20 to 50% of the real evapotranspiration in forested areas, while it accounts for 20 to 40% for row crops; the remaining part comes from the (evapo)transpiration of the infiltrated water. Thus, interception does not represent the largest part of the total evapotranspiration processes.

After being infiltrated, a part of the water stored in the soils and in the shallow saturated part of the epikarst is later retrieved by plants consumption (transpiration) and by evaporation (due to underground air ventilation). Most of the water uptake by the vegetation comes from the soil (the shallow saturated part of the soil “LS”, see Figure 2—3). As mentioned by Schwartz et al. [2013], studies on various karst areas – mainly for dry climates – suggest a limited use of epikarst water by the trees. Roots depth depends on tree-species and on their age. As written by Crow [2005], usual roots depth for a tree may reach 1.5 m to 3 m but more than 90% of the tree’s total root length develops in the upper 1 m of soil (even less in karst areas as soils are not that depth). As a consequence, only a few roots may penetrate the epikarst and retrieve water – at least for a given period in the year. In practice, ET from soils and epikarst is computed from the potential evapotranspiration (PET) plus the evaporation from interception (E_V) and it depends on the water availability in soils and in the epikarst (H). The Figure 2—12 gives the general model for the reservoirs.

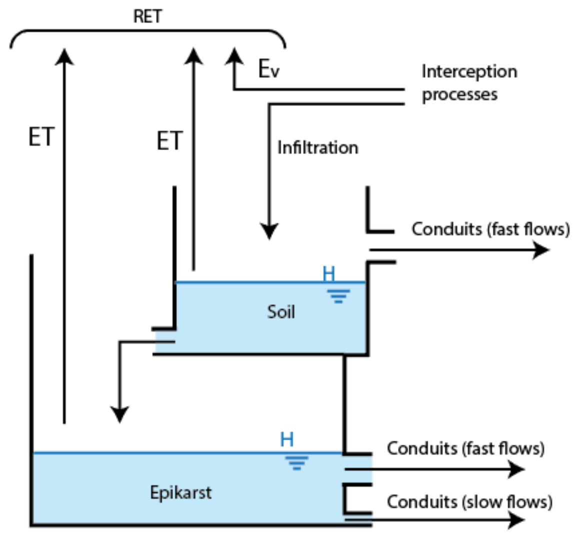


Figure 2—12. General model of flows through soils and epikarst; depending on the saturation of the reservoir, a part of the flows may by-pass the soil or the epikarst and reach the conduit network. Water stored in these reservoirs contributes to evapotranspiration ET. ET depends on PET, E_V from the interception and H, the water stored in soils and epikarst.

The evaluation of the effective infiltration in karst aquifer must then explicitly take into account these components (see application in §. 6.3.3).

2.3.1.3. Condensation (C_k)

Although in karst systems of temperate regions most of the recharge results from precipitation and glacier melting, some authors introduced the fact that karst aquifers may be partially recharged by **condensation** of the air fluxes circulating through the vadose zone. As written by Dublyansky and Dublyansky [1998], condensation processes may occur in the vadose zone of all karst aquifers especially for those located between 25° and 70° of latitudes lying below 2'600 m of elevation. This process is interesting because it makes it possible for an aquifer to be even recharged without precipitation.

For these considered latitudes (Northern hemisphere), recharge by condensation is expected to dominate in warm periods, i.e. April to September while water may evaporate from the aquifer during winter periods as warm air from the underground flows out towards the atmosphere. Even if the process theoretically applies for all karst aquifers presenting a thick vadose zone, the intensity of the condensation is strongly conditioned by the climatic regime, and the morphology of the aquifers and of the outcropping zones.

Several methods do exist to estimate the condensation knowing the **air water-content** and the **ventilation**. Values of detailed microclimatic studies in caves reported by Dublyansky and Dublyansky [1998] indicate that the amount of condensed water by the air circulating in caves ranges between a few grams (3 to 6 g/m^3) to several dozens of grams (up to 80 g/m^3). These may be seen as extreme values depending on the season, the elevation, the moment of the day, the air-flux, etc. After having studied 15 sites in Crimea and in Western Caucasus during dry seasons (4 to 6 months), authors estimated a seasonal recharge by condensation ranging between 4 and 5 L/s/km^2. Extended over the annual cycle, authors estimate that recharge by condensation is about 1.5 to 2 L/s/km^2. It then represents a few percent of the annual recharge rate of the flow-system (max 10%).

Working on ventilation processes, Lütscher and Jeannin [2004] suggested that an average ventilation for a 1'000 m-thick karst aquifer may reach 150 m^3/s.km^2 (order of magnitude). In these conditions, for a 1'000 m-thick karst aquifer and considering the different ranges of air water content proposed by Dublyansky and Dublyansky [1998], recharge by condensation ranges between 0.5 to 12 L/s.km^2!

Thus, for a more widespread type of karst aquifer presenting a vadose zone of 100 m-thick, **recharge by condensation may reasonably reach (and may even exceed) 1 L/s.km^2**…

2.3.1.4. Effective infiltration (I_{eff})

Once the water passes through the vadose zone, it can be considered as **effective infiltration**. Effective infiltration may still be completed by contribution from the condensation C_k or diminished by evaporation in the vadose zone. The "**net recharge**" is defined as the residual water that reaches the phreatic zone or the top of the aquiclude unit.

In his work on the hydrology of the Gallusquelle (Swabian Alps, Germany), Sauter [1992] developed a detailed recharge model for a covered karst aquifer by explicitly considering interception and evapotranspiration processes on the spring catchment. The author already considered these two processes in the calculation of the effective recharge over his test-site. Indeed, the catchment is characterized by a low contrast of elevation and by various land-uses. 60% of the Gallusquelle catchment is covered by forests (70% of coniferous and 30% of deciduous species). The remaining 40% of the catchment is composed of cultivated fields (65% for grassland and the rest of arable land). Starting from the work made by Sokollek [1983], who extended the computation of the PET with the Haude method (Haude [1955][1]), Sauter observed that the main deficiency of this formulae is the non-consideration of interception processes. He then developed three separate interception sub-models;

[1] The Haude formulae is based on air temperature and air humidity. It has been strictly developed for grasslands, cultivated and forested environments.

the first one for the coniferous area, the second one for the deciduous area and the third one for the cultivated fields.

Regarding the upper (soil equivalent) reservoir, Sauter fixes a residual storage of 50 mm. The author also considers that recharge does occur during the summer period even if the soils moisture is deficient as small recharge events may be observed at the spring. This observation suggests that the upper reservoir may be by-passed for heavy rainfalls before the soils and sub-soils become fully saturated (same observations in Perrin et al. [2003] for the Milandre cave). Water may be diverted to enlarged cracks in the epikarst zone and reaches the lower unsaturated zone of the aquifer. He observed that rainfall excessing **6 mm/day** may contribute to an **effective recharge** of the lower aquifer – even if the upper reservoir remains deficient. Thanks to this model which provides a better discretization of the recharge components for the successive aquifer compartments, the author estimated an **effective infiltration** of about 390 mm/yr (i.e. a specific recharge rate of 12.2 L/s/km^2). For comparison, Jeannin and Grasso [1995a] found 399 mm, 550 mm and 482 mm at Milandre (Swiss tabular Jura) for three consecutive years.

2.3.2. Storage

Storage (S) is defined as the amount of water stored in the flow-system for a given time. **Storage changes** (ΔS) are obtained from the Equation 2—5 for a defined time-step; it corresponds to the difference between the **instantaneous recharge** and the **instantaneous discharge** flowing out the hydrological system. ΔS may be positive of negative. Thus, for a given period, S may reflect a gain or a loss of water for the flow-system. For a considered flow-system, the storage capacity mainly depends on three parameters: the effective porosity of the aquifer zones (see §. 2.1.3.2), the drainage capacity of the flow-system and the thickness of the aquifer (saturated + unsaturated zones). The Figure 2—13 shows how these parameters control the storage capacity for a given flow-system.

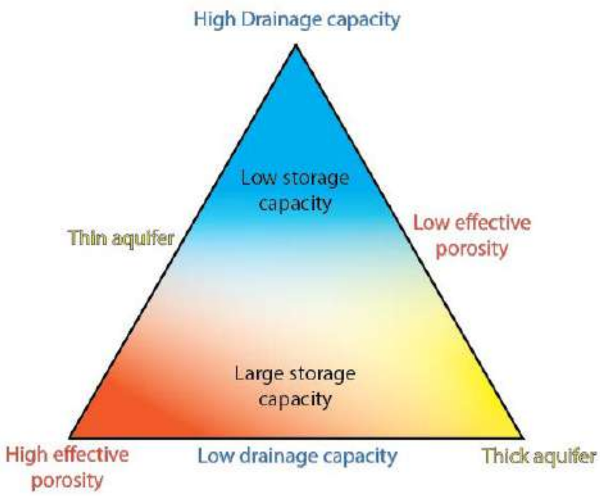


Figure 2—13. Combined effects of the drainage capacity, the aquifer thickness and the effective porosity on the storage capacity of the aquifer

Two types of storage can be distinguished in karst aquifers: the **minimal low-flow storage**, which makes it possible for the flow-system to maintain flows after a prolonged period without recharge and the **seasonal storage** reflecting the amount of water stored in the aquifer between the annual low- and high-flow periods.

A third type of storage does exist in karst aquifers: the **short duration storage** during a recharge event. Indeed, due to the relative high infiltration rate, to the organization of the voids and to the presence of overflow outlets, karst aquifers may temporarily retain and slow down one part of the infiltrated water. Depending on these site-specific characteristics, system's hydrological responses are usually non-linear. Short duration storage mechanisms are variable from a site to another and required dedicated monitoring and additional data to be reproduced. Therefore, this short duration storage is not further discussed here. A sketch of a possible method for its analysis is presented in Malard et al. [2014a] (see Appendix 10.3).

Storage in karst potentially takes place in **different zones of the aquifer**: in soil, in the epikarst, in the vadose and in the saturated zone of the aquifer. Even if soils and epikarst may be treated as secondary when looking at the decametric or hectometric scale of the aquifer, both play significant role on hydrology and hydrochemistry the infiltrated water (see Aquilina et al. [2006]; Perrin et al. [2003], and Schwarz et al. [2009]). At the scale of a flow-system, different authors (Atkinson [1977]; Jeannin [1996]; Smart and Friedrich [1987], etc.) demonstrate that 50% of the stored water lies in the epiphreatic zone while the other 50% divides into the soil and the epikarst. The Table 2—6 lists different values from the literature concerning the storage capacity in the different compartments of karst aquifers.

Sites and authors \ aquifer compartments	Soils	Epikarst	Vadose zone	Phreatic zone
Atkinson [1977] (Great Britain, carboniferous limestone)				Conduit storage: 0.031% Fissures and matrix storage: 0.92% (coeff. ~0.01)
Teutsch [1988] (Swabian Alps)	60 mm			
Sauter [1992] (Swabian Alps)	50 mm	20 to 30 mm for a 3 m thick zone (i.e. coeff. ~0.01)		Conduit storage: 0.2 to 2.3 mm for a 2 to 15 m thick saturated zone (i.e. coeff. ~0.0003) Fissures and matrix storage: coeff. 0.01 to 0.02
Jeannin and Grasso [1995a] (Swiss tabular Jura)	Water humidity storage: 140 mm			
Grasso [1999] (Swiss tabular Jura)	138 mm			
Emblanch et al. [2003] (Southern France, Vaucluse karst system)	126 mm for both epikarst + unsaturated vadose zone (the authors do not mention the soils in the evaluation)			
Perrin et al. [2003] (Swiss tabular Jura)	Up to 138 mm (values from Grasso) mostly in soil + epikarst			
Worthington et al. [2000] (various sites)				Conduit storage: from 0.05 to 2.8%
Meeks and Hunkeler [2015] (Swiss folded Jura)	50 mm			

Table 2—6. Values from the literature regarding the storage capacity for different compartments in karst aquifers (non-exhaustive); there are very few values for the epikarst and for the unsaturated zone.

Regarding **soils**, evaluations show that the soil-storage capacity ranges from 50 to 140 mm and may include the **epikarst zone**. These differences may result from the average thickness of the soils (soils are 1 m thick for the Swiss jurassian karst aquifer and up to 5 m in certain locations; in the Swabian Alps, soils thickness ranges between 20 and 80 cm, see Sauter [1992]).

In the **vadose zone**, the storage capacity is difficult to assess as this zone is never assumed to be fully saturated. There are only few studies that intended to evaluate the storage capacity of the unsaturated zone. Most of them come from the University of Avignon (France) and focus on the Fontaine-de-Vaucluse karst system (see for instance Emblanch et al. [2003]). Therefore, these authors defined the unsaturated zone as the intermediate zone between the soils and the saturated zone – they did not explicitly distinguish the epikarst from the lower vadose zone. Then, the values which have been assessed by the authors cover the tandem epikarst + lower vadose zone…

Depending on the drainage capacity, the lower part of the unsaturated zone may periodically flood for several dozen to hundreds of meters. Groundwater is supposed to store in the **epiphreatic conduits** as well as in **fissures** of the **low permeability volumes**. It is expected that karst system presenting only a few base-flow outlets with a limited drainage capacity (generating significant head-losses) and without overflow spring are more favorable to storage than other aquifers presenting large outlets and overflow springs.

2.3.2.1. The minimal low-flow storage

The **minimal low-flow storage** is defined as the amount of water released by the aquifer after a prolonged period without recharge.

Such amount of water is usually assessed by analysis of the **recession curves** for a flow-system. Different mathematical laws do exist in order to extrapolate the recession curves (see Bonacci [1993]; Drogue [1972]; Ford and Williams [2007]; Forkasiewicz and Paloc [1965]; Mangin [1970a]; Paloc [1969]; Schoeller [1965]; Toebes and Strang [1964], etc.). Most of these authors use logarithmic and exponential laws. These are applied from the last inflexion point of the recession curves and are extrapolated until reaching zero. This period refers to the **persistence** capacity of the system without being recharged. Field data show that extrapolations tend to overestimate the flow decrease, i.e. to underestimate the volume of the storage.

Low-flow storage may represent a significant groundwater volume. An example is provided by Grasso [1999] who estimated the low-flow storage capacity of the Milandre karst aquifer (adjacent to the Beuchire-Creugenat karst system), in analyzing recession curves. The author found a storage capacity ranging between 600’000 and 900’000 m^3 for the sub-system of Milandrine-amont for which the catchment area nearly covers 4.5 km^2. This corresponds to an average storage of **133** to **200 mm**. Jeannin and Grasso [1995b], who previously worked on the same site, postulated that only one part of the low-flow storage takes place in the low-permeability volumes of the epiphreatic zone. By analyzing the water table fluctuations in boreholes penetrating the low permeability volume of the aquifer, they obtained a storage ranging between115’000 and 162’000 m^3, i.e. **26** to **38 mm** (by considering an effective porosity from 0.7 to 1%), then most of the storage is expected to develop in the soils and in the epikarst. Working on the same site, Perrin [2003] confirms that soils + epikarst zone may store up to **138 mm**. He concluded that the storage in the phreatic zone is of moderate importance for this site compared to the epikarst. This observation is coherent as phreatic and epiphreatic zones related to this flow-system are of moderate extension.

For a wet year, this storage may not be solicited. In this case, the amount of groundwater is not replenished during the recharge period. On another hand, for a dry year, the low-flow storage may be significantly drained and several hydrological years may be required until it recovers its initial state.

In the frame of a FOEN project, ISSKA [2015a] made an analysis on the low-flow storage for different karst flow-systems in Switzerland. Results show that it represents 20’000 to 50’000 m^3/km^2 (**20** to **50 mm**) which may be distributed in soil and epikarst (~50%) and in the phreatic zone (~25% in the conduits and ~25% in the low permeability volume of the phreatic zone). At the scale of Switzerland, the total estimated low-flow storage ranges between **0.2** and **0.4 km^3**. Uncertainties remain large on these assessments as low-flow spring measurements are not always accurate, and also because the occurrence of real prolonged periods without any recharge are extremely rare, especially for karst systems of relative great extension. A more detailed publication is pending.

2.3.2.2. The seasonal storage

The seasonal storage is annually replenished, unlike the low-flow minimal storage which is supposed to not be solicited for a wet year. Still in the frame of the FOEN project, ISSKA [2015a] analyzed the seasonal storage capacities for different flow-systems in Switzerland. Hydrological regimes of four well-documented karst aquifers from different contexts in Switzerland (Tabular Jura, Folded Jura, Helvetic Alps and Central Alps) have been simulated using a semi-distributed hydrological model. For each system, computed recharge is compared to the observed discharge in order to assess volume variations of the storage within the aquifer. Resulting simulations provided seasonal storage variations globally ranging between values of 40’000 and 70’000 m^3/km^2 (i.e. **40** to **70 mm**) depending on the system. The maximal computed value was 160’000 m^3/km^2 for an anthropogenically modified system. With the exception of this extreme value, storage represents 3 to 10% of the groundwater recharge for these zones. This depends on the drainage capacity of the system, the geographic context and the season. It may considerably vary from a system to another and from a year to another. At the scale of Switzerland, the seasonal storage in karst aquifers should oscillate between 0.23 and 1.1 km^3, the mean storage being about 0.4 km^3. The storage is assumed to mainly take place in the soil and epikarst, as well as in the periodically flooded conduits of the epiphreatic zone. The seasonal storage in the low permeability volumes of the aquifer is *a priori* negligible.

2.4. Conclusion

This chapter 2 fixes the main concepts which are used in the next chapters for the development of KARSYS and of related extensions. It does also provide general key values of hydrodynamic properties for epigenic karst aquifers and flow-systems based on a strong review of literature. Main concepts and key-values of this chapter may be summarized in the following Table 2—7.

Aquifer:	Soils	- Thickness: 50 cm to 1 m - Highly permeable - High effective porosity
	Epikarst	- Thickness: 1 to 10 m - Divided into 3 zones - High effective porosity: up to 1% - 1 schaft each 30 to 50 m
	Unsaturated vadose zone	- Effective porosity: 0.1% - 25 to 100 shafts pro square kilometer
	Epiphreatic zone	- Effective porosity: 0.1 to 0.5% - Hydraulic heads fluctuations: from a few meters up to 500 m
	Phreatic zone	- Divided into 2-3 zones - Effective porosity: 0.01 to 0.1% - Hydraulic gradient: max. 0.1% for low-flows
Flow-system	Recharge zone	- Catchment area: autogenic and allogenic parts - Diffuse and concentrated infiltration
	Drainage zone	- Fast and slow flow components - Flow rates controlled by recharge (vadose zones) and hydraulic heads (epiphreatic zones)
	Discharge zone	- Hydraulic base level - Permanent and overflow springs
Hydrology	Recharge	- Large infiltration rate: up to 100% - Evapotranspiration is usually the limiting factor for infiltration - Recharge by condensation: up to 1 $L/s.km^2$
	Storage	- Main storage: soil + epikarst (50 to 140 mm) and epiphreatic zone (1 to 5 mm per meter) - Three types of storage dynamics: (i) the seasonal storage, (ii) the low-flow storage, (iii) the short duration storage

Table 2—7. Main concepts and key values for the development of hydrogeological characterization approaches

3. *Main issues in karst and related users*

The following section describes the main **issues in karst environments** which are still difficult to manage and the **related users**, i.e. people who are responsible for making issues and karst environments suitable and their expectations in terms of information. This section may be seen as a preliminary work before developing dedicated approaches as it describes issues and needs for the users to find **solutions or best practices**.

3.1. Issues

The following section lists and presents the main issues regarding natural resources and environment in karst. Issues are mainly described from examples - mostly in Switzerland - but also abroad. This section aims to identify practitioners who interact with karst and their expectations regarding the management of natural resources and environment in karst.

3.1.1. Drinking water supply

Karst aquifers provide a large part of **drinking water**. In Switzerland karst aquifers represent 18% of the drinking water supply (Spreafico and Weingartner [2005]). Water supplied from springs (mainly from karst springs) reached 400 mio m^3/year in 2010 (SSIGE [2010]). Several communities and cities, such as Montreux (VD), Vevey (VD) and La Chaux-de-Fonds (NE) directly depend on karst groundwater (Heller and Neuman [2001]). Other cities, such as Yverdon-les-Bains (VD), Bienne (BE) or Neuchâtel (NE) are partially supplied from karst groundwater. In the canton of Neuchatel, nearly 2/3 of drinking water is supplied by karst aquifers, see Tripet et al. [2000]). A lot of small towns, dispersed over the Swiss territory are also concerned (Goldscheider et al. [2010a]; Weingartner [1983]).

However, observations realized during the Swisskarst project showed that, due to the heterogeneous distribution of groundwater resources, tapping strategies and devices in karst aquifers are often not optimal (Malard and Jeannin [2013a]). Main problems are related to groundwater **quantity (availability)**, **tapping modes**, **groundwater quality**, **resources protection** and **exploitation costs**.

3.1.1.1. Quantity - availability

In karst environments, Groundwater exploitation often meets **quantity** issues. Difficulties are related to thick unsaturated zones and to groundwater which mostly flows through metric or decametric conduits to converge at the spring(s). In these conditions, water may easily be captured at springs while on the surrounding massif, identifying the best location for the groundwater extraction plant is a challenge. The problem of quantity in karst environment is therefore a spatial issue.

Another problem related to groundwater quantity in karst environment is to fully cover needs during low-flow conditions. As groundwater flows in karst aquifer quickly respond to surface-flow conditions (seasons, snowmelt, storms, etc.), groundwater **availability** depends on the time. During dry periods (droughts), problems of groundwater quantity may become critical in valleys – downstream the springs - but more specifically over surrounding massifs. Groundwater availability may become not sufficient to address the consumption which increases during this period (Milanović [2004]). In Switzerland, problems of water quantity frequently occurred in karst regions, especially in the Jura Mountains. Two examples are given hereafter:

- During summers 2003 and 2011, the water company of Saint-Imier (BE) has run into difficulties to provide sufficient water from their devices (Syndicat des Eaux des Franches-Montagnes, personal communication). Communities (nearly 15’000 consumers) are supplied by groundwater flowing out of the Raissette spring (mean discharge rate ~400 L/s, dropping to ~100 L/s for summer periods). Due to summer droughts in 2003 and 2011 (up to four months without recharge in 2011), the regime of the spring declined substantially to a few liters per second in November leading to an emergency situation. During the last decade, the water company searched for an additional water resource. The Sauges deep borehole (~600 m depth) was drilled in 2008. It tapes the confined and highly productive Malm karst aquifers over 400 m of screens and now covers a significant part of the water consumption – even for low-flow periods;
- In the valley of Joux (VD), pasture and mountainous activities have been artificially supplied in water by the Swiss army during the summer 2003 as water resources from karst springs were not sufficient to maintain activities (Bissig [2006]). A similar operation has been reiterated in July 2015. Water for pasture and mountainous activities comes from a few shallow karst springs which discharge rates do not exceed a few liters per minute under low-flow conditions. In 2003 and 2011, after the prolonged periods without recharge, the karst springs finally dried up and no other water resources were available in the whole region. The water was brought from the valleys, i.e. more than 600 m lower!

In valleys, where springs usually emerge, available groundwater resources are restricted to the natural regime of the springs. Naturally, springs discharge rates are permanently fluctuant within the year and long periods of drought may lead to significant decrease in the water availability. Where possible, usual strategy to address this problem consists in the **overexploitation** of the spring during low-flow conditions (see the Lez spring for example in southern France, Avias [1995]); assuming that the depletion can be completely resorbed during the winter times.

Then, strategies to address problems of groundwater quantity in karst environments mainly deal with **tapping modes**.

3.1.1.2. Tapping modes

Tapping modes in karst aquifers have been partly presented in Malard and Jeannin [2013a] for Switzerland. In most cases water is simply captured from permanent **springs**, i.e. at the downstream end of a relative extended catchment, unlike for other environments, where groundwater is mainly tapped by boreholes or drainage galleries.

In karst environments, tapping water from springs is the most obvious and widespread way of getting water. Drainage galleries starting from springs or from a larger emissive area are also well developed in order to concentrate more water at a point. In all cases, the hydrological regime of the springs has to be studied before being tapped. Overexploitation of groundwater may be a strategy to ensure water resource during low-flow periods, but full groundwater replenishment should be guaranteed during the winter time.

Boreholes or **wells** in karst aquifers are less developed compared to other environments as the success could not be 100% insured. However this observation should be balanced as in some countries, boreholes in karst are a well common practice (for instance in Kentucky, Florida, etc.). When tapping groundwater from boreholes or wells, difficulties are related to a successful implantation of the devices (Malard and Jeannin [2013a]). Indeed, due to difficulties to assess the density, the distribution, the size and the hydrological functioning of the conduit network, many wells are not sufficiently productive. As displayed in Figure 3—1, boreholes may remain within the unsaturated zone of the aquifer or they may penetrate only the **low-permeability volumes** surrounding the **draining-conduits**. Further problems in karst are related (i) to the large thickness of the unsaturated before penetrating the phreatic zone and, (ii) to the potential presence of voids (air-filled voids, sediments-filled voids, debris-filled voids, etc.) which are additional **difficulties when drilling** (i.e. additional costs).

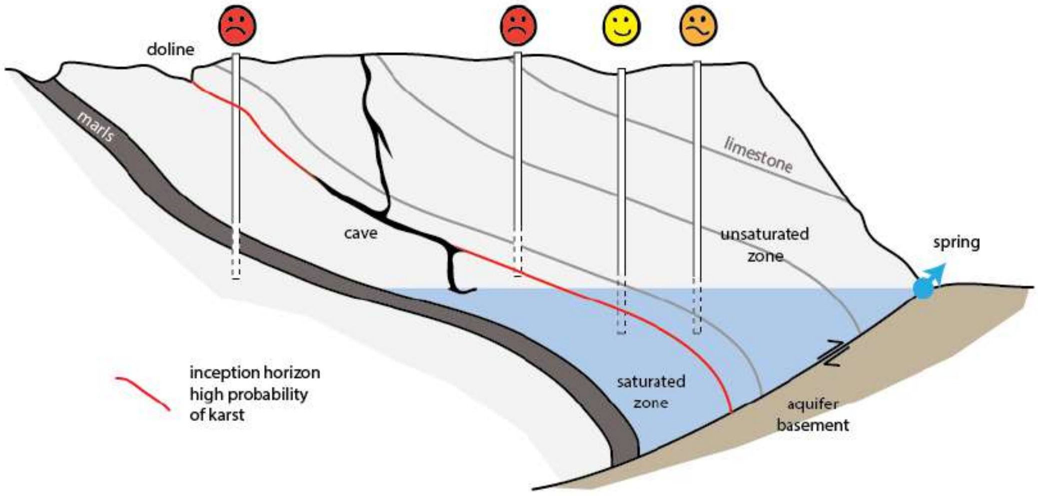


Figure 3—1. Information related to the location of the phreatic (saturated) zone and of the expected horizons of high probability of karst is essential to succeed in drilling wells.

Nevertheless successful projects do exist and some of them may even exceed the users' expectations. The Foule deep supply-well in Moutier (BE, Switzerland, see Mornod et al. [1970]) is an example of a successful well. It reached the targeted groundwater quantity (exploitation discharge regime ~180 m^3/h) and quality (absence of turbidity and bacteriological content).

Problems of groundwater **availability** may also be combined with **quality** problems.

3.1.1.3. Groundwater quality

In theory, the Swisskarst project did not explicitly consider the water **quality issues**. In practice, various case studies were indirectly or directly in touch with **contamination** and **vulnerability** problems (see for instance the case study of the Brévine supply well, ISSKA [2014a]). Quality issues in karst aquifers are briefly discussed hereafter and additional information on the topic for Switzerland (including groundwater temperature) is placed in Appendix 10.4.

The main problem concerns the **conservation** of the groundwater quality and the **remediation** of contaminated groundwater. As mentioned by several authors, karst aquifers are **highly vulnerable** and the quality of karst groundwater may be strongly affected by various **contaminants**.

The quality of karst groundwater is also highly related to hydrological regime fluctuations (Libra et al. [1986]; Vesper [2008]). On the one hand, during low-flow conditions the dilution of contaminants is low, leading to eventual problem of quality. On the other hand, the probability of contamination by mobilization of new contaminants increases with storm events or seasonal high discharge rates. These events also lead to a reinforcement of the water turbidity which is seen as a degradation of the groundwater quality. Guaranteeing groundwater quality usually requires the establishment of **protection zones** (and/or **vulnerability maps**) and appropriate **measures** to prevent the aquifer from contamination.

The case study of the Brévine supply well (NE, Switzerland, see ISSKA [2014a]) is related to repeated events of bacteriological contamination that affect the groundwater quality of the well. For two decades, the recharge area of the pumped groundwater was assumed to be located directly around the well, and the established protection areas and associated mitigation measures were not able to avoid contamination. The application of KARSYS made it possible to analyze existing data within a new conceptual model which evidenced that water comes from the conduit network of the karst aquifer. The model suggested that the catchment area extends further upstream than initially supposed. Thus, based on the model, appropriate mitigation measures have been decided and the frequency of contamination has been significantly reduced.

3.1.1.4. Exploitation costs

Building and maintaining water supply-networks are often complex in karst environments. Groundwater resources may be quite deep due to thick unsaturated zones and quite far from consumption places. These induce that water is transported over long distances. The case of La Chaux-de-Fonds (NE, Switzerland) is a good example of such **complex supply network**; the city is supplied by water coming from the Areuse gorges, located 400 m below and more than 17 km away. Communities in Les Franches-Montagnes (canton JU, Switzerland) are another example of a complex supply-network. Groundwater resources are located in the valley of Saint-Imier (canton BE, Switzerland), 300 m below and more than 10 km away. Different devices (boreholes, spring's capture) are together exploited for guarantying water quantity and quality. All these infrastructures may involve **considerable costs** for maintenance and energy.

Tapping karst springs may also induce additional costs to maintain equipment as devices could be strongly **damaged** by flood events (sand abrasion, clogging, etc.).

The application of measures related to the protection zones also involves considerable costs because these **zones are often of great extension** and concern many human activities (agriculture, landfill, wastewater treatment plants, factories, etc.).

In this view, the exploitation of **large karst springs** may be difficult to maintain at reasonable costs because of their vulnerability. In some regions, due to urban development or activities over the catchment, the exploitation of major karst springs is therefore progressively abandoned (Hobléa et al. [2008]) and replaced by the exploitation of **smaller springs**, or by wells located closer to consumption places. In this last case, groundwater storage makes it possible to extract water along the whole hydrogeological year. A sustainable management of withdrawals has to be respected in order to maintain the balance between recharge and withdrawals.

3.1.1.5. Protecting resources

3.1.1.5.1. Vulnerability, concepts and methods

As defined by many authors (i.e. Leibundgut [1998], COST Action 620, Zwahlen [2003] or Ravbar and Goldscheider [2009]), the "**intrinsic**" vulnerability of an aquifer is a measure of its attenuation capacities against pollution (Leibundgut [1998]; Vesper [2008]). Protective cover, soil thickness, infiltration processes diffuse vs. concentrated are main elements susceptible to increase the transit time of groundwater from the infiltration place to the tapping device. Regarding this definition, karst aquifers are considered as the **most vulnerable** type of aquifer over the world. The two main reasons are: the **high effective recharge** rate and the **fast groundwater flows** without filtration or delay. Thus, potentially contaminated water may be directly injected into the aquifer and may directly affect the groundwater quality.

Although the intrinsic vulnerability is not dependent of the nature of the contaminant, the "**specific vulnerability**" has been defined as dependent from the nature of the contaminant (solubility, mobility, degradation, etc.). In the same way, a distinction is made between "**source vulnerability**" and "**resource**

vulnerability" according to the hydrogeological target, respectively the aquifer or the tapped spring (Kavouri et al. [2011]; Zwahlen [2003]).

Vulnerability and documented cases of contaminated groundwater have been widely studied in karst aquifers and various **methods** for assessing distribution and vulnerability degree over the catchment have been proposed (Gogu and Dassargues [2000]). Usual methods applied in karst areas are of **weighting-rating** type: DRASTIC (Aller et al. [1987]), GOD (Foster [1987]), SINTACS (Civita and De Maio [1997]),EPIK (Doerfliger et al. [1999], EPIK is the official method applied in Switzerland), PI (Goldscheider [2005]), COP (Vias et al. [2006]) and PaPRIKa (Plagnes et al. [2010]). A detailed review has been proposed by Gogu and Dassargues [2000] (except for the recent ones: COP, VULK, PI and PaPRIKa). These methods consist in combining superimposed information on a plan view (soil cover, permeability, etc.) and provide distributed scores which give an indicative appreciation of the source / resource vulnerability. These address a large audience of decision-makers, resource managers, etc. Resulting maps provide comprehensive supports and guide regulations or protection measures over the catchment area.

Although these methods are based on similar concepts, their application may lead to **very different results** for a same site. Different authors discussed these deviations for their site:

- Andreo et al. [2006] successively applied the PI and the COP methods on their pilot site of Sierra de Líbar (Spain) as both of them have been intentionally developed for karst media. Results show that both of them provide a map of elevated to very high vulnerability; but in details, the COP method entails much more contrasts in interpretation as it is function of more parameters, including the thickness of the unsaturated zones. Finally, for this case, it appears that these two methods provide comparable results.
- Marín et al. [2010] applied successively DRASTIC, GOD and COP methods on their pilot site of Alta Cadena (southern Spain) and observe that solely the application of COP method – which has been specifically developed for karst environment – was in accordance with their knowledge about the site and with results of post dye tracing tests.
- Marín et al. [2012] made another comparison in applying the karst-dedicated vulnerability methods COP and PaPRIKa for the Lez catchment (Southern France) and in Alta Cadena. They observe that resulting maps show significant differences. Regarding the Lez catchment the application of the COP method show contrasted classes of vulnerability (from extremely low to extremely high vulnerable) while the application of the PaPRIKa method only provides few classes ranging from high to extremely high vulnerable. Finally, they point out that – with the exception of few areas - the results could not be compared at the scale of the catchment (even the tendency).

Jeannin et al. [2001] proposes an original method for assessing intrinsic vulnerability (VULK). VULK is a **1-dimensional solver** computing transport through embedded sub-systems with different characteristics (thickness, hydraulic conductivity, porosity, etc.). As results, VULK provide restitution curves for specific signal of infiltration. Although VULK is a physically-based method which has been developed to make vulnerability less arbitrary, it has not been very popular. This is probably because it requires much more efforts than weighting-rating methods. Since 2001, it was applied on a few sites only (see Ducci [2007], southern Italia). VULK may be seen as an interesting alternative or a complementary method to the weighting-rating methods but improvements should be made to make it easier applicable.

Whatever the selected method, its application on a site should be validated by measurements and/or tests on the field. Common practices recommend to validate high and low vulnerable zones by dye tracing tests (Andreo et al. [2006]). Nevertheless, such validation in a restricted area may solely be considered as a local validation under the prevailing hydrological conditions. As vulnerability is a non-measurable parameter, there is no efficient method providing a validation at the catchment scale about degree and distribution of the vulnerability. This is a real limitation in the selection of an "appropriate" method and in the accreditation of the results. Most common vulnerability methods remain **relative** and **indicative**.

3.1.1.5.2. Protection zones in Switzerland

In the frame of groundwater intake creation, Swiss regulations impose the delineation of three different **zones S1, S2, S3** whatever the type of the aquifer (Tripet et al. [2000]): S1 aims at protecting the waterworks structure against damage and prevents from direct entry of pollutants close to the intake. S2 prevents from microbiological and non-degradable pollutants. The remote and large S3 provides additional safety. A set of **land-uses restrictions** is allotted to these zones. Activities and construction are prohibited in S1 while few activities are permitted in S2. Regarding S3, quarries, waste disposals are prohibited and industrial activities are regulated.

Since 2016, regulations regarding protection zones have been adapted for karst aquifers (OEaux [1998], revised January 2016, Appendix 4, Chapter 1). This new revision intends to reduce inherent conflicts between groundwater protection and land-uses. Indeed, existing protection S3 zones in karst areas usually cover a large area, thereby restricting some activities (agriculture, construction, etc.) without however guaranteeing more protection for the groundwater resources. New protection **zones S_m and S_h** have been defined ("m" for areas of medium vulnerability and "h" for areas of high vulnerability) for replacing the actual S3 zone. Unlike for S3, constructions are authorized in these areas once it has been demonstrated that they do not impact the groundwater used for drinking. These new regulations will progressively be applied on the field; however, existing areas will not all be revised in the short term.

3.1.1.6. Conclusion

Groundwater supply in karst environments may reveal difficult to ensure, especially regarding problems of **quantity** (in space and in time) and problems of **quality**. Groundwater resources are difficult to protect because of the aquifer's vulnerability and because of the large protection zones they require. Some of these problems may be prevented by a strong knowledge on the aquifer and by adequate strategies for tapping groundwater, i.e. (i) the location of the groundwater resources as well as of the karstified horizons for getting sufficient quantity, (ii) the extension of the recharge area (catchment) in order to estimate the resources potential and to assess vulnerable zones. By taking these parameters into consideration when designing the project, sustainable strategies for supplying could be proposed and implemented. Besides investigations on site, this evaluation requires the application of a **dedicated approach** which results provide relevant information: (i) for improving knowledge, (ii) for assessing the feasibility, (iii) for listing possibilities, and at least (iv) for making decision. Different approaches do exist (see §. 4) but their application often fails in providing relevant and concrete results to ensure that tapping strategies will be successful and sustainable.

In a lot of cases, issues related to the location of the groundwater resources and to possible tapping strategies could be addressed by the establishment of an explicit **conceptual model** of the aquifer. The Figure 3—1 is an explicit conceptual cross-section based on the geology and on the supposed hydrology. It could already be considered as an indicative model providing concrete arguments for locating the best site for a borehole. Such explicit conceptualization of the aquifer and of the groundwater was the starting point to develop **KARSYS** and to apply it for assessing tapping strategies.

3.1.2. Natural hazards

Karst environments are considered as hazardous environments. Hazards could be distinguished into two categories: **geological disorders** and **hydrological hazards** and mainly provoke floods, collapses and landslides. Hazards may threaten human lives and anthropic constructions.

Regarding Switzerland, financial damages induced by **floods**, **debris flows**, **landslides** and **rockslides** are estimated around 8'000 million € within the last 40 years, (Hilker et al. [2009], data from the Swiss flood and landslide damage database since 1972). In spite of their costs, past events associated to karst disorders are poorly documented and further researches have to be carried out in order to associate events related to karst mechanisms (for instance floods related to overflow springs or collapses related to cave breakdowns, etc.).

“Karst” is even not mentioned in the Swiss database, meaning that floods or landslides related to karst mechanisms are completely unsuspected. As a consequence, there is no consensual approach relative to **specific karst hazards mapping** in Switzerland – although karst environment covers 20% of the territory. Risk maps do exist in these areas but do not explicitly consider karst processes for risk purposes…

3.1.2.1. Geological disorders: collapse, landslide, etc.

Geological disorders gather sinkhole collapses, landslides, rockslides. Even if they are related to the hydrological functioning of the aquifers, these disorders occur locally and sometimes independently from hard meteorological conditions or with delay.

Waltham [2008] (and later Waltham et al. [2010]) proposed a complete review of principles and mechanisms of **collapses** generation in karst areas. These are a conjunction of a geological or geomorphologic vulnerability predisposition (highly soluble beds, contact with impervious) and a triggering or aggravating factor (groundwater table oscillations, privileged axes of groundwater flow-paths, etc.). As explained by Klimchouk [2002], collapse hazards are more pronounced and frequent in subjacent (thin-covered) karst. Observations show that denudated karst areas (i.e. without cover) are the least likely to generate collapse hazard. However, this observation should be balanced as denudated karst areas are less settled than covered karst areas and thus, reported events of collapse are less frequent. Furthermore, in covered karst areas, the soft ground may disappear in a single movement, leading to a sudden and rapid collapses. Beside mechanisms which lead to the generation of collapses and sinkholes in non-influenced areas (Ford and Williams [2007]), additional anthropogenic causes or triggering effects are usually evoked for the generation of collapses (Gutiérrez et al. [2014]; Parise and Gunn [2007]). For instance, in urban zones, collapses often result from **leakage** of drinking- or storm-water pipelines (Crawford and Groves [1995]) or from forced-infiltration devices (cf. §. 3.1.5). Each year, leakage causes several collapses in the city of La-Chaux-de-Fonds (canton NE, Switzerland) where most of the construction develops on karst area. This phenomenon is widespread in the community and it seems obvious that it may endanger the stability of the infrastructures and sometimes the security of the persons. The presence of old underground quarries or subterraneous anthropogenic galleries is also a significant cause of collapsing in urban zones (Pepe et al. [2013]; Toulemont [1987]; Van Den Eeckhaut et al. [2007]). In suburban zones, apparition of collapses may also be related to the implantation of geothermal probes (mainly open-loops system); as for instance in south England where numerous cases of collapses in chalk due to open-loops systems have been reported (Cooper et al. [2011]). However such case was almost never mentioned in Switzerland.

Collapses may also be related to **groundwater table fluctuations** which remove materials filling the pre-existent voids until the soil breaks. This phenomenon may be aggravated by the presence of an artificial and impervious cover (asphalt, etc.). Indeed, below the cover, the water pressure may increase leading to higher erosional capacities (see for instance Figure 3—2, lower picture).

Collapse and subsidence hazards in developed and populated karst areas are frequently taken into account in the natural- or geo-hazard maps (Cooper et al. [2001]; Kaufmann and Quinif [2002], etc.). Ideally, these prevention and management plans for collapses occurring in populated zones should at least consider the geological or geomorphological predisposition as well as the **triggering factors**. Aside from the Swisskarst project, this problematic has been evaluated for the canton Neuchâtel (Switzerland) and a karst-collapse hazards map has been delivered to the cantonal authorities (see ISSKA [2014b]). This map is based on a spatial analysis and combination of:

- The predisposed horizons of high karstification potential: i.e., specific stratigraphic horizons, specific thrust or fault paths, cave paleo-phreatic levels, etc.
- The density factor which refers here to the already known density of collapses (mainly dolines);
- The extrapolation of these information provides a map of the “**collapsing-susceptibility index**”; similar maps are being implemented for other Swiss cantons (e.g. Vaud, etc.).

Figure 3—2. Above: example of karst collapse occurring in a street in La Chaux-de-Fonds (NE); apparition of these collapses in ultra-urban zones is intensified by breakdowns or leakages of drinking- or storm-water pipes. Middle: sudden collapse in sub-urban zone; apparition of this sinkhole close to the house may be enhanced by the storm-water infiltration device. Below: collapse in rural zone; this is related to the fluctuations of the groundwater table, which frequently reaches the level of the road basement.

Regarding **landslides**, these are also related to the conjunction of geological and hydrological factors. Two types of landslide dynamics do exist: (i) **fast and sudden landslides** (rock falls, rockslide) and (ii) **slow-moving landslides**.

Fast and sudden landslides in karst areas usually result from the rise of high hydraulic loads in the massif for high-flow events (storm, snow-melt, conjunction) which leads to flanks disruption. Because of the erosion processes or of the partial "**declogging**" of ancient collapsed conduits, flooded conduits may develop close to the surface. As the groundwater pressure rises, geotechnical weaknesses may force the water to emerge, provoking sudden and fast land- or rockslide (see Figure 3—3). Huang et al. [2012] documented more than 300 sudden landslides events in Southwestern China which is a large karst area. They found that about 88% of the documented landslides were triggered by rainstorm, 2% were caused by earthquakes and the 10 remaining percent have been probably triggered by human activities (mostly engineering works: mine, roads, quarrying, etc.).

Slow moving landslides in karst areas may have various causes: the valley incision and slopes decompressing after the glaciers retreated, the groundwater movement through permafrost, the tectonic activity, etc. (see Huntley and Duk-Rodkin [2008] who discussed causes for landslides in the karst region of the MacKenzie River). Active landslides may also be found close to the permanent outflow zone (i.e. close to springs), especially in following contexts: large emissive zone (with several outlets), non-cohesive geological structuration (embedded thin banks of marl and limestone), high hydraulic groundwater fluctuations, etc. In these cases, the propagation of the landslide results from the mobilization of the materials in the downstream parts of the flow-system.

3.1.2.2. Hydrological hazards: flood, mudslide, etc.

3.1.2.2.1. Flash floods and inundations

In all karst terranes over the globe, **floods** may be strongly dampened or enhanced by karst overflows. Examples are numerous in Switzerland: Geo 7 [2013]; Malard et al. [2014a]; Vouillamoz et al. [2013]; in France: Jourde et al. [2007]; Lastennet and Mudry [1995]; Maréchal et al. [2008]; in Italy: De Waele et al. [2010]; in Balkan countries: Bonacci et al. [2006]; Caronna et al. [2013]; Ravbar and Kovačič [2010]; in the U.S: Currens et al. [1993]; in China: Guo and Jiang [2010]; Xiang et al. [1997]; in Ireland: Naughton et al. [2012], etc. From these readings, two types of flood may be distinguished:

- **Flash-floods** are generated by intense rainfalls over a short period, storms or conjunction rainfall / snowmelt. They lead to a fast increase of the stream flows which may endanger human lives and cause extensive damages along river banks and floodplains as described by De Waele et al. [2010]; Delrieu et al. [2005]; Jourde et al. [2007]; Maréchal et al. [2008]; Ravbar and Kovačič [2010]. From the hydrogeological point of view, the flash-flood event of Vaison-la-Romaine, France in 1992 (Lastennet and Mudry [1995]) is one of the most *a posteriori* documented event in karst region.
- **Seasonal floods** correspond to recurrent and usually predictable periods of high-flow. These are responsible for temporary lakes or ponds in karst depressions as described by Kranjc [2006]; Lopez-Chicano et al. [2002] or Naughton et al. [2012] (poljes, turloughs, etc.).

Flash floods are considered as quite unpredictable; they usually involve the activation of ephemeral outlets suddenly discharging a high amount of water and they are responsible for most of the disasters (human lives and constructions). **Mudslides** are frequently recorded during flood-events and represent an additional risk of disasters (e.g. of expensive damages). In some cases, flood-events may be triggered or enhanced by artificial constructions, mainly dams or reservoirs in karst regions (see examples: Xiang et al. [1997] or Benderev et al. [2006]).

3.1.2.2.2. Mechanisms

Flood d**ynamics of** are complex to assess (or to forecast), mainly because the hydrology of karst flow-systems is often not well understood. As it has been pointed by various authors (Horat and Naef [1996]; Jourde et al. [2007], etc.), standard approaches in hydrology (rainfall-runoff models) fail in reproducing (or even understanding) the regime of the floods hydrograph as they do not explicitly consider hydrological and **hydraulic specificities** of the flow-systems. Driving parameters such as a valid delineation of the catchment area (and possible changes for high-flows), the heterogeneous distribution of the storage capacity, the distribution of the conduit network, the inter-relation between the permanent and the overflow outlets, conduit clogging-declogging under extreme conditions (Lastennet and Mudry [1995]) are usually not taken into account. Indeed, the fast flows distribution in karst strictly depends on the following factors (see Figure 3—3):

(i) The evolution of the hydraulic gradient in the aquifer which may enlarge the underground flow-system and by extension the catchment area of the considered spring or group of springs (both permanent and overflow springs);

(ii) The location of the conduits and their drainage capacities; the existence of underground thresholds or upper galleries acting as additional streams by-passing the flows and/or makes them faster. This mechanism is frequent in karst hydrology and it may lead to “diffluences” (Phillips and Walls [2004]). In many sites, the non-consideration of this mechanism makes it impossible to accurately reproduce the systems discharge rate. But on the other hand, evidencing and dimensioning this mechanism often remains difficult as it requires an assessment of the fluctuations of the hydraulic gradient in the aquifer for each neighborhood systems. Flows may be temporary stored in perched galleries or dispersed to adjacent flow-systems;

(iii) The activation of overflow outlets for which peak discharge rates usually exceed those of the permanent base springs and represent potential aggravated risks.

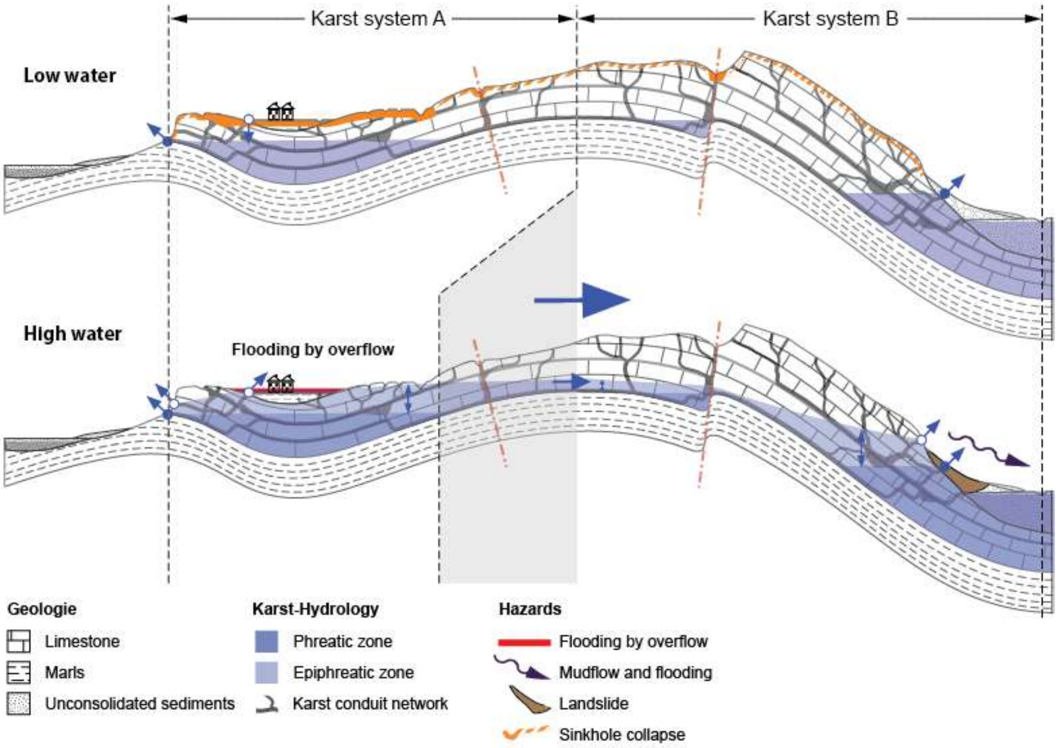


Figure 3—3. High-flow events in karst environments may provoke hazards at land surface (Jeannin [2014]). Landslides/rockslides, subsidence/collapses and sinkholes formation occur more frequently in the range of the karst groundwater oscillations. Debris flows and floods usually occur in areas downstream from perennial and temporary karst springs or in the area of diffuse groundwater exfiltration. Due to underground thresholds between systems A and B, aquifer B may suddenly receive a considerable amount of water coming from aquifer A for high-flows. Intensity of the flood in the system B suddenly increases and may provoke associated hazards (mudflows, landslides, etc.).

As a consequence, floods dimensioning and prevention measures imply to assess the characteristics of flow-systems for high-flows: the evolution of the hydraulic gradient, the position and the organization of thresholds or by-pass conduits as they control the modality/intensity of the floods (Jourde et al. [2013]) as well as the functioning of the overflow outlets (activation and potential regime: peak and discharge duration).

Approaches do exist to reproduce floods in karst terrains in order to prevent feared events. Most of these have been developed in southern France or in Balkan countries. Floods mechanisms have been studied using **hydrographs analysis** and **statistics** (Jie et al. [2003]), **neural networks** (Kong A Siou et al. [2010]; Kong A Siou et al. [2013]) or using **reservoir models** (Fleury et al. [2013]) or **semi-distributed models** (Bailly-Comte et al. [2012]). Based on these models, a recent forecasting tool has been proposed for the city of Nîmes (Fleury et al. [2013]). It prevents from flood events using (i) meteorological forecasts and (ii) the saturation degree of the karst aquifer (i.e. a real-time indication on the available storage). Finally, the flood forecast is based on a "Rainfall vs. Drain water-level" abacus, which makes it possible to assess the intensity of the runoff reaching and overflowing the surface stream in function of (i) the predicted rainfall intensity and (i) the level of the water table in a surveyed karst conduit. Various alert thresholds have been defined, each corresponding to specific measures that must be complied in the field. Nevertheless, even if these papers mention a complex organization of the karst conduits and the existence of overflow outlets (resp. for the Lez spring and the

Fontaine de Nimes), hydraulic processes are not explicitly taken into account in the floods simulation. As a consequence accurate devices (or models) for flood forecast are still rare and very simplified.

In another vein, Gill et al. [2013] promote the use of a **distributed pipe-flow model** (using Infowork®) in order to reproduce seasonal floods in a series of Irish turloughs (= ephemerally flooded ponds) in lowland karst areas which act as equilibrium pits of the saturated karst systems. The main advantage of this approach is to assess separately the water table fluctuations in pits (here at a daily time-step) as it **explicitly considers the organization of the conduits**. Such an approach implies that the geometry / organization of the conduits, the position of permanent and overflow outlets, and the dimensioning of the catchment have to be known or at least inferred prior to design such a pipe-flow model. At the present stage, their approaches do not offer a forecasting tool – but further developments in this sense are ongoing.

As mentioned in conclusions of the CCHydro Project (BAFU [2012]) which focused on **global changes** effects on the evolution of the hydrological regimes in Switzerland, it appears that the Jura and the Prealps regions would be more affected by flash flood events (as well in frequency as in intensity) in the coming decades. As these are karst environments, floods problematic should explicitly considers karst hydraulic processes to properly address the issue (see Malard et al. [2014a]). Past events tend to demonstrate that flash-floods should be considered as a significant topic for the **regional land planning**. In sensitive areas, objectives of flood-hazards assessment would be to initiate a **forecasting device** which makes it possible to anticipate when and where flash-floods may occur and what their expected magnitudes are (as for instance the real-time forecasting model developed for the FEDRO[1], which predicts overflows of the karst flow-system, see Jeannin et al. [2015a]).

3.1.2.2.3. Swiss cases

Two case-studies of karst flood-events have been analyzed in the frame of the Swisskarst project: the inundations of Porrentruy (JU) and the floods of the Suze River in the city of Biel (BE).

Inundations of Porrentruy (JU) in 1804 and 1910 are significant flood events resulting from the **overflow of karst aquifers** (BG Ingénieurs Conseils [2011]; Lièvre [1915]). For the 1804's event, it is mentioned that the overflow springs (Creugenat, Creux-des-Prés, etc.) together discharged up to 100 m^3/s (a-posteriori evaluation). This is considerable compared to annual usual floods (~20 m^3/s). As a consequence to these events, city and surrounding fields remained flooded for several days / weeks leading to poor harvests, earning losses and sanitary problems. In the last century, several moderate-to high-flood events have been recorded (especially in 1973 and 1983) - each resulting in **substantial costs**. The case study of floods in Porrentruy has been first presented by Vouillamoz et al. [2013]. The case study and the characterization of hydrological and hydraulic processes responsible for floods will be further analyzed in §. 6.3

The city of Biel (BE) has been exposed to flooding by the Suze river overflow. The case study has been described by Malard et al. [2014a]. This paper is given in Appendix 10.3. After having presented the problem of the unusual high-flow regime of the Suze River - which is likely influenced by the presence of karst aquifers upstream. In the following paper, the authors propose an approach to assess **the "buffer-like" properties** (i.e. the short-duration storage) in karst aquifers during flood events.

3.1.2.3. Conclusion

Natural hazards in karst environments are still topical issues, especially regarding floods and collapses which are the most critical for the society. These hazards are related to groundwater dynamics which in turn are controlled by properties of karst aquifers and by recharge modalities. A pragmatic and reproducible **approach is then required** in order to reproduce groundwater dynamics and to test various **hazard scenarios** for which

[1] Federal Roads Office (www.astra.admin.ch/?lang=en)

results will make it possible to define **prevention measures**. KARSYS has been developed in this view, in order to assess and to **forecast geological and hydrological hazards** as well as their related **impacts**.

3.1.3. Renewable energies in karst: geothermal and hydropower

Use of **renewable energies** (solar, wind, hydropower, geothermal) is globally increasing. Thus, a lot of natural systems they offer a significant potential (hydraulic, heat, wind, current, etc.) are progressively prepared or equipped for getting energy. This induces the realization of dams, galleries, deep boreholes, windmills, hydro-turbines, solar panels, etc.

As they offer a structured network and a concentrated water and heat flux, karst environments may be *a priori* favorable to support the development of **hydropower devices** or **geothermal probes**. Nevertheless, characteristics of hydropower plants or geothermal devices should be carefully designed as they could be disturbed by **karst hazards** as other building initiatives. Conversely, impacts of these constructions on karst environment must also be carefully addressed.

3.1.3.1. Geothermal energy in karst

3.1.3.1.1. Development of geothermal probes in karst areas

3.1.3.1.1.1 Statement

As well as for other settled terranes, karst environments are concerned by the development of geothermal devices. Two major types of devices are distinguished: **deep geothermal extraction** (hydrothermal and geothermal systems) with relevant yield and **shallower geothermal heat pump (or probes)** for "domestic" uses. The profitability of both devices depends on the evolution of the temperature gradient with depth and on the groundwater flux potential - the higher the geothermic gradient is, the more water could be captured and the more the device is effective. In Switzerland, due to the growing interest for renewable energies, the implantation of geothermal devices notably increases these last decades (up to +15%/year in Switzerland in the 2000s, Colliard [2004]; Lund et al. [2004]).

Two types of geothermal vertical probes could be distinguished; the **open-loop systems** and the **closed-loop system** (Lund et al. [2004]; OWRC [2012]). Open-loop systems extract the groundwater from a well, inject it through a heat exchanger, and discharge the temperature-altered water back into the aquifer in a return well or to a surface stream or lake. In closed-loop systems, water (or heat transfer fluid) circulates through one or several vertical or horizontal loops installed below the ground or in the aquifer zone.

Both systems work on the exchange (heating or cooling) of joules with the groundwater. In order to ensure the efficiency of the installation, the groundwater should be at a sufficient temperature (and a relative interesting gradient with depth) and a rapid renewal in the capture zone of the installation – reflecting a significant permeability of the aquifer. Depth of boreholes usually ranges from 50 to 400 m.

3.1.3.1.1.2 Temperature gradients and heat efficiency in karst aquifers

3.1.3.1.1.2.1 Temperature gradients

Due to high permeabilities and to fast circulations, the karst groundwater does not warm up as much as the groundwater circulating through fissured or granular aquifers. Haenel [1971] observed that the measured temperature gradient in boreholes is 2 to 8 times lower in karst aquifers than those measured in other geological environments of Switzerland (~0.03°C/m). Indeed, most of the ascending **geothermic flux** is washed away by the groundwater flows (Mathey [1974] found that nearly 80% of the flux is captured by the groundwater flows for the Areuse karst aquifer). This implies to address specific considerations regarding implantation and functioning of geothermal intakes.

Various authors assessed the evolution of the temperature gradient in karst aquifers (Badino [2005]; Cartwright [1971]; Drogue [1985]; Jeannin [1990]; Lütscher and Jeannin [2004]; Mathey [1974], etc.) and noticed that the evolution of the temperature gradient according to the depth is not homogeneous – as for other environments. This is strongly affected by (i) the location (i.e. the depth) of the saturated zone, (ii) the presence/geometry of the conduit networks, and (iii) the hydrology of the flow-system.

The evolution of the temperature gradient could be distinguished in the vadose **heterothermic** and **homothermic** zones and in the saturated zone. Based on a series of measurements, Lütscher and Jeannin [2004] provide a conceptual model of the temperature evolution in different zones of karst aquifers. The authors demonstrated that in temperate climatic areas, the air circulation controls the distribution of the temperature in the upper unsaturated zone of karst aquifers. Two zones are defined: the **heterothermic** zone influenced by seasonal variations of the outside temperature and the **homothermic** zone where the gradient is stable over the year. In this zone, more the karst media is ventilated – by conduits - more the temperature gradient is high (>0.5°C/100 m). At the reverse high water flows (in the epiphreatic zone) and/or low air circulation tends to reduce this gradient to trends lower than 0.5°C/100 m. Close to the saturated area the gradient falls to 0.3°C/100 m. In the vadose zone, the temperature increases due to (i) the gravitational energy converted in thermal energy (>2°C/km) along the gravitational axis (Badino [2005]; Jeannin [1990]) and (ii) the input of the outside air heat according to the **ventilation** capacity. Regarding the evolution of the temperature in the saturated zone of the aquifer, Lütscher and Jeannin [2004] found that the **temperature gradient** does not significantly evolve in the zone of the phreatic circulation. Observations also reveal that below the karstified base level, the temperature gradient significantly increases due to the lack of circulation – but conversely the available amount of water is low as permeabilities significantly decrease. In this zone, groundwater is in **thermic equilibrium** with the surrounding rocks and the gradient similarly evolves as for other environments.

Thus, geothermal potential in karst is far from being interesting – at least from point of view of the temperature gradient. **Ascending heat flux through karst is low** compared to other rock massifs. Considering for instance a 200 m long probe at an elevation of 650 m in karst environment, the highest recorded temperature will range between 8 and 10°C if the probe penetrates the saturated zone (see Figure 10—2) instead of 11 or 12°C for a similar device in non-karst area (molassic basin, etc.)... However, as karst aquifers are able to provide **large fluxes of water** through few **concentrated conduits**, it may present an interesting heat renewed potential that other geological media cannot provide equally.

3.1.3.1.1.2.2 Role of the conduits

As mentioned by Jeannin [1990], the assessment of the groundwater heat potential could not be strictly restricted to the aquifer properties but it should also **consider the flow-system properties**, especially the circulation in the conduits. Indeed, conduits act as a key parameter for heat transport in karst (Covington et al. [2011]). Knowing the principles that govern geothermal processes in karst aquifers, properties that affect the evolution of the temperature gradient in karst and the heat distribution are of two kinds:

- The **physical properties** of the conduit network: density and distribution of the conduits, length and depth of the groundwater circulation, size of the conduits, etc. These properties are fixed and are specific to a system;
- The **hydrological regime:** fluctuations of the systems hydrological regime over the year notably affect the heat transfer within the system (Badino [2005]). As mentioned by Covington et al. [2011], over a relative long timescale, heat exchanges in fulfilled karst conduits are dominated by heat conduction through the surrounding rocks under turbulent flows. For a similar timescale, in open channel, radiative heat exchanges are of relative great importance.

Badino [2005] demonstrated that the density and the distribution of karst conduits impact the ascending propagation of the geothermal gradient. Isolated conduit has a restricted area of influence while numerous and equally distributed conduits will act as an "impervious" screen for ascending heat flux leading to inefficient thermal device on the ground (cf. Figure 3—4). In this view, poorly karstified rocks (dolomites, marly limestone, etc.) or rocks that have been recently exposed to the karstification will have a restricted influence on the ascending propagation of the geothermal flux (case a.). On the opposite, well karstified rocks or aquifers exposed to several phases of karstification will present a higher density of conduits (i.e. higher equivalent permeability, case b.). These are expected to **drain the geothermal flux** in the phreatic zone, towards the spring. Such zones are usually characterized by a temperature deficit over the ground and may present a heat-excess at the springs draining the massif.

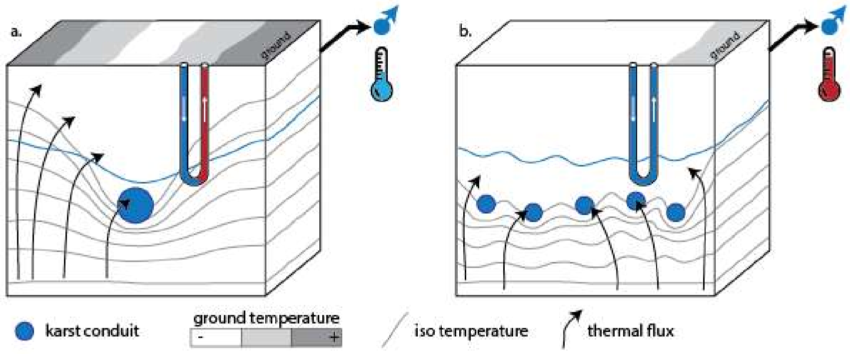


*Figure 3—4. Considering that conduits are efficient for heat drainage, their density and distribution within the massif and the groundwater flux impact the ascending geothermal heat flux. At some locations, aquifers of type (**a.**) reveal favorable for the implantation of geothermal probes while karst systems of type (**b.**) may offer more interesting conditions for springs heat exploitation as most of the geothermal flux is absorbed by the flows and carried out at the spring.*

In addition to the density/distribution of the conduits, the groundwater flux also governs the drainage of the geothermal heat. For a large flux, both groundwater and aquifer will present low temperatures. For small flux, the groundwater flowing through the conduits will absorb most of the geothermal flux and will reach the equilibrium temperature of the aquifer and a part of the geothermal flux will be released upward. Considering the variability of the groundwater flux in the year (up to a factor 1'000 between low- and high-flow conditions) the situation of an equilibrate flux draining the geothermal heat-flux is not stationary. Different karst systems may present one or several periods in the year (short or long) where groundwater flux is equilibrate. Once the groundwater flux increases, aquifer and groundwater temperatures should decrease.

Here-above demonstrations show that exploiting heat in karst aquifers is not a trivial task. **Heat propagation is mainly controlled by the groundwater flux**, resulting in contrasted thermic zones. Designing geothermal probes or tapping heat at springs with return expectations requires a good knowledge of the aquifer properties.

3.1.3.1.1.3 Problems related to geothermal probes in karst

Drilling geothermal probes in karst environments may provoke **disturbances** on groundwater (quantity and quality) and on the environment. Three types of hydraulic risks do exist for the aquifer and may lead to negative consequences over the ground:

- **Artesianism** and **depressurization** of the phreatic zone in confined parts of the aquifer;
- By-pass from an upper aquifer to a lower one (i.e. from the lower one to the upper one depending on the hydraulic head);
- Forcing infiltration may create or enlarge preferential flow-paths and provoke disturbances on the ground such as **collapse or subsidence** (see in Great-Britain, Cooper et al. [2011]; Figure 3—5). The recent increase of shallow geothermal heat pumps (mainly open loops devices) in karst aquifer increases collapses in suburban regions (houses, railways, etc.).

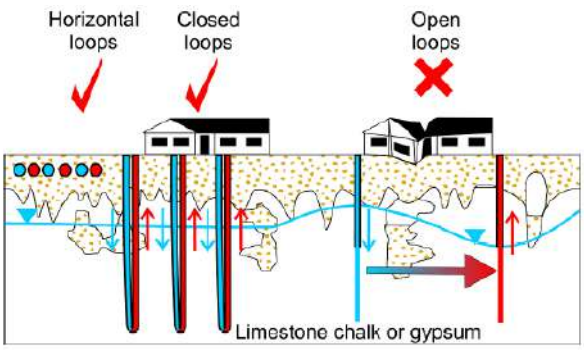


*Figure 3—5. Open-loop systems in karst aquifer enhance sediments mobilization or dissolution and may provoke land-subsidence (Cooper et al. [2011]). These mechanisms frequently occur in confined /semi-confined aquifers. This lead UK authorities to develop a decision support tool (**GeoSure**) which gives indication on areas to karst collapses susceptibility and recommends the type of devices to implant (open or close loop).*

In addition two types of contamination hazards do exist for the groundwater:

- Chemical contamination by release of **thermic-fluids** into the aquifer (mainly due to deficiencies of closed-loop systems).
- Change of the **groundwater temperature**. Swiss regulations mention that decrease/increase in groundwater temperature must not exceed 3°C at the radial distance of 100 m from the drill (Eugster [2009]). This regulation is well adapted in porous or fissured aquifers where the groundwater temperature may evolve radially from the geothermal probes but it seems less relevant in karst aquifers. Furthermore, karst groundwater is expected to present more natural fluctuations of temperature compared to porous or fissured aquifers (see Appendix 10.4.1) - even if large fluctuations of temperature are exceptions;

Various configurations of geothermal probes implantation in karst aquifer are presented in Figure 3—6 in considering potential hazards for the groundwater, the **expected thermic efficiency** and the usual **status of authorization**. From a hydrogeological point of view, **risky configurations** are assumed if: (i) probes may intersect two or more superimposed groundwater bodies because of a potential groundwater by-pass, (ii) probes are located in the direct vicinity of a groundwater intake like supplied springs, wells, etc., because of a potential groundwater contamination (ii) probes may intersect an artesian aquifer, because of sealing problems. On the other hand, from the point of view of the heat efficiency, fully-flooded and deeper probes may reveal the most profitable. As depicted on the figure, these aspects (regulations, risks and profitability) may reveal contradictory when looking for implanting a probe.

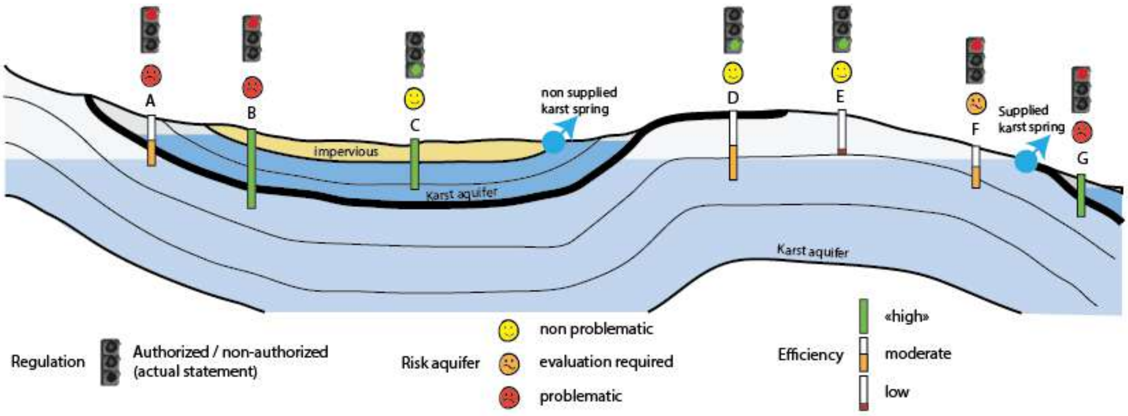


*Figure 3—6. Various scenarios of geothermal probes in karst; **A:** although the probe may reveal efficient, this scenario may impact the groundwater quality as the probe connects both aquifers. In theory, usual regulations strictly prohibit this scenario but implementations in practice are difficult as they require a consistent knowledge on the structuration of the aquifer with the depth; **B:** although the probe is located in a non karst area, it intersects two superimposed aquifer and may connect them. This configuration may reveal efficient for heat production if the probe intersects the conduits but it may also impact the groundwater. Usual regulations should prohibit this scenario – at least if the*

geological background is sufficient to assess the extension of the karst aquifer below the non-karstic formations… ***C:*** *the probe is located in a non-karst area even though it intersects the underlying karst aquifer. This scenario a priori does not present hazard for the karst groundwater – at least until the karst aquifer is non artesian;* ***D:*** *the probe is drilled in karst area and it reaches the saturated part of the karst aquifer. This configuration is not supposed to be problematic for the groundwater as long as it is located far from the supplied spring. However, some cantons strictly prohibit the probes to penetrate in the phreatic zone. In such conditions the efficiency of the probe is supposed to be moderate;* ***E:*** *the probe is located in karst area but it does not penetrate the phreatic zone. Although this scenario is not supposed to be problematic for the groundwater, the efficiency of the probe lying exclusively in the unsaturated zone is supposed to be moderate and to spatially evolve;* ***F:*** *the probe is drilled in karst area, close to the supplied karst spring. As a potential impact on the groundwater does exist (chemical contamination, etc.), this scenario is usually prohibited,* ***G:*** *in this scenario, the probe is drilled in karst area and it intersects two superimposed aquifer. As the lower confined aquifer is here artesian, a real risk of artesian by-pass has to be considered. Even if the probe may reveal "highly" efficient, it should be prohibited in such a situation.*

3.1.3.1.1.4 Swiss cases

In Switzerland the Federal Office for Environment (FOEN) promotes geothermal energies according to the environmental and water resources respect (Eugster [2009]). The FOEN fixes the frame and the main **guidelines** for a suitable exploitation but cantons are in charge of **regulating** geothermal probes as the sub-soil is their property. In general, geothermal probes are *de-facto* prohibited inside S1, S2 (federal rules) and sometimes S3 groundwater protection zones. They are also prohibited in zones of waste deposits or already contaminated. **Restrictions** may also concern the density and the depth of the probes.

In practice, cantons meet difficulties when the project is planned in karst area as it may present more risks for grounds and groundwater: contamination by the fluids, aquifer by-pass, stability of the ground, etc. Some cantons prohibit geothermal probes in karst area and strictly apply this principle where karst is outcropping (ex: Bern). Other cantons require a hydrogeological study in order to evaluate the project feasibility and its impact on the groundwater resources (cantons Fribourg, Valais, etc.). In reality, for most of the cantons, it reveals difficult to apply the regulation rules they have defined because they often don't have consistent **decision supports** and authorizations may sometimes be questionable.

These regulations may also reveal problematic because on the one hand geothermal probes may be very appropriate in some places, and on the other hand, zones where probes may encounter problems or may endanger the groundwater cannot be easily delineated without a sufficient knowledge of the karst aquifer functioning (Jeannin [2014], see Figure 3—6). Even for cantons they strictly prohibit probes in karst areas, the distinction between karst and non-karst areas remains difficult to fix because of covering formations or because of the complex organization of the geological formation that result from tectonic arrangement.

3.1.3.1.1.5 Conclusion

Implantation of **geothermal probes** (vertical heat pumps) in karst aquifer still remains complex. Implantation criteria should be balanced as conflicts do exist between appropriate locations from the point of view of thermic efficiency and related impacts on groundwater. As regulations for implantation are under the cantons authority - although they may not be familiar with karst aquifers - many of them strictly prohibit probes in karst environment or they apply restrictive guidelines (as for instance to not penetrate the phreatic zone). But even for such cases, regulation rules reveal difficult to implement as they require a consistent knowledge of the geometry of the karst aquifers as well as concrete documents for supporting decisions. Then, cantons are interested for a systematic documentation of the aquifers and of their properties in order to **address authorization permits** in a consistent way. Before the Swisskarst project starts, there was no dedicated approach to address such questions and cantons were disarmed to apply consistent regulations. Since the Swisskarst project was run, the KARSYS approach now reveals suitable to address these questions.

However, regarding heat efficiency, in-depth studies are still required to discuss the real thermic potential of the saturated and unsaturated zones of the karst aquifers. Such in-depth studies would be crucial in order to provide consistent guidelines for dimensioning geothermal probes in karst regions.

3.1.3.1.2. Springs heat exploitation

As indicated above, undertaking geothermal probes in karst environment may reveal hazardous from the point of view of the thermic efficiency and regulations may also reveal discouraging. As alternative solutions, **karst springs** may offer an interesting heat potential which is now still under-exploited (expecting for thermal springs, Goldscheider et al. [2010b]). Depending on the hydraulic properties of the karst aquifers and on the groundwater flux, heat exploitation at springs may reveal interesting. As springs are located at the downstream part of the flow system - they should offer the maximum heat potential (as already demonstrated by Drogue [1985]). In coupling **heat exchanger** in the water circulation at the main discharge point major springs could supply in heating numerous buildings with moderate cost.

Investigations in karst regions of the Vaud canton, i.e. Jura and Prealps (ISSKA and e-dric [2010]) focused on the assessment of springs heat potential by combining springs temperature and annual fluxes. Results show that springs heat potential may reach 273 GWh/yr in the Jura part and about 330 GWh/yr in the Prealps. On the whole canton, the annual heat potential offered by springs exceeds 600 GWh. This is far from being negligible, especially when considering that springs are often close to housings or to industrial zones. However, this resource is actually not optimally exploited although economic costs or global risks are weak. Indeed, such installations are usually cheaper and more suitable than expensive and unsuccessful boreholes. Few devices are already in use and most of them are installed in thermal karst springs.

Thermal springs in karst environments (i.e. springs that exceed 5°C above the mean annual air temperature as defined by White [1957]) are evidences of geothermal anomalies. These result from particular tectonic contexts which make it possible for hot water to quickly flow along fault zones and to emerge at the ground surface. Thermal waters emerging from karst aquifers are far from being negligible as they constitute the most important thermal resources after those emerging in volcanic contexts (Goldscheider et al. [2010b]). These thermal waters often show a particular mineralization and are used for various purposes (thermal baths, specific industries or heating). A review about principles of thermal water circulation in carbonate aquifers is proposed by Goldscheider et al. [2010b]. Numerous publications do exist regarding thermal sites in karst aquifers as they usually present a complex hydrogeological scheme and are of economic value. Most of these concern the city of Budapest (Dublyansky [2000]; Erőss et al. [2012], etc.). In Switzerland, thermal water resources are further discussed by Vuataz [1982] Bianchetti et al. [1992]; Muralt et al. [1997]; , etc. (see example of the F5 geothermic borehole project at Yverdon les Bains, Vuataz et al. [1999]). It could be here mentioned that most of thermal sites result from hypogenic karstification processes. Unfortunately, as hypogenic karst-processes are not well understood and not yet well modeled, these are not explicitly mentioned in mots hydrogeological studies.

3.1.3.1.3. Deep geothermal extraction in carbonate (karst) aquifers

Many references related to deep geothermal heat extraction in carbonate aquifers do exist. It should be therefore observed that “karst” is not always explicitly mentioned. In Switzerland (and Germany) the boundary between shallow and deep geothermal extraction - under normal geothermal gradient -has been fixed at ~400 m deep (CREGE [2012]). At that depth two kinds of systems may be distinguished: **hydrothermal** and **geothermal** ones (Hofmann et al. [2014]).

Hydrothermal systems (or high enthalpy systems) are designed for power production. Groundwater of relative high temperature is retrieved from permeable to high permeable formations where the permeability may be boosted by hydraulic fracturing. After it has passed through the heat exchanger, the cooled water is then re-injected into the aquifer to maintain the pressure of the groundwater. Economically interesting systems must present a groundwater temperature higher than 100°C, a production rate ranging from 50 to 100 L/s and an associated pressure drawdown of 1.5 to 3 MPa (Schulz et al. [2005]).

On the opposite, **geothermal systems** (or low enthalpy systems) do not present the minimal temperature and discharge requirements for electricity production even after thermal, hydraulic or chemical stimulation methods. Such stimulation methods are described by Hofmann et al. [2014]. These geothermal systems are mainly used for direct heating purposes (domestic districts, buildings, etc.).

As mentioned above, the key of a successful deep geothermal exploitation lies on a sufficient permeability allowing the extraction of significant amount of warm/hot groundwater. In porous or fissured media, the rocks permeability significantly decreases with the depth and tends to be very low at great depth. This is a handicap for heat extraction and it often implies to enhance permeabilities using hydraulic fracturing, blasting or chemical actions. Depending on the context, in deep carbonate aquifers, **old epigenic karst** or **hypogenic karst** may be present and may offer a significant permeability and even an artesian regime (up to 100 m^3/h in the Belgian carboniferous limestone, Licour [2014]). In many places of the world, these deep carbonate aquifers are seen as an interesting target for geothermal or hydrothermal exploitation (Zhenguo [1988] Stober and Jodocy [2009]; Schumacher and Schulz [2013]; etc.).

In Switzerland, pilot projects regarding deep geothermal have been carried out and documented: Flury et al. [1991]; Boissavy and Hauber [1994]; Vuataz et al. [1999].

3.1.3.2. Hydropower in karst regions

56% of Switzerland's electricity comes from **hydropower** (OFEN [2010]). This production is mainly supported by 45 mountain dams in the Alps (e.g. Grande Dixence Dam, Mauvoisin Dam, etc.). Most of these dams lie in crystalline massifs as they are offer most impervious substratum for the reservoir. Power production is usually operated by private companies while the distribution is usually under the responsibility of public services (cantons).

3.1.3.2.1. Characteristics of hydropower plants in karst and existing types of device

In a first view karst environments cannot be considered as an appropriate environment for building dams. There is no surface water and limestone usually does not offer a real impervious substratum for making the reservoir impervious unlike in many other geological contexts. However, karst environments may offer an interesting flow concentration and an interesting hydraulic potential which could be managed for power production. Two types of hydropower-plant projects may be designed in karst; the **external hydropower plants**, involving surface storage and the **internal hydropower plants**, involving groundwater exploitation (Jeannin [2014]).

3.1.3.2.1.1 External hydropower plants

External hydropower plants consist in building an **outside dam** in an appropriate site (valleys, poljès, canyons, etc.) with a downstream turbine. In the Dinaric karst, several elevated poljés in Bosnia, Croatia and Serbia which were frequently flooded in the past have been equipped with dams (see Milanović [2004]). Poljés are connected by galleries, allowing water transfer from upper dams to lower ones in order to insure power generation. According to the high precipitation rates, such plants are really efficient. The Trebišnjica Hydropower plants system is one of the most complex power projects in the Dinaric karst (~650 MW). It provides 30 to 40% of the Bosnian power consumption as well as a significant part of the Croatian power consumption.

3.1.3.2.1.2 Internal hydropower plant

Internal hydropower plants consist in damming the rock mass or in building a **dam in a cave** in order to store a sufficient amount of water to produce power. Generated power may be used for producing electricity or for conveying deep water to the surface (for water supply). The turbine may be installed underground or outside, downstream to the system's outlet. Such projects are usually smaller in scope than external hydropower plants.

The most famous example of projects of internal plant is probably the Ombla power-plant project (68 MW), which has been presented by Bonacci [1995] and Milanović [2004] but it is not realized so far.

Improvements have been made in the field of **micro-turbines** during the last decades and underground installation already exist in France with the example of la Verna Chamber (Viguier and Bertuola [2006]). A dam has been built in the main chamber and the water is driven outside to the power plant (4 MW).

The Areuse karst system (NE, Switzerland) is another example of hydropower project. The karst system was investigated at the beginning of the 50's as a potential site for power-production (Kiraly and Morel [1976a]). A plant has been installed downstream the spring.

Another example of an underground hydropower power pilot plant for water supply is given by Nestmann et al. [2013]. The pilot plant of Gua Bribin (Indonesia) dams a large horizontal conduit at a depth of 100 m below the ground. The aim of the plant is to pump the water to the ground surface through a hydropower conveying system. This 300 KW plant is designed for a maximum bearable hydraulic head of approximately 30 m and an optimal groundwater discharge of about 1.9 m^3/s. Under such conditions, the plant may provide 65 L/s to the 220 m elevated reservoir Unlike the Verna project, the dam here completely obstructs the karst conduit and the plant benefits from the hydraulic load of the whole aquifer under high-flow conditions (and not solely from those of the dam elevation).

Principles of internal power plant feasibility in karst media and evaluation elements of the profitability of such projects have been synthetized in the Vaud canton (Jeannin et al. [2010b]). In theory different types of devices may be proposed to capture karst groundwater (Figure 3—7).

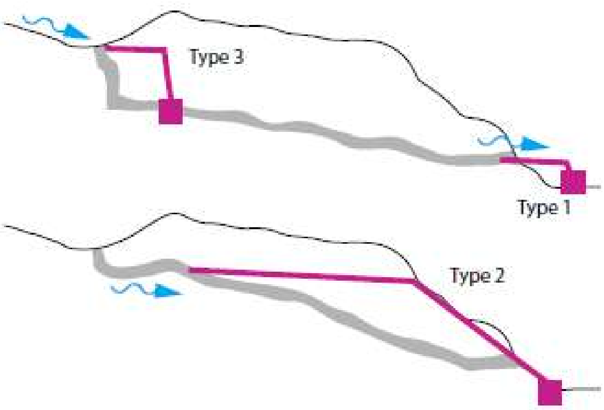


Figure 3—7. Different capture techniques for hydropower production in karst aquifers (Jeannin [2014])

The **Type 1** may be installed in case of perched spring located several meters or dozens of meters above the valleys floor. The Areuse spring (Neuchâtel, CH) is equipped with this type of hydropower plant. However, elevated springs are often temporary springs. In that case, base springs may be partly obstructed in order to make the overflow spring permanent and both springs may be tapped for power production (similar to the Ombla hydropower-plant project).

The **Type 2** consists in diverting an underground vadose stream via an artificial tunnel or pipe connected to a downstream turbine. This type could be similar to the la Verna Chamber project (Franc) or to the Areuse power-plant project (Switzerland) as the regime of the spring is partly regulated by the artificial management of the “lac des Taillères” (Kiraly and Morel [1976a]).

The **Type 3** consists in an underground turbine located in the underground stream, within a cave or a borehole reaching the stream (case of the Gua Bribin pilot plant).

3.1.3.2.2. Related problems and difficulties

Regarding **external hydropower plants**, one of the main difficulties when building the reservoir and the dam is related to the multiple sinkholes and sinking features over the ground which may provoke considerable water losses. Several cases of dam’s malfunctions have been described through the literature. Problems usually come from the fact that properties of the environment or of the aquifer have been misjudged or underestimated when designing the project. Some dams appeared to be basically inefficient to store the water: Anchor Dams, Wyoming (Jarvis [2003], it was never put into operation), Hales Bar Dam, Tenessee (up to 54 m^3/s, ~10% of the Tennessee River’ normal flow, Milanović [2004]), Montejacque Dam, Spain (Van Beynen [2011]) and have been abandoned. Other dams developed considerable **water losses** by leakage which increased with time. Most of them have been reduced by grouting or sealing treatments (numerous cases in Balkan countries and in Iran, see for instances Boreli and Pavlin [1965]; Milanović [2004] Bonacci [2009]; Fazeli [2007];).

Some other dams do not present considerable water losses beneath the dam but on the back flank of the reservoir, inducing a limit in the reservoir filling (up to 50% of reduced infill in the case of the Salanfe dam, Switzerland, Bianchetti et al. [1992], or Tseuzier dam, Wildberger [1979]). Such problematic may also be partially solved by grouting or sealing treatments in the flanks of the reservoir.

Main difficulties for designing **internal power plant** are (i) to locate the conduits which are the most appropriate features for capturing groundwater and (ii) to evaluate the power potential. Furthermore, such project may require complex technical solutions that are still being developed. Tools and methodology enable for site location or potential assessment in karst aquifers are missing from the literature. This conducts to certain reluctance from managers to concretize such projects. Impact on the environment should also be prevented as the rise of the groundwater head in the massif may have consequences on existing (and mostly unknown) caves and on the ground surface (landslides, hydrological modification of other springs, etc.). These are mainly the reasons why the Ombla power-plant is still not realized.

Moreover, such projects should also guaranty the **safety of the installation** as they are not without risks on civil construction or on the environment: dam collapse, landslides, earthquakes, etc. (Milanović [2004]).

3.1.3.2.3. Conclusion

Power production in karst is still a challenge. On the one hand karst possesses some characteristics making this resource interesting: (i) low impact on the surface environment (= no esthetic degradation), (ii) opportunity to produce electricity in areas where building a dam reveals extremely challenging (Milanović [2004]; Zargham and Ezatollah [2007]), and (iii) a wide distribution of potential sites (20% of the Swiss territory, 20% of the earth) close to urbanized areas where electricity is consumed (i.e. losses Joules reduction). But, on the other hand, such projects raise numerous engineering difficulties and potentially environmental disorders which should be adequately assess. Furthermore, the success of this type of project (high efficiency and low impacts) depends on the prior geological and hydrogeological investigations on site.

3.1.4. **Civil engineering in karst environment**

3.1.4.1. Problems

Problematic cases of **construction** in karst environments are frequently reported in the international literature. Impacts on karst aquifers often occur and may directly affect water quantity or quality (contaminant, turbidity), during all the building and exploitation stages. Works could also modify groundwater flows and generate hydrogeological disorders for long or ever which may still threaten the construction. Milanović [2004] presents many case studies of constructions in karst all over the world for which initial plans have been revised in course because of a poor assessment of hydraulic mechanisms of the karst aquifer. The author could be seen as a reference in this topic. Other case studies have been related by many authors; they mainly concern constructions such as **dams** (cf. §. 3.1.3.2.1.1), **tunnels** (Day [2004] Alija et al. [2013];), **gates**, **highways** or **railways**, **mines** (Marinos [2001]), **waste deposits**, etc.

Besides **geotechnical damages** that may occur because of environmental modifications (collapses, sediments infilling, instability, etc.) constructions often conduct to modification of the catchment areas (Bonacci [2004]) by changing the aquifer base level (i.e. drop of the hydraulic gradient, for instance when intersecting a karst conduit lower than the outlet of the system) or by flooding the system (i.e. rise of the hydraulic gradient, for example when filling a dam or a reservoir with water). This practice often lead to (i) an enhancement of flood events in the adjacent areas (case of the Ogosta Dam, Bulgaria, Benderev et al. [2006]) and/or (ii) to a dewatering of areas (case of the Flims Tunnel in Switzerland, which is responsible of the Cauma lake partial regression, ISSKA Jeannin et al. [2009]). Such modifications may also change the aquifer’s storage capacities and the hydrodynamic responses of the outlet(s). Construction problems in karst environments are related to water, voids and sediments (Table 3—1).

	Potential problems
Water	- Fast and significant water inflows (filled water voids release) - Temporary fast water inflows - Drainage of significant inflows from the saturated zone - Drainage of variable inflows from the unsaturated zone - Clogging of drains by calcification - Coatings corrosion - Impact on the regime of the surrounded springs - Contamination of surrounded springs (turbidity, pollutants) - compaction and instabilities induced by the drainage
Voids	- Instabilities - Falling blocks (or mud-packs) - Front digging problem - Anchorage problems of the TBMs - Uncertainty on the rock thickness (bottom, cap)
Sediments	- Instabilities - De-clogging (muds, sands, etc.) - Front digging problem - Anchorage problems of the TBMs

Table 3—1. Main karst-related problems when digging a tunnel (from Jeannin [2007])

3.1.4.2. Main issues in Switzerland

In Switzerland, most perturbations related to karst have been observed during the building of dams (see §. 3.1.3.2.1.1) or the digging of galleries / tunnels (Jeannin [2007], Filipponi et al. [2012]; Anagnostou and Ehrbar [2013]; , etc.).

The following Table 3—2 synthetizes the karst-related incidences for a sample of civil infrastructures in Switzerland, mostly for tunnels (see details for each case in Appendix 10.5). The table points out the fact that, for some of these infrastructures, expected karst-related hazards were often not taken into account or were underestimated, leading to unexpected problems which required additional measures or equipment that were not designed in the initial phase.

For most of the following examples, initial plans have been modified due to the presence of karst, resulting in additional costs. These examples demonstrate that nowadays, approaches or methods reveal indispensable in order to prevent the nature (expected voids location and distribution) and the consequences (hydrological and geotechnical disorders) of karst-related hazards in civil engineering.

Swiss Cases	Incidence on the construction	Incidence on the environment	Karst hazards initially expected	Modification of the initial plans during construction
Concise tunnel (VD / NE)	Water inflows, instabilities, additional equipment	Weak	Yes	Yes
Engelberg tunnel (OW)	Water inflows, declogging and sediment infilling	-	Yes but underestimated	Yes (Additional costs ~70 Mio Fr., the initial project was estimated ~80 Mio. Fr)
Flimserstein tunnel (GR)	Water inflows	Partial and irreversible dewatering of lake and springs	No	Yes (additional costs ~100 Mio Fr.)
Kerenzerberg tunnel (GL)	Water inflows + flooding during the operation phase	Weak	-	No
Mont d'Or tunnel (Switzerland / France)	Water inflows, declogging and sediment infilling	Irreversible springs dewatering	Yes but underestimated	Yes
Ölberg tunnel (SZ)	Water inflows	No	No	Yes
Raimeux tunnel (JU)	Weak	Weak	Yes	No
Rawil gallery (BE / VS)	Water inflows	Relevant (micro-displacements of the Tseuzier dam)	No	Yes (construction stopped)
Twann tunnel (BE)	Water inflows	Weak	Yes but underestimated	Yes
Vue-des-Alpes Tunnel (NE)	Instabilities, additional equipment	No	Yes	Yes
Milandre Highway and Neu-Bois Tunnel A16 (JU)	No	Weak	Yes	No

Table 3—2. Synthesis (non-exhaustive) of the problematic encountered in Swiss tunnels passing through a karst massif (sources: Schneider [1980]; Bianchetti [1993]; Jeannin and Wenger [1993]; Wildberger [1994], Bollinger and Kellerhals [2007]; Jeannin [2007]; Filipponi et al. [2012] and Anagnostou and Ehrbar [2013])

3.1.4.3. Solution – prevention means

Methods have been developed by different authors in order to prevent karst related hazards in such construction using geomorphological and hydrological surveys (ex: Jeong et al. [2003], Casagrande et al. [2005]), using geophysics (ex: Li et al. [2013]), using GIS (ex: Li and Li [2014]) or applying simulation tools (ex: Ge et al. [2009]).

In Switzerland, the **KarstALEA method** (developed by SISKA and EPFL, cf. Filipponi et al. [2012]) is dedicated to the prediction of potential karst disorders during the project phase (or even during the building stage) by predicting voids location / size and frequency as well as water and sediments inrushes. Application of KarstALEA for the drill of the safety gallery of the Ligerz road tunnel is presented in Malard et al. [2015b] (Appendix 10.6) and Jeannin et al. [2015a]. KarstALEA entails the implementation of an explicit 3D conceptual model of the karst aquifer in order to precise the expected location of the karst conduits. This step is essential for applying KarstALEA and it was one of the main development focuses for KARSYS.

3.1.5. **Clear (and waste) water evacuation – artificial injection**

3.1.5.1. Definition and uses

In suburban and natural areas, the land use and the progressive soil sealing imply to organize efficient **drainage networks** in order (i) to prevent these areas from flooding during storm events, but also (ii) to drain "clear" water from treatment plants or households. In most environments, where infiltration rates are limited, clear water is drained by organized sewer-pipes networks toward natural streams. In karst environments, infiltration features are often managed with the objective to **force infiltration** into the aquifer (Beck et al. [1999]).

Nevertheless, such strategies in karst environment may generate strong disturbances on groundwater quality or over the ground if specificities of karst aquifers are not explicitly considered. Processes of water evacuation in karst are not widely described in the literature, except in U.S. (see examples of the Pennsylvania Stormwater Best Management Practices Manual - PA State [2006], or the Stormwater Design Guidelines for Karst terrain in the Chesapeake Bay Watershed (KWG [2009])).

The question of storm water and treated water drainages through the karst aquifer is essential in karst environment. Water injection may be distinguished in two types: **suburban areas** and **natural areas**. Water injection in suburban areas may mix wastewater, treated water and storm water while water injection in natural areas only concerns storm water. Water injection in natural areas is seen as prevention mean against floods. Streams are diverted and overflows spread over large areas where the water infiltrates through particular karst features. In suburban areas - depending on the degree of separation between the wastewater drainage system and the storm drainage system - infiltrated water may be more or less "cleaned".

Water injection could be performed into existing open karst features (caves, dolines, crevices, etc.), or dispersed over a semi diffuse area (soil-covered karrenfield or dry valleys) where the water "slowly" infiltrates into the aquifer. In another context - or in addition to existing open karst features - the water may be evacuated through **injection wells** (Class V injection wells, EPA [1999]).

3.1.5.2. Related problems

The non-consideration of hydrological specificities in karst when designing injection devices could lead to various disturbances on the groundwater quality or over the ground, similar than those observed for the geothermal heat probes (see §. 3.1.3.1.1):

- **Groundwater contamination:** contaminants in polluted runoff and spills can pass rapidly from the surface into groundwater with a limited or even no filtration and may endanger the groundwater quality. Then water injection in karst aquifer may badly impact the water resources in disturbing the spring's rate discharge or increasing pollutants migration (chemical or biological) or in strengthening turbidity;
- **Clogs:** It also happens that solid matters transported by the flows can lead to plugging of the conduit's network. Then, evacuation capacities will be greatly reduced. As a consequence hydraulic heads within the karst media could significantly increase and lead to unclog old unknown conduits or weakened boundaries of the system. Such phenomenon may have negative incidences over the ground: floods, mudslides, etc.
- **Collapses and subsidence**: Concentrating runoff to particular infiltration features may enhance and/or accelerate the development of sinkholes or larger subsidence areas. This lead to serious consequences regarding the stability of public infrastructure, roads and buildings (and may even be dramatic for human life). The phenomenon of soil and sub-soil leakage is through the karst features is designed as "**suffusion**" (Crawford and Groves [1995]). The risk mainly concerns soil-covered karst as already observed for the geothermal heat probes (see Figure 3—5);
- Caves and species degradation: increasing groundwater discharge in caves may threaten the caves morphology and/or endanger animal species, which benefit from a special protection.

Such disturbances may lead to strong damages for the environment and to additional costs for the society.

3.1.5.3. Conclusion

Evacuation of clear and waste water must be carefully planned according to the vulnerability of the karst aquifers in order (i) to bring a minimal impact on the groundwater quality and (ii) to preserve the stability of the ground surface (Mijatovic [1993]). Clear and waste water infiltration through karst aquifers should not be strictly prohibited as in some places, there is no other alternatives (for instance in endorheic valleys or in large plateaus). Nevertheless, the sub-soils characteristics, the aquifer storage capacities and the groundwater circulations have to be well documented before using existing features to **force infiltration** and before designing **injection devices**. An explicit 3D model of the karst aquifer, of the sub-soils, of the inception features and of the speleogenetic zones appears as essential to properly assess the infiltration capacities of the karst aquifer for water evacuation.

3.1.6. Ecological services

Karst environments are of great significance for the **ecosphere**. As they are characterized by (i) the absence of water on the ground, (ii) the soils scarcity, and (iii) the chemical rocks properties, karst environments host a **specific ecology**. Due to these “stress” conditions, flora and fauna living in karst are often of moderate growth / renewal and then considered as relatively fragile (or vulnerable).Works on the topic of specific biodiversity in karst environments do exist and could be mentioned: Vermeulen and Whitten [1999], Clements et al. [2006]; , etc. Caves always provided habitats or refuge for a wide number of species which could hardly develop outside of this stable and relative safe environment.

Water emerging from karst aquifer is supposed to be also of great significance for environmental issues, mainly by contributing to the recharge of other aquifers (i.e. alluvial) or by supporting a large part of **surface streams discharge or during dry seasons**. Karst systems also contribute to supply upper or adjacent porous aquifers. Indeed karst environments are strongly sensitive to infiltration and could be considered as a privileged vector for recharging fissured and porous aquifers. As karst aquifers sustain surface stream discharge during dry seasons, this has for consequence to maintain activity of aquatic fauna and flora even for prolonged droughts which occurs under temperate, Mediterranean or arid climates. Nevertheless, this phenomenon has not been widely explored excepting in U.S. Tobin [2013] found a clear correlation between baseflow in dry seasons and the proportion of karst and unconsolidated aquifer units within the basin. During baseflow conditions, the contribution of karst groundwater to the river discharge may reach 65%; although the proportion of karst aquifers - compared to the size of the basin - barely reaches 5%. Gooseff et al. [2005] made a similar work in Utah using chemical and isotopic analysis. They found that karst aquifers represent the **essential contribution to the Logan river** discharge during late summer and fall (more than 80%). In Switzerland, the contribution of karst groundwater to the rivers discharge for rivers draining more than 50% of karst areas ranges between 24 and 74% (see §. 7.2.2.).

3.1.7. Heritage and Tourism

All over the world, **landscapes** resulting from karst processes are frequently considered as unique and **particular heritages**. Surprising geomorphological features (canyons, arches, karrenfields, fairy chimneys, etc.), caves (painted or not) or large karst springs are major attractions for **tourists** in all parts of the world. As related by Florea and Vacher [2006], patrimonial and touristic values of large karst springs in U.S.A is of high economic interest. Numerous springs are managed as state parks (Big Spring state Park in Missouri, Mammoth Spring or Withrow Spring state in Arkansas, Ellenberger karst springs, Colorado Bend State Park in Texas, etc.). Florida’s four largest first-magnitude springs (average discharge up to 3 m^3/s for the main one) bring about 1 million visitors spending $65 million/year! In addition to the increase of water demands in Florida and to associated pressures on the groundwater, this huge volume of ecotourism spurred to a lot of publications and state-commissioned studies on these springs.

In the frame of the **IUCN** protected areas program (Williams [2008b]), a review of karst (and karst-like) landscapes informs on the existing **World heritage sites** that are related to karst processes. Even if the list continuously evolves, it should be mentioned that a large proportion of World Heritage sites derives their specificities from the karst or karst-like processes. Diversity of these sites depends on lithology, context and climate.

This interest for karst environments requires the development and the application of **management practices** in order to regulate the impact resulting from touristic activities as the overexploitation of these sites may endanger their integrity (example of the Lascaux cave, etc.).

3.2. Users (people interacting with karst in Switzerland)

The previous demonstrations focused on the different uses of the karst environment and of the karst groundwater makes it possible to identify the **users**, i.e. the people that are in interaction with karst an all related problems. Depending on their tasks and responsibilities, these users require different approaches, methods and information on the karst functioning which are actually far from being optimal and universal.

People in Switzerland interested in getting sufficient information concerning specific aspect(s) of karst environments and karst hydrology are presented hereafter (Table 3—3). The Table 3—4 provides a synthetic overview of the main users and their respective **fields of interest** for the karst.

Category	Mission or business regarding hydrology and environment	Interest in karst
Administration		
Federal Offices (OFEV, Swisstopo, OFROU, OFAG, OFEN, DDC)	FOs are responsible for providing basis data related to geology, hydrology, hydrogeology, climatology, etc. in the form of database or maps at the scale of the state. FOs are responsible for elaborating reference documents for environmental and water legislations (groundwater protection zones, natural hazards maps, water contamination standards, etc.) FOs are also responsible for the implementation of federal obligations: - Funding and supervision of constructions that are under federal jurisdiction (national roads or tunnels, etc.); - Support the cantons for applying federal regulations (incentives, consultancy services, etc.).	FOs are interested in: - Basis data regarding karst hydrology (karst zones, sources location, etc.); - Systematic maps (hydrogeology, geomorphology, geology) at the national or the cantonal scale; - The development of pragmatic methods for supporting the application of federal regulations (ex. KarstALEA method, Filipponi et al. [2012], or EPIK, Doerfliger and Zwahlen [1998]).
Federal companies (ex. Swiss Federal Railways)	The SFR is responsible for the development and the management of the railways network and of the related infrastructures: tunnels, stations, etc.	In the frame of construction works, SFR may be concerned by karst-related problems (mainly in tunnels). Their interests are then similar to those of the FOs.
Cantons	Cantons have to transcribe and to apply federal regulations regarding environmental and water laws (LPE, LPEaux) and associated ordonnances. In	Cantons are interested by: - Pragmatic methods for applying federal and cantonal regulations regarding natural hazards (ex. Beuchire-

	practice, cantons have to elaborate: - The natural hazards maps[1]; - The cantonal water protection zone maps (1/25'000)[2]; - The cantonal prescription maps (geothermy, land-uses, urbanization, etc.); Cantons are also responsible for: - The maintenance of the water supply system. However this competence is often transferred to communities; - The funding and supervision of cantonal constructions (roads, tunnels, etc.)	Creugenat site, §. 6.3), groundwater resources and protection zones (ex. Bernese Jura, Appendix 10.7), geothermal probes (§. 3.1.3.1.1), etc. - The valorization of karst heritage (classification of natural sites of interest, geotopes, tourism sites, etc.)
Communities	Regarding water and environmental ordonnances, communities are responsible for the following obligations: - To ensure domestic water supply and the sanitation of wastewater by delegation of the cantons - To elaborate the wastewater management plan (GEP) Most of the communities also elaborate their natural hazard maps.	Communities are interested by: - Local studies related to groundwater resources: tapping strategies, contamination sources; - Recommendations and feasibilities regarding clear water evacuation (§. 3.1.5) - Natural hazard maps
Water authorities		
Public water trade unions	By delegation of communities, these are responsible for ensuring domestic water supply and wastewater sanitation[3] (construction, exploitation and maintain of the water-tapping devices and water networks)	Karst interest and requests from public water trade unions are comparable to those emanating from communities. Their concerns are mainly related to local studies on exploitation and contamination of the groundwater resources.
Research organizations		
Research and academic institutions	R&A institutions (Universities, Fachhochschule and Federal Institutes of Polytechnic and associated research institutes like WSL[4], EAWAG[5], PSI[6], etc.) don't have any public service mission. However, these institutions often cooperate with the federal offices as consultant or expert for specific questions related to water and environment.	As these institutions often cooperate with public services, they are mainly interested for getting data and information on the aquifers functioning. These institutions are usually not interested by getting finalized and oriented products as those required by the administrations
Associations:		
Non-Governmental Organization	Swiss NGOs entail numerous development agencies and humanitarian organizations (ICRC, UN, Helvetas, etc.) which work on the field of water-supply, wastewater sanitation and emergency construction (shelters, etc.).	NGOs interests and requests concern: - Local studies focused on groundwater tapping strategies, source contamination, protection zones, etc. - Basic data: groundwater monitoring program

[1]http://www.bafu.admin.ch/naturgefahren/11421/index.html?lang=fr
[2]http://www.bafu.admin.ch/grundwasser/07508/07722/index.html?lang=fr
[3]Art. 703, Code civil Suisse
[4]Eidg.Forschungsanstalt für Wald, Schnee und Landschaft : http://www.wsl.ch/
[5] Wasserforschungs-Institut des ETH-Bereichs : http://www.eawag.ch/
[6]Institut Paul Scherrer : http://www.psi.ch/

		(regional scale); - Materials: books, brochures or videos for educational purposes.
Apex organizations	Somme apex organizations are active in the field of water and environment (SCNAT[1], SSIGE[2], SDESR[3], VSA[4], ProNatura, SSS[5], etc.) don't have any public service mission. Apex organizations act for syndicates, private companies or non-benefit associations, providing legal (right of appeal), facilities and communications means.	Apex organizations may have to manage karst related problems in the frame of their activities. Their interests or requests are usually of two kinds: - Development of consensual methods for approaching karst-related problems (ex. Practice Directions in Karst, Schmassmann and Hitz [2010], or establishment of criteria for the selection of karst geotopes, see Reynard et al. [2012][6]) - Consulting for environmental diagnosis in case of right of appeal or penal actions (environmental damages, etc.)
Civil associations: - Water and environmental protection - Flora and fauna - Cavers - Etc.	A lot of associations are involved in the questions of water and environments from multiple points of view (sciences, education, heritage, fishing, sports, etc.). These associations may be reunited in apex organizations (see above, ex. ProNatura, SSS). At local or federal scale, they act for: - Remediation (restoration) of sites (rivers, littoral, etc.) - Protection; / preservation actions (sites classification, etc.); - Producing data or observations on a site; - Surveys and site documentation; - Lodging complaints or bringing civil actions regarding environmental damages with support from apex;	Civil associations working in the field of water, environment and geology may face karst-related problems. Excepting cavers whose interests in karst is obvious; interests and requests from other associations may concern: - Consulting in local sites (project feasibility, environmental impact studies, etc.); - Theoretical or pragmatic courses on karst hydrology or karst heritage; - Materials: books, brochures or videos for educational purposes;
Industry:		
Civil engineering firms and consultants	They bring their expertise in various projects ordered by federal offices, cantons, communities and private companies in the field of water and environment: - Project dimensioning - Project impact assessment - Work supervision	Engineers and consultants often interact with karst related-problems. Their interests and requests concern: - Basis data regarding karst hydrology (discharge rate, aquifer oscillations, etc.) - Consulting in local or regional sites - Environmental impact-studies, construction projects feasibility and recommendations on the construction-processes (e.g. supervision of works)
Hydropower companies (also partly valid for windpower	Private or public companies are responsible for power production. Most of the hydropower dams are located in Alpine non-karst areas but a few of them have to face to karst related problems (Emosson, Tzeusier, Salanfe, etc.). In	Companies are interested by the planning and the optimization of the hydropower plants production. Their concerns are mainly related to hydrological predictions and to new management strategies for exploiting the hydraulic force.

[1]Swiss Academy of Sciences : http://geosciences.scnat.ch
[2] Société Suisse de l'Industrie du Gaz et des Eaux : http://www.ssige.ch/
[3]Société des Distributeurs d'Eau Suisse Romands : http://www.sdesr.ch/
[4] Verband Schweizer Abwasser- und Gewässerschutzfachleut : http://vsa.ch/
[5]Société Suisse de Spéléologie : http://www.speleo.ch/
[6]The completion of the geotopes inventory has been performed by a members delegation of the SCNAT under the directory of the FOEN

companies)	karst areas, a few hydropower plants do exist (Lac de Joux - Vallorbe, Areuse, Aubonne); it mainly consists of run-of-river facilities.	Their requests and interests in karst concern: - Basis data on karst hydrology (outlets discharge rate, aquifer oscillations, etc.); - Evaluation of projects feasibility and profitability (i.e. models and middle-terms to long-terms simulation results); - Karst-related hazards assessment (hydrology and geotechnics, waterproofing dams, etc.).
Other industrials concerned by the exploitation of water resources	Such private companies (bottling companies, thermal baths, etc.) exploit a part of the groundwater resources for particular uses. They usually search for a specific water quality or for thermal characteristics.	Such industrials working in karst areas look for: - Groundwater quality monitoring program; - Tapping strategies (success chance, profitability, groundwater risks, etc.).
Tourism		
Public touristic offices	These offices are responsible for promoting natural heritages on their territories.	These are interested by a didactic and tourists-oriented documentation of their sites of interest – from a patrimonial point of view. They may also be interested by improving the management of the touristic sites while respecting their integrity.
Private companies	Touristic private companies in relation with karst mainly concern: the touristic caves or the trekking activities.	As for the public ones, these companies are interested by promotional documents that attract the visitors or by improving the management of their touristic site (didactic trail in cave, etc.)

Table 3—3. Overview of users and their interests for karst related information in Switzerland

Users may be roughly grouped in four categories: (i) those that are looking for the peculiarities or resources provided by the karst (groundwater, energy, tourism, etc.), (ii) those that are responsible for management (groundwater resources, natural hazards, clear- and waste-water management, etc.), (iii) those that are interested by studying and understanding the natural processes that control the evolution of environments and related resources and (iv) those that seek to protect environments and resources. As interests from the users for the karst may be common, the following Table 3—4 intends to organize the users interests.

Users	Basic data (maps, inventories, etc.)	Karst aquifers characterization at global / regional scale	Local karst aquifers characterization	Dedicated tools for the organization and visualization of karst information	Pragmatic methods for resources management and hazards assessment	Courses and education documents	On-site specific studies (caves, etc.)
Federal offices	X	X	X	X	X	X	
Federal companies			X	X			
Cantons		X	X	X	X		
Communities			X	X			X
Public water trade union		X	X	X			
Research and academic institutions	X			X		X	X
Non-Governmental Organization	X		X			X	
Apex organizations	X		X		X	X	
Civil associations			X			X	X
Civil engineering firms and consultants			X	X	X		
Hydropower companies			X	X			
Industrial							
Public touristic offices and private companies				X		X	X

Table 3—4. Synthetic overview of users and their respective field of interest for karst-related information (focus on Switzerland).

3.3. Conclusion: making karst more accessible for users?

This chapter shows that karst environments are concerned by various and specific issues regarding resources (water), production of renewable energies (heat, hydraulic potential), evaluation and prediction of natural hazards (floods, collapse, landslides, etc.), construction, land-planning, protection and promotion of natural heritages, etc. The management of these issues in karst environments poses a number of specific problems and involves a set of various users (administration, research, private sector, civil associations, etc.). In order to take the best solutions for each of these problematics, decision makers require specific information. These information ideally combine environmental parameters (related to the context: geology, soils, vegetation, etc.) and the specificities of the considered issues (resources, energy, hazards, vulnerability, etc.). Whatever the issue, the here-above sections showed that knowledge about karst is not always sufficient for the issue to be properly assessed. Presented case studies show that a lot of projects in karst could have been succeeded (i.e. negative incidences could have been reduced) as long as karst specific properties have been explicitly taken into account.

Main problems come from the fact that (i) hydraulic specific properties of the karst are not well understood and (ii) karst is not likely to be present on site – and then not considered. It seems then obvious that users need basis data on karst (spatial information), dedicated approaches / methods to address their respective issues and at last a technical dedicated support (assistance) to assess specific problems.

These are the main missions of SISKA. KARSYS is an illustration of such an approach; it has been developed in order to improve the management of groundwater resources in karst aquifers and it has been widely disseminated in Switzerland in order that users appropriate for applying on their own issues. This chapter addresses the question of users who are concerned by problems related to karst aquifers. It was a significant topic of the NRP61.

4. *Approaches to the hydrogeological characterization of karst*

4.1. Characterization approaches

This section discusses the usual approaches for the characterization of hydrological properties of karst aquifers. Two main approaches and their outputs are developed: the structural and the functional approaches.

4.1.1. Definition

A **characterization approach** is a set of principles and investigations combined in a way to characterize the variations in space and in time of a physical system. In classical hydrogeology, the characterization of an aquifer refers to the description of the **groundwater flow-systems** and its evolution in time (see Tóth [2009]).

In practice, the characterization implies to determine and to quantify physical parameters which control the **geometries** and the **hydrodynamic properties** of the aquifer (i.e. parameters field and boundaries conditions):

- The physical properties of the reservoir (geometry, cover, sub-compartments, type of porosity, etc.);
- The organization of the water filling (confined, unconfined, thickness of the unsaturated zone);
- The recharge: modus, variations;
- The flows migration (direction, gradient, flux, permeability).

In this way homogenous aquifers are described as a set of **gravitational flow-systems** in which the groundwater transfers from the recharge areas to the discharge areas (Tóth [2009]).

In karst hydrology, flow-systems are seen as heterogeneous due to the conduit network. These transfer groundwater from recharge areas to one or several discharge points; usually the karst springs. The difficulty when characterizing karst aquifers is related to the flows in conduit networks. Conduits are small structures compared to the size of the aquifer, but they are able to efficiently transfer most of the catchment recharge to the outlets (Atkinson [1977]; Worthington et al. [2000]). Then most of the existing approaches focus more or less directly on characterizing **properties of karst conduits**.

Characterization approaches should address one or several **karst-related questions** on a site. These questions may be related to hydrogeology, hydraulic, thermic, conduits modelling, transport, hydrochemistry, speleology, aquifer mapping, etc. The approach includes a formulation of the question and translates it from pragmatic terms into karst-specific terms. It enumerates the **general principles** to be considered and it includes a logical succession of **investigation methods** to be realized.

As related by Betancur V et al. [2012], characterization approaches in hydrogeology (but not specific to karst) may be of two types: (i) **descriptive**, providing a representation of the aquifer spatial properties (output =

conceptual model) or (ii) **quantitative**, providing numeric descriptors of the flow-system functioning (output = **numerical model**). A descriptive approach implies the representation of a set of principles (including explicit assumptions), while a quantitative approach requires mathematical formulations based on a conceptual model which is usually implicit or semi-explicit.

Figure 4—1 intends to organize characterization approaches in karst. This diagram is inspired by Jeannin [1996] Betancur V et al. [2012]; and Ghasemizadeh et al. [2012]. It may be further refined for hydrological and hydraulic approaches of simulation (see Figure 4—10).

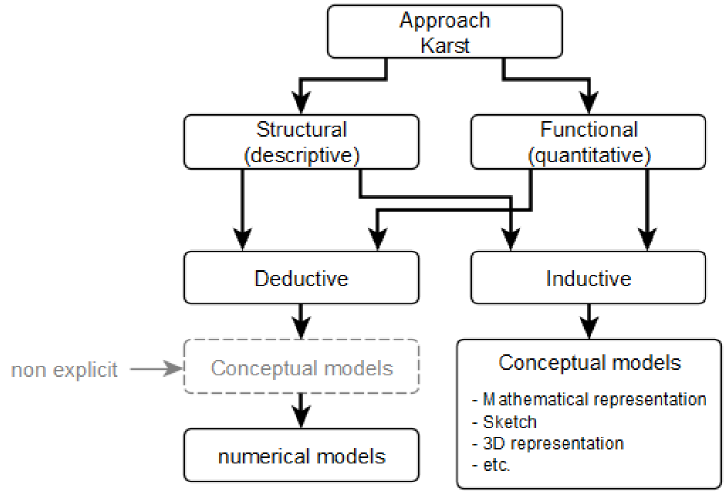


Figure 4—1. Organization of the characterization approaches in karst

Two types of approach have been promoted in classical karst hydrology in order to describe properties and functioning (hydraulic, dissolution, speleogenesis, etc.): the "**structural**" approach – mainly descriptive – as developed by Drogue [1974] and the "**functional**" approach – mainly quantitative - developed by Mangin [1974] are termed as fundamental approaches. The functional approach intends to describe the **time dimension** (i.e. mainly the hydrological response) without considering the spatial properties of the system. On the opposite, the structural approach focuses on the **spatial properties** of the system and often neglects the time dimension.

Structural and functional approaches may be either "**inductive**" or "**deductive**". Inductive approach starts from on-site observations and attempts to provide a model which describes the observations. On the contrary, deductive approach starts from pre-established **physical models** (i.e. Darcy [1856]; Snow [1969], etc.) and focuses on data related to the model's parameters. Inductive approaches intend to provide **conceptual models** as results (several possible forms) while deductive approaches provide **numerical models** as final realization without explicitly present a conceptual model.

The selected approach should order and describe the different tasks to apply to address karst-related questions. The extreme degree of a formalized approach is assimilated as a **hydrogeological method** – including a detailed flowchart for systematic and comparable applications as for engineering. Such hydrogeological methods do exist in karst aquifer, as EPIK (Doerfliger et al. [1999]), ARAK for Aquifer Rechargeability Assessment in Karst (Daher et al. [2011]) or KarstALEA (Filipponi et al. [2012]) and deal with management and protection of the karst aquifers.

Although most hydrogeological methods may be considered as consistent and efficient, all of them may not meet all the conditions of pragmatism, cost-effectiveness and applicability as required for being applied (see Bakalowicz [2005a]). Some of them remain at least theoretical and cannot address issues in practice.

Hydrogeological methods should observe fundamental principles and should reach a compromise between "**degree of complexity**" and "**applicability**" which could be adapted to the characteristics of the studied site, the existing data, etc. Similarly, as written by Vesper [2008] ["*The site-specific nature of an applied approach* *provides important local solutions, but it does not always address the fundamental scientific questions or mechanisms that can allow the answer to be generalized to other systems*"], hydrogeological methods may answer specific issues without solving fundamental questions. These limitations come from the method's formalization and simplification.

4.1.1.1. The structural approach

The **structural approach** was introduced by Drogue [1974] and Kiraly [1975]. This approach is based on an **analytic description** of the media by an adaptation of the usual hydrogeological approaches applied in fissured media (Castany [1982]). Authors like Drogue [1974] and Burger [1983] consider that the karst aquifer may be assimilated to a fissured media drained by a set of fractures. The approach aims at inferring the development of the karst conduit network from the geological context, mainly the presence of tectonic disturbances as they generate preferential weaknesses along which the dissolution is enhanced. In the view of the authors, the groundwater circulation is dominated by lithological contrasts and by the density/distribution of the faults (see for instance Eraso [1986] who introduce the concept of "plans de drainage").

The structural approach as developed in the 1970ies promotes the use of a set of investigation methods which are inspired and adapted from the fissured media: pumping tests, geophysics, geological mapping, tectonic and microtectonic analyses, etc. (see § 4.2).

The structural approach has been widely applied as it provides spatial results which are usually required in the frame of applied studies (for instance the delineation of the catchment area).

Main limitations of the structural approach are:

- Applications usually require a significant amount of observations on site (geology, tectonic);
- Applications often require the deployment of expensive investigations (boreholes, geophysics, dye tracing tests);
- Applications are often time consuming.

KARSYS may be considered as the actual culmination of structural approaches which have been developed these last 40 years.

4.1.1.2. The functional approach

The **functional approach** was introduced by Mangin [1974]. It results from the system science applied to temporal data. Unlike the structural approach which focuses on the description of the media, the functional approach focuses on the study of the systems outputs (mainly discharge variations and physico-chemical parameters in water: mineralization, compounds, temperature, etc.). The functional approach aims at reproducing the observed flows and transport variations in order to **infer geometries and properties of the flow-systems** out of these time variations. Even if the pure functional approach does not consider the spatial organization of the aquifer nor the flow-system, some authors still intended to apply this approach with the aim to infer spatial parameters of the aquifer, for instance for inferring conduits geometry and/or properties (Cornaton and Perrochet [2002]; Kovács [2003a] or Birk et al. [2006]) or for dimensioning source protection zones (Civita [2008]).

As mentioned by Marsaud [1996], a set of methods have been elaborated by various authors promoting the functional approach: hydrological budget (water balance) analysis, flow duration curve analysis, correlative, spectral or wavelets analyses, quantitative dye tracer tests, hydrogeochemistry analyses, etc. (see § 4.2). A lot of them have been improved these last decades (Labat et al. [2000a] and Labat et al. [2000b]).

The use of the functional approach is often restricted to the academic domain as it does not provide much information on the spatial parameters of the aquifer as usually required by applied issues. It rather provides characteristics of the global functioning. Then, application is often used to address fundamental questions of the karst hydrology and it mainly concerns **flow and transport simulations**.

Several limitations may be discussed regarding the functional approach. As the functional approach does not explicitly define and quantify the relations between the temporal functioning and the spatial organization of the aquifer, the formulation may be described as less rigorous (Jeannin [1996]). As a consequence, interpretation may be quite different from one author to another.

As a prerequisite, the use of a functional approach requires to already know some characteristics of the aquifer and of the flow-system. This often requires to measure the hydrological regime of the outlets for a sufficient period of time. In many cases these conditions are difficult to satisfy as the quantity of the required data often exceeds the available resources (time and money).

As system properties are inferred from spring's data, hydrogeologists must be sure that monitoring on site does reflect the real functioning of the flow-system. Data should then respect a set of conditions to be validated: the nature of the monitored data (discharges, including overflow springs, or hydraulic heads while being sure it is representative of the aquifer), the duration of the time series, time steps, the quality of the data (gaps, precision, etc.). These are also difficult conditions to satisfy.

At least characteristics of the systems functioning inferred from datasets often depend on the considered hydrological conditions. Most approaches were developed with the aim to characterize the flow-system independently on hydrological conditions, but most of them reveal inappropriate. These limitations often restrict the use of the functional approach to address applied issues.

4.1.1.3. Conclusion related to these usual characterization approaches

Usual characterization approaches that are described above often provide an interesting picture of the global functioning of the flow-system but they fail to provide a consistent picture of the real aquifer properties and their relations with flow processes (hydrology, hydraulic).

In practice, application of one or another approach is usually **conditioned by the available means** and resources. In this case, approaches are not strictly selected on the basis of characteristics of the studied site or on the basis of the applied issues; these depend on the available equipment in institutions: institutions with chemical laboratories will mainly apply approaches that investigate chemical or isotopic compounds, institutions with geophysical equipment will mainly investigate structural aspects, etc.

Usual approaches are **rarely systematic**. Depending on the site, the available data and resources and on the issues, approaches often require slight adaptations to be applied. This leads to a difficult implementation of a same approach over different sites. Consequently, results are **often not reproducible** and they cannot even be compared from one site to another.

Usual approaches often require a **lot of data** to be operated - especially discharge data at the outlets. Such data are rarely available. This requirement induces to limit the investigation of karst systems to those which are already monitored…

Regarding limitations, the ideal approach would be both structural and functional (Bakalowicz et al. [1999]) including inductive and deductive iterations. These last decades, many authors attempt to combine these two approaches in parallel: the first approach is used for the interpretation while the second approach is used for validation at least when the conceptual model has been defined (see for instance Kovács [2003b] or Fournillon [2012]).

4.1.2. Outputs

As hydrogeological approaches may be deductive or inductive, they provide two types of outputs: a conceptual model or a numerical model.

4.1.2.1. Conceptual models

A **conceptual model** is a schematic and qualitative description of a natural [hydrogeological] existing system using (or based on) general principles. The conceptual model may be **general** (i.e. related to a typical context, for instance coastal-karst, hypogenic karst, etc. or related to a process: hydraulic, thermic, etc.) or **site-specific** and it is usually a synthetic representation as written by Ghasemizadeh et al. [2012] [*"conceptual models may be seen as simplified representations of specific characteristics and processes of a real aquifer system. Such conceptual models can be presented as a picture, diagram and flowchart or in written form"].* Anderson and Woessner [1992] or Betancur V et al. [2012] wrote that a conceptual model is an <u>indispensable</u> prerequisite for the construction and the analysis of a numerical model.

Fournillon [2012] defines two kinds of conceptual models: **static** and **dynamic**. According to the author, the static model (developed in 3D) is a representation of lithologic contrasts of the formations that compose the aquifer as well as its structural compartmentalization. This model is based on the synthesis of geological knowledge and data of the site. In addition, models inform on the potentialities for the karstification development. Static conceptual models may be seen as an interpretation based on the structural approach. Conversely, the dynamic conceptual model is an interpretative representation linking structural aspects to functional responses. It is based on inferred properties of the flow system (hydrochemistry, hydraulic, etc.).

4.1.2.2. Numerical models

A **numerical model** is a quantitative representation of a real aquifer or flow-system and intends to answer questions related to groundwater quantity, quality or transport. Ideally, and as mentioned by various authors (Bredehoeft [2005]; Goldscheider and Drew [2007]), conception of numerical models first requires the establishment of a conceptual model specific to the site and based on general principles.

4.2. Application workflow

This section describes the workflow for applying characterization approaches. It presents the succession of the steps to apply: methods, tools, etc. in function of the selected approach. The Figure 4—2 proposes a systematic workflow to address a karst-specific question. Issue and characteristics of the site both constrain the approach. The approach conditions the hydrogeological methods which finally provide a model (conceptual, numerical, etc.) for which results are supposed to address the initial question (depending on uncertainties). Terms of the workflow are described hereafter. This may seem as a trivial aspect but experience and literature review showed that terms and methods are used in a different way by the different institutions and specialists working in the field.

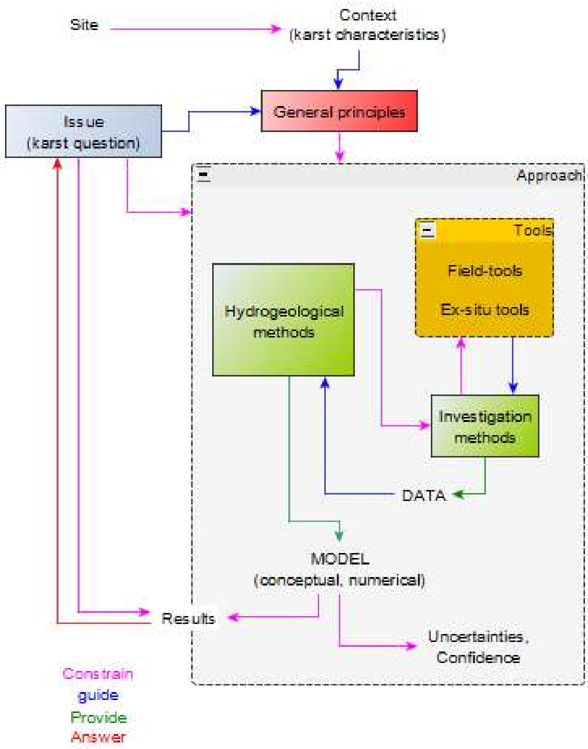


Figure 4—2. Systematic workflow of a characterization approach to address a karst-related question.

Issues (karst question): as demonstrated in §. 3, interest for karst aquifers and their functioning first depends on the uses (water supply, floods prevention, construction, etc.). A clear definition of the karst-related question or problematic constrains the selection of an appropriate approach.

Context: the type of the karst aquifer and of the flow-system guides the general principles and the related assumptions to take into account in the approach (§. 4.2.1).

General principles: depending on the objectives (issues, form of expected results), the type of aquifers (context) and the pre-existing information, general principles may be assumed (§. 4.2.2). General principles should be explicit as well as the related assumptions (i.e. simplifications). They constrain the selection of the appropriate approach.

Approaches: the approach is selected according to the previous criteria. It encompasses a logical succession of steps which provides interpretations (models) by applying a set of methods in a formal order.

Methods: methods refer to a well-established process for acquiring descriptive or quantitative data in the field (**investigation methods**) or transform existing data to physical properties (**interpretation methods**). The selection and the application order of investigation and interpretation methods depend on the selected approach, the existing data, the available means (time, resources), the validity domain and on potential uncertainties. Investigation methods are of three types (field measurements, in situ experiments and remote surveys) while interpretation methods are not further classified.

Tools: tools are defined as physic instruments that support investigation and interpretation methods. Tools are of two kinds: field tools (instruments, engines, etc.) and ex-situ tools (software, laboratory measurement devices, etc.).

Two examples of this characterization are presented hereafter for a given question (Figure 4—3). The given question is: "*How can we provide the extension of the catchment area?*" The figure shows that whatever the selected approach (structural or functional), the characterization workflow is expected to be the same. Only methods and tools will change.

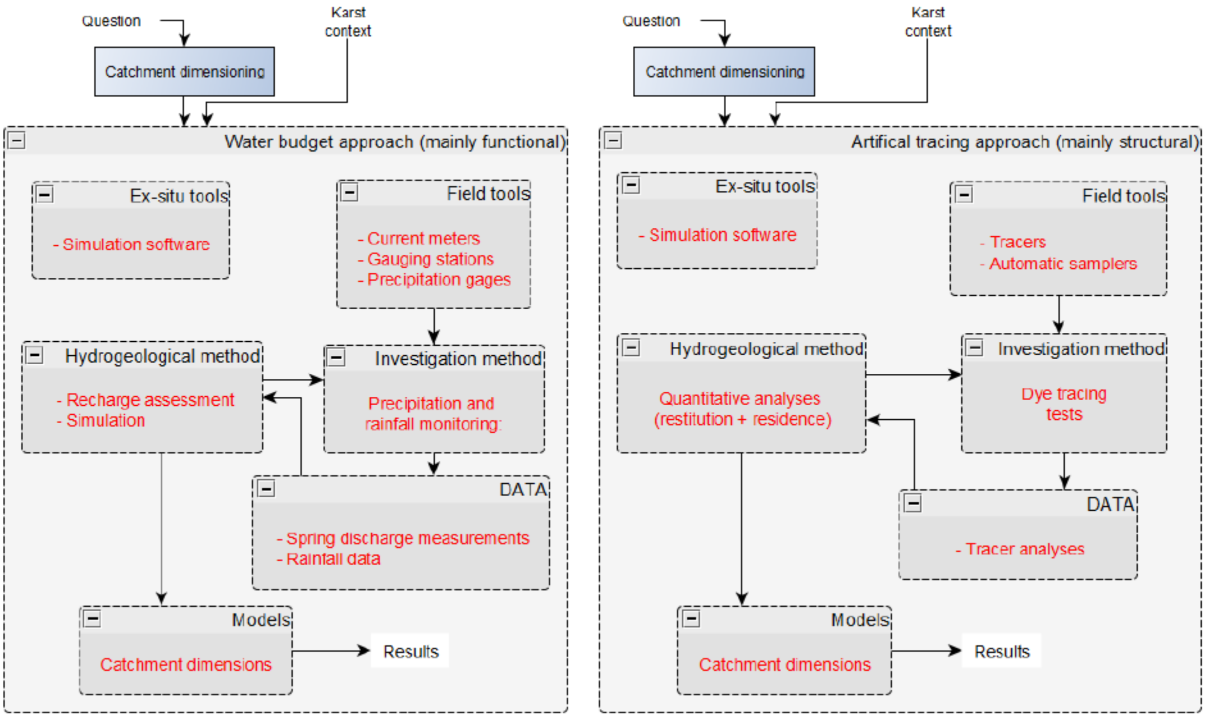


Figure 4—3. Two examples of application of characterization approach to address the question of catchment dimensioning in karst area; left: by applying the water budget approach (= functional approach) and right: by applying the artificial tracing approach (= structural approach)

4.2.1. Karst contexts

The "**karst-context**" is one of the first aspects to take into consideration before selecting the characterization approach as admitted principles may significantly differ from a context to another, ex: epigenic vs. hypogenic karst context, etc. The karst context depends on the **environment** (geography, climate) and on the **geological history,** as both controls the development of the aquifer.

By knowing the "karst-context" helps in choosing parameters and natural processes to be considered for the modelling of general principles. Such diversity in type of karst aquifers implies to consider various concepts and potentially to apply different sets of characterization approaches depending on the nature of the aquifer and on similarities with classic porous or fissured media.

Various **classifications** of karst aquifers and of flow-systems have been promoted these last decades. These are based on lithological and structural criteria (Marsaud [1996], Klimchouk and Ford [2000]), morphology (Palmer [1991], Ford and Williams [2007]), recharge criteria (epigenic or hypogenic, Mylroie [2003]), discharge criteria (Mangin [1994]; Rashed [2012]), chemical criteria (Shuster and White [1971]), or a combination of criteria (Quinlan et al. [1992]). These classifications aim at characterizing aquifers (or systems) by using a systematic process which makes it possible to compare them with each other. Objectives of these classifications are also to provide a first description of the aquifers (or systems) and to validate the applicability of an approach knowing the application domain.

4.2.2. Models of general principles

Models of general principles are conceptual models depicting specific characteristics of the system which result from a well-established process. By definition, these models are considered as valid for a defined range of conditions (scale, hydro-climatic context, lithological units, etc.). Various models of general principles have been published in the literature regarding functioning processes of the aquifer: hydraulic, thermic, dissolution, speleogenesis, etc.

Karst aquifers result from a set of natural and continuous processes. As they evolve over the time, their hydrogeological properties change, inducing a permanent evolution of the system: densification and enlargement of the conduit network, erosion, clogging, etc.

Depending on the considered karst context (geography, lithology, climate), on the size of the flow-system, the model of general principles describe parameters and processes of the karstification itself (i.e. development of the karst) as well as parameters and processes that the karstification induces over the environment (hydrogeology, landscape, geothermy, etc.).

Numerous models of general principles have been described in the literature. All of them will not be discussed here; only some of them are listed hereafter as examples for particular topics:

- Speleogenesis: hypogenic karst development (Klimchouk et al. [2000]), karst dissolution model (Dreybrodt et al. [2005]);
- Thermic: model of the temperature gradient in the vadose heterothermic and homothermic zones (Lütscher and Jeannin [2004]), model of heat diffusion and convection in the phreatic zone (Badino [2005]);
- Hydraulic: recharge and storage in karst aquifer (White [1969], Ford and Williams [1989]; Bonacci [1993]), flows and storage in the unsaturated zone (Smart and Friedrich [1987]), in the phreatic zone (ADS, Mangin [1994]) or in the epikarst (Lastennet et al. [1995]);
- Transport: Vesper et al. [2001], Simon et al. [2007], etc.

4.2.3. Investigation methods

Depending on (i) the topic of interest, (ii) the karst context and (iii) the selected approach, a set of **investigation methods** could be deployed to characterize the properties of the system(s) from collection to data analysis (in space and time).

In practice - especially in the applied domain - the choice of the investigation method is first determined by its efficiency to address a given question, and then by the available time and the available resources (including data). The given question is first translated into specific hydrogeological question(s) as in the example presented Figure 4—4.

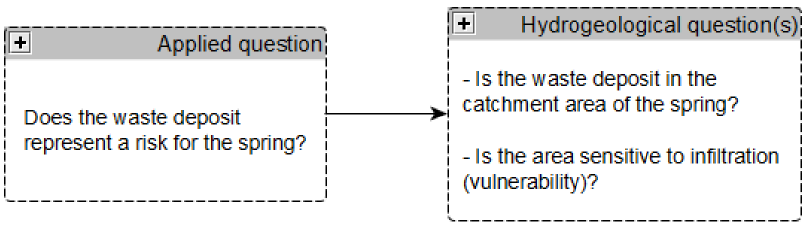


Figure 4—4. The applied question should be first translated into specific hydrogeological question(s) before applying investigation method(s)

Most of the hydrogeological sciences are articulated around this scheme. Methods are thus commonly applied through a more or less **systematic procedure**.

Regarding (i) the applied question, (ii) the karst context, (iii) the general principles and (iv) the considered approach, the choice of the investigation methods theoretically govern the nature and the form of the required data. In practice; it is common that some data already exist on a site (obtained thanks to previous investigations). Consequently, existing data may condition the answer to the hydrogeological question. Figure 4—5 shows the ideal way of applying an approach (A) versus the “in practice” way (B) for a given question.

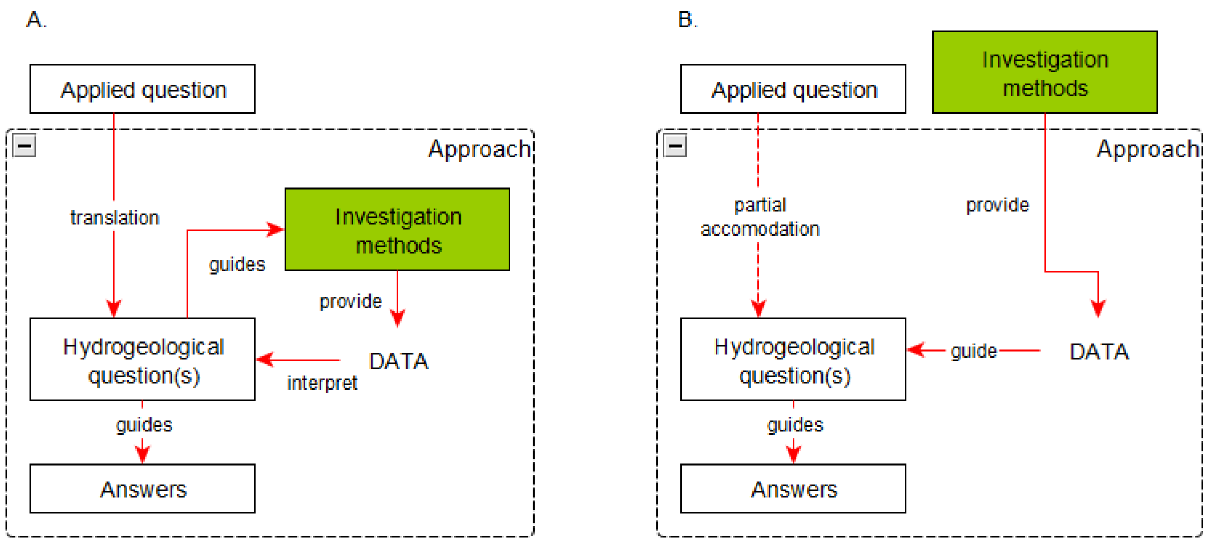


*Figure 4—5. Theoretical way (**A**) versus "in-practice" way (**B**) when applying the approach; due to financial limits and existing data, interpretation methods are usually imposed. In a theoretical way, the interpretation methods are initially selected depending on the questions and they control the investigations to be performed.*

In case (A), users have to address a specific hydrogeological question and look for the method(s) to be applied. In case (B), users formulate a specific hydrogeological question in accommodation with existing data / information coming from previous investigation method(s). Here, investigations methods are selected because of the existing data or because methods are already available. This way is questionable as it may not directly (or fully) answer the applied question. This could be illustrated by the following example (). The given question is: "Is the groundwater naturally protected against contamination?"

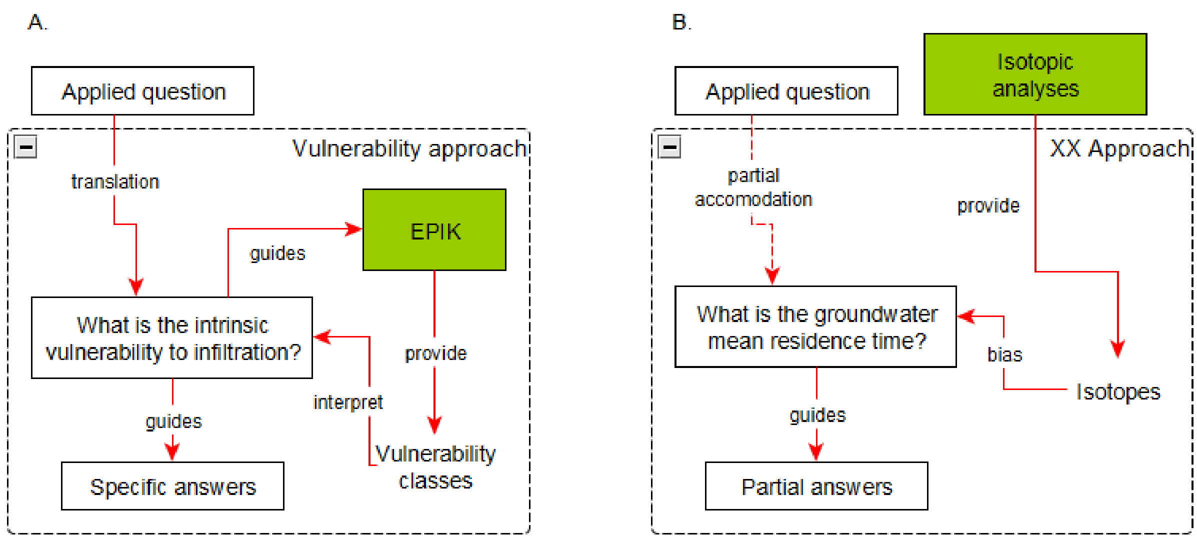


*Figure 4—6. Example of application for an approach in theoretical way (**A**) and "in-practice" way (**B**) for a given question which has been translated into specific hydrogeological question(s). In case (**A**), the hydrogeological question is inferred from the given question and guides the investigation method(s) to be applied. In case (**B**), existing data (here water isotopes obtained from previous campaigns of analyses) bias the hydrogeological questions which partly answer the original issue.*

Here, in case (A), the answer will indicate how zones of highest vulnerability (resp. of lowest vulnerability) do allocate while in case (B), the answer will give a range of residence times for the groundwater to flow through the whole aquifer. This does not precisely address the original question but it should be observed that such approach is commonly applied to address this type of issue…

Methods may however present limitations from a conceptual point of view (need for a reliable conceptual model) and from an efficiency point of view. As written by Heindl et al. [1984], even a sophisticated method cannot replace consistent data and cannot provide more results than the data record on site.

Regarding the diversity of existing approaches, usual methods in karst have been already discussed in La Moreaux et al. [1984], Goldscheider and Drew [2007]; Dörfliger et al. [2010]; , etc. Methods are usually presented as a catalogue listed by thematic (for instance: hydrological methods, geophysical methods, speleological methods in Goldscheider and Drew [2007] or Dörfliger et al. [2010]). These are barely presented as related to a specific approach. Most of the time investigations methods are applied without presenting a conceptual model of the site and of the considered processes. This often leads to difficulties for implementing methods, interpreting results or assessing uncertainties.

At the end of the book, Goldscheider and Drew [2007] also present the combined use of specific karst-related methods with more standard ones (complementary) to address particular questions in karst. It should be observed that none of these methods may be considered as exclusive. Investigation methods should often be combined to validate the results. As mentioned above, these are rather listed as a catalogue than being organized according to a logical flowchart informing on:

- The selected conceptual models of the system functioning as condition for their application;
- The order (sequence) of their implementation;
- Their validity range (domain) and related uncertainties depending on how they are applied.

In the following section, investigation methods usually entail a part of **measurements**, **observations**, or **experiments** on site to provide data or criteria and a second part of **data analysis** to be interpreted. In this way, the distinction between data and their interpretation is preserved.

Investigation methods start by a **field application on site** (Table 4—1). These are of three types: field measurements, in situ experiments and remote surveys. These provide spatial or temporal data of the real site / system (nature) in the form of “raw” datasets which will be processed in a second phase.

“Raw” datasets must then be formalized, processed and transformed into physical parameters using **ex-situ methods** (numeric, systematic, classes, etc.) which give later the hydrogeological properties of the flow-system. These are applied according to the enounced model(s) of general principles and to the considered approach:

- Hydrological measurements are analyzed using correlative, spectral analysis, wavelets, univariate, multivariate, time-series analyses, etc. and provide indications on permeabilities, groundwater storage. Idem for pumping or injection tests.
- Temperature, water compounds or isotopic analyses (point source, dating) provide indication on the source of the water, the time transit, potential mixings with water from other sources, etc.
- Geological mapping, tracer tests, geophysical methods are usually interpreted for identifying groundwater circulations, aquifer boundaries or catchment areas.
- Remote surveys usually provide characteristics of the ground surface for recharge assessment. These are also combined with other data in most of methods for vulnerability assessment.

	Field measurements	In situ experiments	Remote surveys
Description	Discharge rate measurements, hydraulic head monitoring Climatological parameters (precipitation gages) Geological, geomorphological mapping Microtectonics analysis (Eraso et al. [1982]) Caves surveys (speleogenesis, inception, etc.) Geophysics, non-reactive methods (gravimetry, magnetism) Water physic-chemical analysis (isotopes, compounds, temperature, etc.)	Dye tracing test (Taylor and Greene [2001], Benischke et al. [2007]; Perrin and Luetscher [2008]; Goldscheider et al. [2008]; Luhmanna et al. [2012]) Borehole or other reconnaissance soundings Pumping test, borehole test Injection test Geotechnical tests Geophysics, reactive methods: seismic, resistivity, spontaneous potential, Ground penetrating RADAR (Hoover [2003], Bechtel et al. [2007])	DEM campaign, laser scan Aerial photography Electromagnetism Aerial Radar, Lidar (Tomás et al. [2014]) IR surveys Other remote spectral surveys

Table 4—1. Description of the main investigation methods on site

As written above, none of these methods provide an exclusive result. Measurements and observations are usually processed via several methods in order to reach consistent results. Interpretations of these methods provide conceptual or numerical models.

4.2.4. Tools

Tools are defined as a series of instruments, numerical techniques and software that are used (i) to acquire data on the field depending on the investigation methods or (ii) to interpret the result.

Tools may be classified in two categories: **field tools** (measurement devices, investigation engines) are mostly dedicated for investigation methods (= investigation tools) and **ex-situ tools** (computer programs, laboratory tasks, etc.) that are essentially dedicated to interpretation methods.

Category	Description	Example
Field tools	Engines	Drill machines, pumps, geophysical instruments, etc.
	Measurement devices	Flow-meters, conductimeters, sensors, automatic samplers, etc.
	Remote sensing devices	Aerial photography devices Radar sensors, Lidar, etc.
Ex-situ tools	Computer programs	GIS Geological modelers Simulation models software (grey-box, lumped, etc.)
	Laboratory experiments	Mass spectrometers, etc.

Table 4—2. Two kinds of tools may be distinguished; field tools and ex-situ tools

A tool may be exclusively dedicated to a method, as well as a same tool may be utilized for different investigation methods.

4.3. Hydrogeological mapping in karst

4.3.1. Review of existing mapping processes

Standard guidelines do exist to establish hydrogeological map from a region or a country (Anonymous [1970]; Struckmeier et al. [1983], Struckmeier and Margat [1995]). On the basis of the definition edited by Struckmeier and Margat [1995] *["hydrogeological maps may portray information on groundwater and relevant rock bodies in relation to the earth's surface"].* Hydrogeological maps should address general questions relative to (i) the main characteristics of aquifers such as thickness and permeability (= reservoir) and (ii) the location, depth and flowpaths of groundwater bodies (flow circulation) through a systematic presentation. Catchment area and information relative to groundwater vulnerability may also appear depending. These maps illustrate regional groundwater processes or focus to specific areas or specific aquifers (especially in the case of multilayer aquifers). These are used as support document by decision-makers for any questions related to groundwater resources (protection zone, vulnerability) or flood-hazards (overflowing zones, etc.).

Concepts beyond the existing guidelines mostly refer to classical hydrogeology for porous or fissured media where groundwater flows are controlled by Darcy's law. Concerning karst media, concepts of the guidelines were not fundamentally reviewed but few adaptations for karst aquifers have been suggested by the authors at the end of the book. They add a specific symbol for karst springs and lines for connections proved by tracer tests. However, these adaptations do not appear sufficient to concretely depict the functioning of these aquifers and flow-systems, at least in a pragmatic way to deliver usable information. As the consensus is not well established, it appears that - depending on the geographic/geological contexts and the point of view of hydrogeologists - maps may present significant differences from one author to another.

Maps in karst areas may be categorized in four classes: maps based on geomorphological features, maps based on geological features (lithologies), maps based on speleological findings, and finally maps describing hydrological features which may be considered as "real" hydrogeological maps as described by Struckmeier and Margat [1995].

4.3.1.1. Maps based on geomorphological features

First karst maps essentially display **karst morphologies**; mainly caves, springs, sinkholes, canyons, dry valleys, "reculées", etc. Some of these maps may also track existing connections demonstrated by dye tracer tests. The best example is provided by Paloc [1969] in drawing the hydrogeological map of the Northern region of Montpellier. The author focused on morphologies of karst features on surface. Underground information (= hydrological information) are missing on the map which cannot be used for management or water supply exploitation or solely with a high degree of knowledge and abstraction.

Catchment areas of karst flow-systems are usually delineated according to results of dye tracer tests. A good example of this approach is provided by Taylor and Greene [2008]. The authors offer a 1/24 000 map of karst areas in Kentucky with delineated karst groundwater basins (e.g. catchment areas) based on dye tracer studies. Catchment areas seem strictly defined - even if some tracer tests show diffluent routes crossing the defined boundary. As there are no other indications on groundwater, these diffluent routes are not explained.

Another recent example of morphological based map is provided by Taylor et al. [2005]. The authors suggest to map karst hydrogeological units by combining **geomorphological features** on the basis of a DEM processing and of results from dye tracer tests. This method is applied for delineating catchment areas but it does not investigate subsurface features. There is no information on groundwater…

4.3.1.2. Maps based on speleological findings

Davies et al. [1984]; Veni [2002] and Wildberger and Preiswerk [1997] also established “karst” maps, respectively in US and in Switzerland. These maps and even Weary’s one exclusively provide a **speleological overview** of the karst as they display: caves, sinkholes and springs location but no data about hydrogeological features. These cannot be used in the field of water management (for instance to locate optimal site for a drillhole, etc.).

4.3.1.3. Maps based on lithological features

Other authors propose karst maps based on **lithologies**. Weary [2008] presents the Karst-systems map of the Appalachian Mountains based on karst areas and karst hazards where distinctions are related to the different limestone types (lithology, thickness, overlain by glacially derived sediments, structural features, etc.). According to the scale (1/2’000’000) general hydrogeological properties are expanded to the whole geological facies (permeability, etc.).

4.3.1.4. Maps entailing hydrological information

Kiraly [1973b] was one of the first authors to provide a pragmatic overview of **karst hydrogeology** in mapping the hydrogeological map of the Neuchatel canton at the scale of 1/50’000. This map entails hydrogeological information on porous and karst aquifers on the same support. Karst aquifers (Upper Jurassic and Cretaceous ones) are identified by groundwater catchment areas and the aquiclude basement. Significant caves, sinkholes, springs (perennial or intermittent, and classified depending on the flow rates) are mentioned as well as surficial streams and lakes (both permanent and intermittent). Indexes of porosity give an indication on the water storage capacity. A distinction is also made between confined and unconfined groundwater bodies. Principles of this map were partially taken over by Grétillat [1992] for the establishment of the 1/25’000 Haute-Ajoie Hydrogeological map (Jura) but information related to the geometry of the aquifer, the extension of the flooded zones and the distinction between unconfined and confined area are not mapped. Grétillat’s map mostly focuses on the surface information.

Quinlan and Ray [1981] presented a 1/138 000 map of the karst systems catchment in the Mammoth Cave region, Kentucky. This is another example of hydrogeological map in karst area as **hydrological features** are mapped. Underground drainage zones and catchment areas are delineated according to flow paths which connections have been evidenced by more than 400 dye tracer tests. Flow paths under low-flow conditions are plotted as solid lines while flow-paths are dashed lines when dye tracer tests were performed under high-flow conditions. It is then possible to identify changes in flows direction depending on the hydrological conditions. A pseudo-potentiometric surface of the karst groundwater level is also mapped. These contours are obtained by recorded values of more than 1 500 domestic wells that have been surveyed in the area. With precaution, flow directions could then be “inferred” on the basis of theses contours. Applicability of this map is here more relevant in the field of water supply and land-management according to the vulnerability of the resources. Facing to the observed transient flows for high-flow conditions, groundwater divides are subdivided into sub-basins. This delineation separates areas where water is dispersed from one groundwater drainage zone to another. Even if this map offers pragmatic information on the aquifer drainage, information related to the phreatic / vadose zones are missing. Furthermore properties of the catchment area that govern the infiltration processes (covered formations, non-karstic impluvium, etc.) are not documented.

Currens et al. [2003] offer a 1/100 000 karst map of the Harrodsburg region, Kentucky. This shows the delineation of studied karst systems catchment. As for geomorphological based maps, boundaries of catchment areas are determined by dye-tracer tests. Some karst features are also displayed, but only where tracer tests have been realized. Unlike geomorphological based maps, some flow-paths are represented and a few of them are interpreted using: (i) hydraulic head data from boreholes, (ii) geological structures or (iii) surface features. Exposed karst areas are also distinguished from karst areas overlain by non-carbonate rocks.

Groundwater indications are implicitly used for delineating the karst flow-systems but they are not explicitly represented.

The **Aquifer Base Gradient** approach was introduced by {Butscher_2007a} in order to investigate 3D hydrology of mature and shallow karst flow-systems. This approach was applied to aquifers in northern Switzerland and it makes it possible to delineate catchment areas and major flow-paths. The approach does not distinguish vadose or saturated zones and the authors did not develop mapping processes to plot the resulting information on a map. In its actual form, the use of the information resulting from the Aquifer Base Gradient approach for any other application is difficult and restricted to the authors themselves.

Dongmei and Xing [2006] provide a concept of hydrogeological karst map of the three main karst systems located in the Xinding basin, China. They had to develop a systematic process in a GIS to investigate karst systems by using sparse geological data combined with consistent **hydraulic principles**. The karst hydrogeological map (scale 1/50'000) was obtained by processing aquifer basement geometry and hydraulic gradient upstream of the main karst springs (the gradient is here controlled by the inclination between the main karst springs and borehole potentiometric measurements). The extension of the groundwater saturated zone is deduced from the intersection of the water table inclined plan with the aquifer basement. This approach is really innovative because it brings interesting results solely on the basis of fragmentary data. This map depicts geometry of saturated zone, delineation of the catchment areas and suspected interactions between two or more karst system. Principles used here are quite similar to those developed in the KARSYS approach but 3D tools are here not investigated although these tools would provide an additional means of control and a greater degree of flexibility in the process. Another limitation in their work consists in the availability of data relative to karst phenomena for such large basin (> 1'000 km^2).

4.3.2. Limitations of existing mapping approaches

This review demonstrates that actual manners of depicting karst aquifers, flow-systems and associated groundwater resources on a map still remain miscellaneous as karst aquifers may be seen from various points of view (hydrogeologists, geomorphologists, cavers, etc.). With the exception of the hydrological based maps (and especially those presented by Kiraly [1973b] or Dongmei and Xing [2006]), none of the previous mapping methods really depicts groundwater characteristics. This is a real limitation to represent karst aquifers or the related flow-systems. Therefore, most of these maps fail to address issues related to groundwater supply, land planning, flood hazards, etc.

From use perspective, the hydrogeological map proposed by Kiraly may be seen as the most exhaustive one in terms of information. The map displays information from the underground (aquifer / aquiclude), information from the ground surface (imperviousness, etc.) and hydrological information (surface streams, springs or emergence zones, vadose and phreatic zones of the aquifer, confined and unconfined zones, etc.). However feedbacks show that reading and extracting useful information is difficult for a layperson and even for hydrogeologists! This greatly affects the application of this map as support for authorities or other decision makers.

4.3.3. Karst hydrogeological maps based on KARSYS

Improvements of the KARSYS approach led to a pragmatic method for hydrogeological mapping in karst aquifers. As most users are still working with 2D maps for management, land-uses planning, or enforcement of regulations, concepts for translating KARSYS results on hydrogeological maps have been developed. Indeed, even if they bring a more consistent view of the aquifer structuration and the organization of the groundwater flow-systems, 3D layouts may appear as non-exploitable for decision making, managing or planning. Hence, dedicated mapping processes have been developed in order to illustrate the characteristics of the karst aquifers and the flow-systems that have been documented in a consistent and pragmatic way.

The approach is described in the form of a paper that has been published in Grundwasser in August 2014 (Malard et al. [2014b] see Appendix 10.8). The paper proposes clear guidelines for establishing pragmatic maps of aquifer resources and groundwater flow organization. Two other published papers (Malard et al. [2012] and Malard et al. [2014c], see Appendix 10.10) present examples of karst hydrogeological maps.

Based on KARSYS three types of maps are proposed; each one illustrates consistent information on the karst hydrology at a specific scale (see Table 4—3). The realization of a type of karst hydrogeological map depends on the issues and on the scale in which KARSYS has been applied.

KARSYS topic	Karst groundwater map	Karst aquifer map	Karst flow-system map
Information	Aquifer location Groundwater reserves location: distinction of confined and unconfined groundwater bodies Main baseflow and overflow springs location	Groundwater circulation: main vadose and phreatic drainage axes Phreatic zones extension for high-flows Main baseflow and overflow springs location	System catchment delineation: sub-catchment Inter-system flow exchanges Conduits location: generated conduits
Scale range	Ultra-regional: 1/500'000, 1/250'000	Regional: 1/100'000	Local: 1/50'000, 1/25'000

Table 4—3. Characteristics of karst hydrogeological maps obtained by the application of KARSYS; characterization scale and issues should be defined prior to apply KARSYS in order to provide the most appropriate type of map

In addition to these maps, a template of Identification Cards (ID Cards) for each main karst system, including maps, 3D views, a basic data-base and a series of attachments (typically literature) has been developed. Identification Cards intend synthetizing the main karst system characteristics and the related documentation. They have been developed with the objective of being at once concise and enough complete. They must address questions from cantons, communities, water-supply agencies or any further water-users in karst environments. For these reasons, some aspects of the ID Cards are being adjusted to the respective demands and priorities of users. Furthermore, ID Cards consider the following potential user conflicts and interactions: drinking water supply, hydropower production, artificial snow, irrigation, geothermic. Concepts and first templates of these ID Cards are presented in Demary et al. [2011] and are not further discussed here.

4.4. Conduits network generation in a karst aquifer

This review has been written in addition to the review presented in Malard et al. [2015a] (cf. section 6.1 about the karst conduit generator based on the KARSYS approach).

Conduits in karst hydrogeology are key elements to describe the hydraulic properties of karst flow-systems. As mentioned by Worthington et al. [2000], more than 90% of the groundwater flows through karst conduits, meaning that understanding flows in karst without looking at the organization and the properties of the conduit network is not meaningful [see for instance White and White [2003]: *"any functional model of karst aquifers must [explicitly] take account of the conduits system"*]. For hydrogeologists working in karst, the conduit network refers to the 3D organization of centimetric to decametric conduits and their connection. Whatever the investigation methods, it is still impossible today to identify where karst conduits develop in the aquifer. Conduit network should be sketched or automatically generated according to datasets and principles. However generating karst conduits still remains a challenge. No approach received a large consensus and no dedicated tool does exist today.

4.4.1. Issues in conduits generation

Generating conduit network is of great significance for any applied issues. It may reveal extremely valuable in the field of groundwater tapping as conduits capture and concentrate inflows. In karst, most of the investigations prior to drill a borehole explicitly search for the location and the depth of the main conduits (example of the Oko spring in Herzegovina, or the Lez spring in France, see Milanović [2004]). Assessing groundwater resources, vulnerability, geothermal or hydropower potentials also requires to know the hydraulic functioning of the karst system – i.e. the geometry, the size, the tortuosity, the connection and the "roughness" of the conduit network.

Prediction of conduits may reveal of great interest in the field of natural hazards: for land-planning (floods or collapses) and for construction. Various applications in the frame of geotechnical prevention could be enounced:

- Assessment of occurrence and nature of conduits and voids in the field of tunneling or other underground construction (see KarstALEA, Filipponi et al. [2012]);
- Locating areas of potential collapse, especially in the field of land planning and urbanization.

4.4.2. Principles governing the development of karst conduits

The karstification is a continuous process which evolves in space and time. Most aquifers over the world present a succession of karst conduits resulting from different phases of karstification. Thus conduit networks are formed by the assembly of conduits from distinct generations which usually reflect changes in the hydraulic base level. Recently formed conduits are hydraulically active while others progressively become temporarily active or completely inactive. Inactive conduits may partly collapse or be filled with sediments depending on local conditions.

Whatever the type of karst aquifer (epigenic or hypogenic), hydraulic and dissolution processes govern the development of the conduit network. Nevertheless, between epigenic and hypogenic karst aquifers, some differences do occur in the formation and the development of the conduit network:

- **Epigenic** karst networks - which are the most encountered karst networks over the world - are formed by the gravitational action of meteoric water percolating through the overlaying ground and flowing toward the downstream discharge zone. These networks show an optimized drainage-pattern and act as a hydrogeological vector for the circulation of the groundwater. Epigenic karst networks may be considered as local to regional flow systems. In a stable environment (i.e. where the water base level does not change for a long period) the conduits will logically evolve up to a certain limit by increasing their diameter and by reducing the global tortuosity of the network in order to optimize friction-losses;
- **Hypogenic** karst networks represent less than 10% of the inventoried caves over the world. These are formed by ascending waters from the lower parts of the aquifer and enriched with CO_2 or H_2S (Klimchouk [2009]). Unlike epigenic cave, the usual shape of the hypogenic cave networks does not suggest a drainage-pattern but rather a coalescence of large chambers which appear organized as a 3D maze-like network. In hypogenic karst, gravitational forces are counterbalanced by thermic and dissolved gas processes which allow ascending waters to enlarge bedding planes or tectonic features by dissolution. The development of hypogenic caves is related to intermediate to regional aquifer systems but caves usually form at specific place.

In the following chapters, only epigenetic caves will be considered as they are the most encountered type of caves in Switzerland, resp. in alpine contexts.

As mentioned by White and White [2003], apart from the effective hydraulic gradient, the size and the density of the conduits also depend on:

- The **geological constraints** of the drainage basin which makes it possible the formation of aquifers;
- The **"karstificability" of the rocks**: the chemical characteristics of the limestone (resp. of all soluble rocks) and the fabrics (marble, compact or tectonized limestone, small banks interbedded, etc.) which increase the susceptibility of the considered rocks to karstification;
- The **density and distribution of weakness horizons** in the aquifer which guide and enhance the development of conduits: these weaknesses are usually formed by specific stratigraphic layers and tectonic features (so-called "inception horizons", Filipponi et al. [2009]) on the condition that the orientations of these horizons agree with the hydraulic gradient. As observed by Filipponi in the Alps, 70% of the karst conduit networks formed in less than 20% of the aquifer mass;
- The **amount of discharged water** through the enlarged fissures;
- The **degree of water acidity**;

4.4.3. Existing approaches for the generation of conduit networks (review from the literature)

Approaches for conduits generation aim at analyzing the characteristics of the conduits or at providing a way to generate conduit networks. As presented by Teutsch and Sauter [1991], the **deterministic** approach explicitly simulates physical processes of flow and coupled dissolution leading to conduit network development. The **statistic** approach provides global characteristics of conduit networks based on the combination of observations and statistic rules. **Experimental** approaches could also be mentioned as an alternative to the main approaches. Characteristics of the conduit networks are inferred from direct observations and in-situ experiments (mainly dye-tracing tests).

Approaches may also be distinguished between **static** and **dynamic** (e.g. that included successive speleogenetic models and dissolution kinetics). Jeannin [1996] also describes the **fractal** approach as an alternative for modelling karst conduits, but this approach is less applied than classical approaches. It will thus not be further presented in the following chapters. In practice, nowadays, mostly **hybrid** approaches combining **deterministic** and **statistic** aspects are performed. Figure 4—7 intends to classify the different approaches for conduit generation and the following sections resume these approaches according to the nomenclature proposed by Jeannin [1996]. Starting from temporal data, statistic, experimental and deterministic approaches are usually applied for the determination of the hydraulic properties of the conduit network. Starting from spatial data (or by coupling spatial data), the same approaches may provide a spatial model of the conduit networks. These approaches are described hereafter.

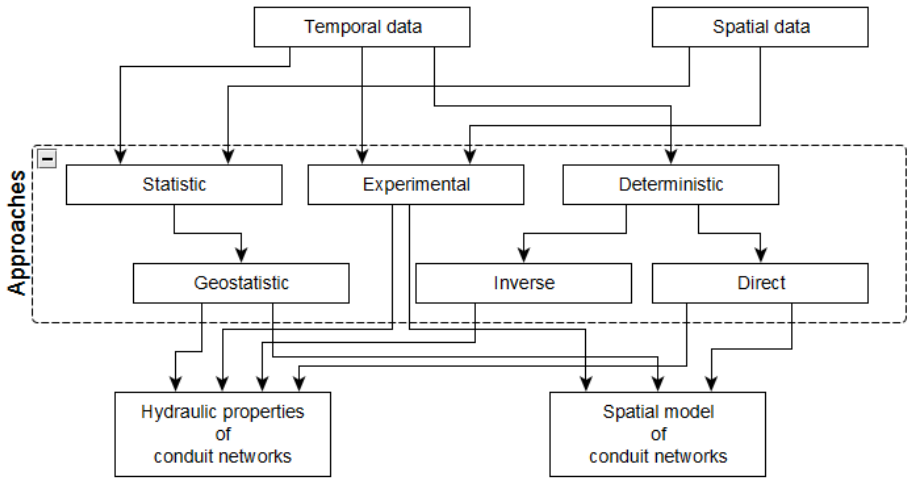


Figure 4—7. Overview of the existing approaches for conduits generation in karst. Approaches combine temporal and/or spatial data to interpret the geometry of the conduit network.

4.4.3.1. Deterministic approaches

4.4.3.1.1. The direct deterministic approach

The **direct deterministic** approach induces a complete description of the physical processes governing the formation and the development of karst conduit network – starting from spatial data. This approach has been described by many different authors, mainly Jeannin [1996], Dreybrodt and Siemers [1997]; Dreybrodt and Gabrovšek [2003].

Direct deterministic models show feedbacks processes between voids, flow and dissolution, and the changes in the hydraulic gradients. They also evidenced the initial slow development of karstification until "breakthrough" and the (geologically) "short time" required to form large conduits after breakthrough. This approach was very useful for understanding theoretical processes, but is hardly applicable in practice. According to Jeannin [1996], the deterministic direct approach is based on:

- The effects of **discontinuities** (joints and faults) and of hydraulic gradients on the karstification;
- The **"less-effort" principles** wherein the conduits develop along features offering the less head-losses. Under relative stable conditions, the evolution of the network tends to reduce more and more existing head-losses by adapting the position and the profile of the conduits in order to reach the state of a mature karst system (see the reference to the "Four State Model", Ford and Ewers [1978]).

According to Jeannin [1996], such approach reveals efficient to determine the main direction of the active conduits under the prevailing hydrological conditions. It assumes to know geological discontinuities and dynamics of the hydraulic gradient in the aquifer. The deterministic approach also assumes other parameters to play a significant role in the development of the karst conduit networks: lithology, geological structures, tectonic features, covering formations, etc.

As an advantage: the deterministic approach provides detailed models which reflect realistic context. Conversely, two main disadvantages may be cited:

- Uncertainties; as models require a lot of parameters, uncertainties may be significant;
- Computation time ; models require extra-computation (Jaquet et al. [2004]). As a consequence, application in practice is very restricted.

4.4.3.1.2. The inverse deterministic approach

In parallel to the deterministic direct approach, Mangin [1975] introduced the **inverse deterministic approach** as an alternative to assess parameters of the karst conduits geometry from the system's global (spring) response (hydraulic or chemical) and by using more or less deterministic interpretation models. Thanks to the combination of spring's hydrographs analysis and deterministic models, the author attempts to assess certain properties of the conduits geometry. However, it remained quite impossible to assess one property of the network without knowing or assuming values of other ones (permeability, geometry, etc.).

Other examples of inverse deterministic approach have been presented in recent papers in order to assess characteristics of the karst conduits:

- Grasso et al. [2003] intend to infer the dimensions of the flooded conduit network ("karstification index") by expressing the ratio [carbonate concentration] / [flow rate] as a quantitative indicator of the flooded conduits-length where the water came through;
- Kovács [2003b] proposes to infer the hydraulic characteristics of the conduits by comparing springs recession hydrographs with analytic formulae deduced from numerical models of simplified conceptual models of karst systems;
- Birk et al. [2006] argue for the dependency of volume estimates on recharge with the conduits geometry. They suggest - considering precautions - that the evaluation of the dependency of volume estimates on recharge conditions may infer information about conduits geometry.

- Mayaud et al. [2014] propose to elucidate the hydrological thresholds functioning of an Austrian karst system by applying time-series analyses on the spring's hydrograph and by establishing a finite elements simulation model in order to interpret hydrological analogies as characteristics of the conduits.

In practice, applications show that inverse deterministic approaches are not self-sufficient to provide concrete characteristics of the conduits. These should be applied in a complementary way (in parallel to direct deterministic or stochastic ones by example) for validation of the assessed characteristics.

4.4.3.2. Statistical approaches

Statistical approaches were introduced by Mangin [1984] who tried to infer characteristics of the karst conduits from springs hydrographs. These approaches are non-spatialized and do provide very global characteristics (e.g. "well" or "poorly" karstified), terms which were neither really well physically defined, nor really applicable.

These statistical approaches have been notably improved in the 90_{ies} and the 2000_{ies}. These concern hydrographs, chemographs and isotopes analyses using times-series, PCA or spectral analyses (Lakey and Krothe [1996], Labat et al. [2000b]; Labat et al. [2000a]; Aquilina et al. [2006]; etc.).Even if these methods have been widely applied (Bonacci [1995]; Jeannin [1992]) most of them remained very "global" and in most cases do not provide any clear spatial idea of the karst flow-system.

Geostatistical approaches were developed as an alternative to pure statistic approaches. They provide probability fields showing where the conduits are supposed to develop. These "more physically based approaches" operate on relations between the geometric characteristics of the conduits (orientation, segmentation, connectivity, etc.) with other parameters (fractures, bedding planes, hydraulic gradient, outlets position, etc.) in respecting statistical rules (density average, variance, etc.). Most of the geostatistical approaches are described by Jeannin [1992]: (i) Simple statistic and cross-methods, (ii) Random walk method, etc.

4.4.3.2.1. Stochastically generated conduit networks

In the last decade, the **stochastic approaches** have substantially developed (Henrion 2011, Collon-Drouaillet et al. [2012]; Pardo-Igúzquiza et al. [2012], Borghi [2013]; Borghi et al. [2016]). It is based on the **probabilistic interpolation** of spatial distributed variables. Conduits are generated according to a discrete fractures network in which additional properties may be associated to each fracture (or set of fractures).

As advantage, this approach makes it possible to generate a multitude of conduits models starting from an initial set of parameters. Effects and the sensibility of the parameters could be tested to assess model uncertainties.

However, because stochastic simulation processes are based on (i) geostatistical laws, (ii) hypothesis and simplified characteristics of the karst geometries, the simulated models often fail in being integrated in the real geological context. As mentioned for instance by Henrion [2011], stochastic algorithms do not consider the genetic processes of fractures (i.e. their interrelationship) but only the final fractures network. In other cases, the generated conduit network can hardly be constrained by reasonable data and general characteristics of karst conduit networks (e.g. Borghi [2013]).

Because of these limitations, several **hybrid approaches** combining deterministic and stochastic aspects have been recently developed in order to control the development of the fractures (t) based on geostatistical and geometric laws from the previous stage (t-1) and to provide a more realistic model in accordance with the geological conditions. An example of such hybrid approach using a Markov Process is presented by Mariethoz and Renard [2011].

4.4.3.2.2. Multiple-points statistics (or MPS)

The **multiple-point** approach (Strebelle [2002]) has been developed with the intention to reproduce curvilinear structures (fluvial deposits, lavas, etc.) instead of using a two-point variogram statistic. MPS is based on the capture of joint spatial variability of point datasets entailing three or more data and summarized the spatial patterns of the points. The process requires the use of a training image and a template. The pattern is obtained combining the training image and the template in order to reconstruct the statistic arrangement of the pattern from the template.

Application of the MPS in modelling karst conduit network is still not widespread and will not be discussed further. However, examples of application could be found in Mariethoz et al. [2010] or Balan [2012].

4.4.3.3. Experimental approaches

Experimental approaches on the field should be also mentioned as alternatives to deterministic, statistic and fractal approaches. Such approaches intent to infer the characteristics of the conduit network (connectivity, thresholds, by-passes, and conduit's size) by performing a series of artificial in-situ tracer tests in order to characterize the flow-system under various hydrological conditions. Smart [1988], Goldscheider et al. [2008]; and Lauber et al. [2014] are the main authors who promote these approaches. Experimental approaches reveal efficient as the may provide concrete characteristics of the conduit network (geometry, size, tributaries, etc.) but application requires (i) to have access to the caves and (ii) to perform long and repeated tests in order to distinguish the physic properties of the conduits from those related to hydrological conditions.

4.4.4. Discussion of existing approaches for conduits generation

Discussed approaches may be used in a complementary manner as no one is currently able to perfectly reproduce the karst conduit network organization / generation. Various limitations do occur related to the properties of the system that are not always fully considered in the proposed models. Here-below are listed certain processes or properties of the aquifer and of the flow-systems that significantly control the development and the organization of the karst conduits.

4.4.4.1. Multiphasing: changes of hydrological conditions over the time

Most of the observed conduit network results from **several phases of karstification** which depend on changes of hydrological conditions over the geological time (fall, resp. rise of the hydraulic base level, etc.). Conduits developed at Phase t-1 may be reused at Phase t or Phase t+1; this is typically the case for overflow conduits (or overflow springs) which formed during a previous phase; these still play a significant role in the system hydrology.

Ideally, previous phases should be explicitly taken into account in the conduits generation process.

Actually, most generators provide a conduit network model based on current hydrological conditions. This is a strong limitation for their use.

4.4.4.2. Karst aquifer zones

As described in chapter 2, the geometry of the karst conduit network depends on the **aquifer zones**. Vertical of inclined conduits develop in the vadose zones and pseudo-horizontal conduits mostly develop in the phreatic zones.

Conduits generation processes must explicitly address these three zones: the **vadose vertical-flows** zone, the **vadose controlled-flows** zone and the **phreatic** zone. In each zone, a specific generation process should be applied.

Most of the above-cited approaches do not explicitly consider the different aquifer zones. For instance, most stochastic methods usually consider a uniform matrix of soluble rocks - without distinction of the epikarst, the unsaturated and saturated zones - where conduits develop along preferential inception features (bedding planes, fractures). This is a real limitation for most existing approaches.

4.4.4.3. Groundwater drainage zone

Furthermore, these methods assume that characteristics of the groundwater drainage zone and of the catchment area of the considered system(s) are already known before modelling karst conduits. Such prerequisite is not always validated and some modeled networks cannot be **integrated in their real geological environment**.

Ideally, modeled conduits should be congruent with the delineation of the system catchment over the ground. Conduits should also organize according to the aquifer volume and possible obstacles and they should be in sufficient numbers to drain the whole aquifer.

4.4.4.4. Inception horizons as control for the conduits development

As described in the previous sections, most of the conduits develop on **inception horizons**. The control of the inception horizon on the conduit's development mainly depends on the hydraulic gradient.

Basically, the conduits generation process should explicitly consider inception horizons and their control on the conduits development. The degree of control of the inception horizons should be balanced depending on (i) the orientation of the local hydraulic gradient and (ii) on the local or regional significance of the inception feature.

4.4.4.5. Hydrological consistence

It seems important that modeled conduit network are consistent with the expected hydrological regime of the flow-system. The networks geometry and the size of the conduits should fit the expected discharge through the flow-system – at least as it is observed on the ground surface and at the springs (see Kaufmann and Braun [1999]).

Then, the conduits generation process must test the **coherence** between the **discharge capacities** of the modeled **conduits** with the **expected regime** of the flow-system. This comparison could be done with different simulation scenarios in order to validate the proposed conduit network. In most publications, modeled conduits are not often compared with the flow-system regime. In a recent paper, Borghi et al. [2016] describe a stochastic generation model. Among a multitude of simulated scenarios, the authors test the most consistent one on the basis of hydrological criteria.

This question of hydrological consistence raises the more general question of validation. What are the best criteria to validate (resp. to invalidate) conduits models?

In §. 6.1, a model of karst conduits generation based on the KARSYS approach is proposed as an alternative of the existing models. This model has been published in Hydrogeology Journal in 2015.

4.5. Flow simulation in karst

4.5.1. Generalities

"**Hydrogeology**" is here defined as processes and characteristics conditioning the water transfer from the recharge zone to the discharge zone (size of the system, infiltration characteristics, organization of the karst conduits, permeability, etc.) while "**hydrology**" is defined as the functional relation linking precipitation to discharge and related components (recharge, flows, hydraulic head variations, etc.).

Flows simulation in karst hydrogeological systems are the topic of many publications since the early seventies. These approaches are used by various practitioners depending on the application domain, the nature/size of the flow-system, the available data, the available material resources, etc. Most of the time, the application constrain the choice of the flows simulation approach according to its reliability to address the hydrological question. Regarding a system (composed by an aquifer and a karst flow-system), hydrological questions are usually of three types (see Figure 4—8):

A. **Assessing the groundwater recharge of an aquifer** (= effective infiltration).As the recharge cannot be measured, its computation requires to correctly assess each components of the Equation 2—5: the equivalent rainfall, the real evapotranspiration, the surface runoff (if exists) and storage processes;
B. **Reproducing the hydrodynamic behavior of the system under specific conditions** (= the system discharge). Based on the previous computed recharge, the simulation of the system discharge at least requires to assess the characteristics of the reservoir (equivalent permeability of the conduits and the fissured media, equivalent porosity, etc.);
C. **Understanding the organization of the karst conduits and reproducing the dynamic of the different outlets**. Activation of perched conduits and/or overflow springs requires to correctly assess the geometry and the organization of the conduit network.

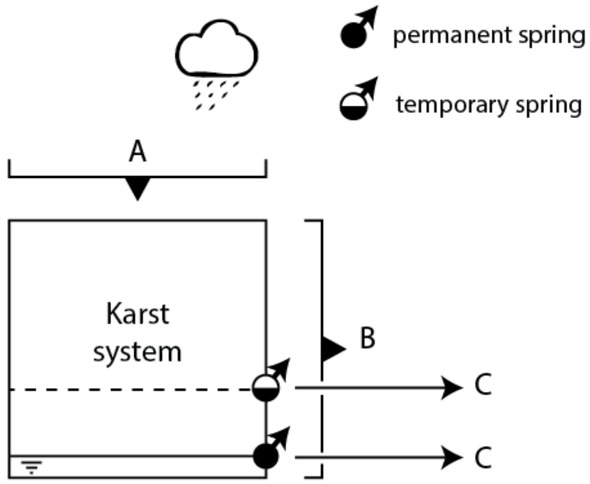


Figure 4—8. Hydrological models in karst have to address one or several of these three main applications: (A) system recharge assessment, (B) system discharge assessment and (C) outlets discharge assessment

The efficiency of flow simulation approaches to address these three types of questions will be discussed in the following sections.

Such Hydrological models may also be coupled with **transport functions** in order to simulate: (i) the hydrochemistry evolution of the groundwater and/or (ii) the displacement (advection, dispersion, diffusion) of selected particles or solutions. These particular fields related to transport and hydrochemistry will not be further discussed in the frame of this thesis but it should kept in mind that “transport” remains a crucial topic in karst leading to research and development of numerous models (see for instance Sauter [1992], Perrin [2003]; or Massei et al. [2006], etc.)

4.5.2. Main aspects of existing approaches for hydrological modelling

As for characterization approaches in karst (§. 4), two fundamental approaches are here equally applied. The **deductive approach** usually tends to simulate the temporal parameters of the system: hydrological regime (daily values) or groundwater resources (annual values) from the physical properties of the aquifer / flow-system. The **inductive approach** mainly tends to infer the spatial parameters of the aquifer / flow-system, starting from the temporal ones: hydrological regime of the outlets, hydrochemical evolutions, temperature, isotopes, etc. In the first approach, the process makes it possible to extrapolate hydrological regime outside of the calibration period (i.e. hydrological forecast) while using the inductive approach, extrapolation may be not reliable.

As numerous and relevant reviews of simulation models have been published these last years (Goldscheider and Drew [2007]; Kresic [2007], Ghasemizadeh et al. [2012]; Hartmann et al. [2014]), only a brief overview and some basic characteristics of the main widespread models will be discussed in the following section.

Regarding hydrological aspects of karst aquifers, in addition to **analytical (black-box)** models, two types of numerical models do exist (Goldscheider and Drew [2007]): the **spatially lumped (or global)** or the **distributed simulation models**.

Another distinction of hydrological models has been introduced by Singh [1988], depending on the issue: **models of physical approach** and **models of system approach**. The first type intends to understand the physic parameters of the systems but does not intend to be reproducible or applicable in a pragmatic way (for engineering projects for example) while the second intends to establish a concrete relation between measured parameters in the field and the addressed hydrological problems. To some extends, this approach may be considered as a simplification as the model does not attempt to reproduce all the physical parameters and processes of the flow-system but only the main specific ones.

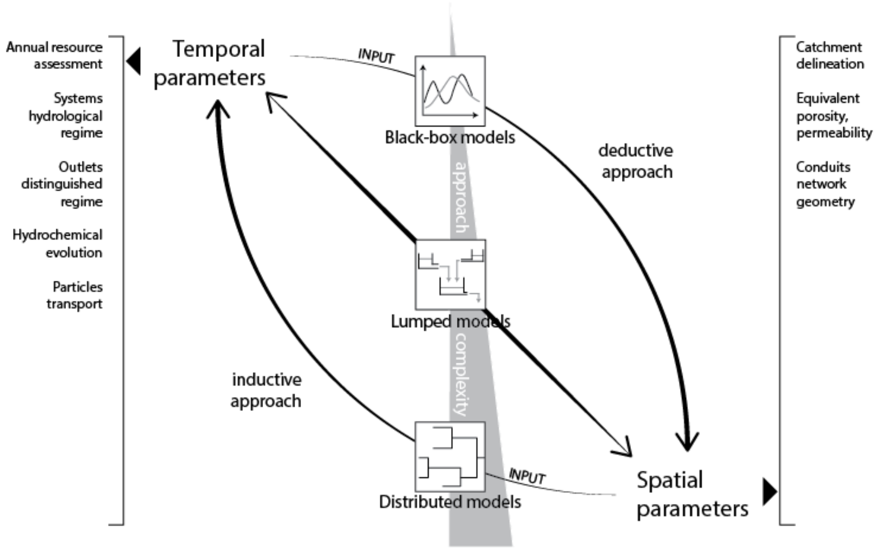


Figure 4—9. Classification of hydrological simulation approaches in karst

4.5.2.1. Black-box (analytic) models

Black-box models are based on empirical relations linking inputs and outputs without physical reliability with the properties of the aquifer or the flow-system (Dreiss [1982]). These models are considered as pure empirical models and they are usually applied when data are scarce or when the knowledge on the physical processes is insufficient. Most of the Black-box models are based on **deconvolutions** or **analytical solutions**. Depending on the data set, empirical relations for a same system may change over the time as the system may present a **non-linear functioning**, making hydrological predictions rather difficult to assess.

Black-box simulation approaches are of two types: (i) analyses of time-series (linear solutions) and (ii) artificial neural network (non-linear solutions)

4.5.2.1.1. Time-series analysis

Most of the hydrological **time-series analysis** have been obviously developed by Jenkins and Watts [1968]. They were adapted to karst hydrology by Mangin [1984]. Applications of these analysis in karst have been studied in detail by Jeannin and Sauter [1998] in a review-paper, especially regarding the interpretation of the results.

Time series analysis may be distinguished between **univariate** and **bivariate** methods; univariate methods focus on an individual time series (ex: flow duration curve, autocorrelation, spectral analysis, wavelet analysis) while bivariate ones combine the transformation of an input signal to an output (ex: cross-correlation).

As related by Grasso and Jeannin [1994] - or later by Jeannin and Sauter [1998]- such methods are seen as efficient to characterize and to extrapolate the discharge rate of the systems outlets (i.e. making hydrological forecast possible) but reveal inefficient in characterizing the structure of the karst systems as time-series analyses are strongly influenced by the frequency of the recharge events.

4.5.2.1.1.1 Flow duration curve

The **flow duration curve** is the simplest method to characterize the hydrological regime of a flow-system (assimilated as one spring) over a minimum period of one year. Daily discharge values of a spring are sorted over "n" entire years and plotted according to 1/(n x 365).The resulting curve may be statistically normalized (Mangin [1975]) in order to be compared with other karst springs.

The shape of the flow duration curve may point out indicative information on hydraulic processes like (i) the perennial or temporary activity of the outlet, (ii) the apparition of sudden water inflow (resp. plateau) corresponding to the activation of perched conduits (by-passes) which bring / divert additional water or the activation of overflow springs which evacuate groundwater from the aquifer, etc.

Such analyses are of great interest to evidence physical changes in the conduit network while the hydraulic head evolves in the aquifer (see for instance Figure 6—9).

4.5.2.1.1.2 Autocorrelation

Principles of the **autocorrelation methods** in karst hydrology are described in Jeannin and Sauter [1998]. These methods allow the correlation of a time series with itself in two domains: the time domain (correlogram) or the frequency domain (spectral analysis).

The correlogram provides synthetic characteristics of a time series (amplitude and periodicity according to the correlation time-shift, etc.). Compared to the correlogram, the spectral analysis highlights the periodicities within the time series. As proposed by Mangin [1984], additional statistical analysis may reinforce the results evidenced by the spectral analysis (by example the Tukey-Hanning weighting function). Based on the values of the correlogram, A. Mangin also defines the concept of "**memory effect**" and "**reserves**" to characterize the karst systems. The memory effect refers to the time (in days) required on the auto-correlogram for the discharge rate to reach a correlation value lower than 0.2. This value is assumed to reflect the storage capacity of the aquifer.

These criteria have been later discussed by Grasso and Jeannin [1994] as it has been demonstrated that the correlogram values also depend on the recharge distribution and not solely from the intrinsic characteristics of the system. This points-out one of the main difficulties of this approach: it cannot well distinguish the effects of the **recharge processes** from those of the **intrinsic hydraulic properties** of the system on the hydrograph.

4.5.2.1.1.3 Cross-correlation and spectral analysis

Several authors described the method of **cross-correlation** and its application in karst hydrology (Padilla and Pulido-Bosch [1995], Jeannin and Sauter [1998], etc.). The cross-correlation usually performs the comparison between the spring discharge rate and the rainfall time series on the basis on the relationships between the two series and the time lag between them.

As related in Kovács and Sauter [2007], the cross-correlation may represent the transfer function of the flow-system, considering that (i) the input data set is a random function, (ii) the system is linear and stationary. In that case (i.e. rare), the transfer function of the system may be obtained by deconvolution (Neuman and De Marsily [1976]).

4.5.2.1.1.4 Wavelet analysis

Wavelet transforms have been introduced in karst hydrology by Grossmann and Morlet [1984] and Daubechies [1990], in order to solve the problematic of non-linearity and non-stationary which is a limitation of the previous cross-correlation methods. **Wavelet analyses** decompose time series into time frequency space. Application of wavelet analysis in karst hydrology have been studied by Labat et al. [2000a]; Labat et al. [2000b]; Massei et al. [2006] or Chinarro et al. [2010], etc.

Wavelet analyses are usually applied to rainfall and discharge rates. They provide a time-scale representation of non-linear processes. Depending on the sampling rate of the data, wavelet analyses may point out time-variable frequencies due to natural or anthropic processes. Usual applications make it possible to precise and to discretize the rainfall vs. discharge rates relationships.

4.5.2.1.2. Artificial Neural Networks (ANNs)

Artificial Neural Networks (ANNs) are a type of black-box models (Johannet et al. [2007]; Kong A Siou et al. [2013]). Such input-output models (Dreyfus [2005]) are based on statistical autoregressive analyses (Nerrand et al. [1993]); they infer their parameters from a calibration dataset and analyses are generalized over an independent dataset. Neural network models are able to address non-linear functions but they cannot provide physical parameters of the aquifer nor the system. Neural networks models are still widely used for karst-flood assessment and/or forecast (Kong A Siou et al. [2010], Johannet et al. [2012];), in taking into account regularization methods (Toukourou et al. [2009]).

ANNs models may be coupled with a semi-distributed model, as presented in Chen and Adams [2006], providing a more realistic model with physical bases.

4.5.2.2. Process-based (numerical) models

4.5.2.2.1. Lumped (or grey-box, or reservoir) models

Lumped models are also termed “reservoir” models (Maillet [1905]) or “grey-box models” (Kovács and Sauter [2007]). They may be declined up to multiple exponential reservoirs (Forkasiewicz and Paloc [1965]) describing the duality of fast- and low-flow components in the system. Detailed explanations on the topic of reservoir models are synthesized in Rimmer and Hartmann [2012]. **Reservoir models** may consist in a **single** reservoir, or in **parallel** linear reservoirs (which are the sum or several exponential functions, see Grasso and Jeannin [1994], or in **serial linear** reservoirs (in which the upper one feeds the downstream one) or independent with linear exchange (based on a Barenblatt-type relation, Equation 4—3). The models may also entail two or more outlets (base-flow and overflow ones).

Lumped models consider the karst flow-system as a whole without discretization of zonal processes. Indeed, the establishment of lumped model does not require hydraulic head data or the knowledge of the internal geometry of the karst conduits. Parameters of lumped models only partially reflect physical values or intrinsic properties of the aquifer / flow-system. By the way, as these models require a large number of parameters; the calibration process is often tricky. Indeed, various combinations of the parameters values may provide the same efficiency without insurance that the hydrological process is well reproduced…

Lumped models could be solely **based on linear relations** between storage and discharge (Hartmann et al. [2014],) but they may also **include non-linear relations** (Equation 4—1). Indeed, in addition to usual reservoir models, other authors propose a various type of reservoir models including non-linear laws (see Jukic and Denic-Jukic [2006] and Tritz et al. [2011]).

$$Q = \frac{dS}{dt} = a.S^b$$

Equation 4—1. Linearity equation; ***Q*** *is the discharge,* ***S*** *is the stored volume of water,* ***a*** *and* ***b*** *are model parameters reflecting empiric system properties.*

Several sub-types of lumped models do exist (see. Figure 4—9); they are briefly commented hereafter.

4.5.2.2.1.1 Single event analysis

This method focuses on the characterization of the discharge signal of one single recharge event. The discharge curve may be decomposed into three separated components: the **rising lumb**, the **fast recession** and the **slow recession**.

As established by Forkasiewicz and Paloc [1965] in karst media, the **recession curve** (rate of drying up) of the main permanent spring discharge rate after a seasonal or chronic event of recharge may be described by the **Maillet formula** (Maillet [1905]) is usually employed to draw the exponential decrease of the spring regime as a function of time (Equation 4—2). Simple exponential or multiple exponential reservoir cascading models (Forkasiewicz and Paloc [1965]; Schoeller [1965], Mangin [1970b]; Heindl et al. [1984]; Bonacci [1993]; etc.) have been proposed in order to assess the characteristics of the various rock reservoirs (mainly three reservoirs: the fissured rock reservoir, the conduit network and the “intermediate” system) as isolated from each other.

$$Q_t = Q_0 . e^{-kt}$$

Equation 4—2. Expression of the discharge equation for exponential reservoirs (Maillet [1905]); $\boldsymbol{Q_t}$ *is the discharge rate at “**t**” [m^3/s],* $\boldsymbol{Q_0}$ *the initial discharge at “$\boldsymbol{t_0}$” from the start of drying up [m^3/s],* ***k*** *the recession coefficient, and* ***t*** *the elapsed time from the start of drying up [days].*

Authors observe that for the same spring it seems awkward to establish a recession standard curve over a set of years as the recession coefficient evolves from a season to another one - suggesting that the recession cannot be extrapolated using a simple exponential decrease. They notice that the final parts of the recession fit a linear decrease corresponding to a slow reservoir vidange of laminar regime.

Instead of applying exponential reservoirs, hyperbolic function models may also be used to describe the recession modalities of a spring discharge (Drogue [1972]). Principles of the approach remain at least the same. This method is then commonly applied to assess the system’s outlet recession over a long period without recharge.

In reality reservoirs discharge cannot be considered as a successive cascading process but rather as a simultaneous discharge process. Kiraly and Morel [1976b] pointed out the fact that the distinguished components of the hydrograph do not strictly refer to the vidange of aquifer volumes of distinct hydraulic conductivities.

Mangin [1975] also introduced a **single event method** based on the combination of two functions; the first one simulates the contribution of the unsaturated zone, while the second one reproduces the contribution of the saturated zone. Depending on the computed parameters, the author proposed a classification of karst systems into five categories based (i) on the ratio between the groundwater volume of the saturated zone and the total annual resource and (ii) on a characteristic value of the recession curve noted two days after the peak flood.

These methods of single-event analysis may be seen as simple methods. In reality, they rather provide information on the recharge events frequency and modalities instead of providing clear or explicit characteristics of the flows system.

4.5.2.2.1.2 Semi-distributed lumped models

This type of models is inspired from lumped ones but instead of considering the karst system as a whole and applying a unique lumped model, the karst flow-system is decomposed in different sub-systems. Each sub-system is defined by a specific lumped model taking into account characteristics and processes of each compartment (soil, epikarst, conduits, matrix, etc.). **Semi-distributed models** are based on a combination of "independent" sub-systems which are simulated by a series of reservoirs considering linear laws (Bailly-Comte et al. [2012]; Koch and Bene [2013]; Fleury et al. [2013]; Ladouche et al. [2014]) and aggregated in order to provide the hydrological regime at the outlet(s) of the system.

In the frame of the Swisskarst project, the application of a semi-distributed hydrological model (RS3.0, e-dric [2012] or MINERVE, Foehn et al. [2015]) for the systems recharge assessment has been tested and discussed (Weber et al. [2011]; Weber et al. [2012]). The section 6.3.3.1.1.1 is dedicated to application of these models.

4.5.2.2.2. Spatially distributed models

Spatially distributed models intend to reproduce the physical properties of the karst hydrogeological system in order to simulate its hydrological response (Teutsch and Sauter [1998]). In theory this type of model brings more indications on the system than black-box models or lumped ones because systems are spatially discretized in sub-systems with their own hydrological characteristics which are routed together. Unlike lumped models, distributed models may be used for predictive hydrological simulation outside of their calibration range.

Nevertheless, such models are difficult to implement as they require a large amount of spatialized data concerning: aquifer boundaries, catchment boundaries, the conduits geometry, the hydrogeological properties of the matrix, etc. In most cases these data could not be completely obtained from measurements or investigations methods, then models implementation and the reliability of the results may be questionable or at least difficult to validate. These difficulties limit the applicability of this type of model although they are the most descriptive models to depict the hydrogeological properties of the aquifer and of the flow-systems...

As written by Kovács and Sauter [2007] who compiled an excellent review related to karst hydrodynamic modelling, most of the spatially distributed models respect the **diffusivity equation** derived from Darcy's law (momentum conservation) and the **continuity equation** (mass conservation). The most common distributed models in karst are based on the combination of **discrete flows** (i.e. fractures and conduits flows) and **continuum** (guided by heterogeneities) at a various degree. Continuum flows are mostly described by the Darcy's law (Equation 2—1) while discrete flows respect the Darcy-Weisbach (Equation 2—4). As described by Kinzelbach [1986], distributed models may be discretized into regular rectangular cells (Finite Difference Method) or into triangular/quadrangular irregular cells (Finite Element Method).

4.5.2.2.2.1 Equivalent porous Medium models (EPM)

EPM approach implies the discretization of the models in adjacent elementary units and the discretization of the hydraulic field parameters to these units. The model results in an equivalent permeability tensor in which hydraulic heterogeneities are averaged. Depending on the scale and the considered flow regime (steady-state or transient), such model may provide acceptable results when assessing groundwater resources at regional scale and steady-state conditions to fairly bad results when simulating particular event at local scale and transient conditions. Furthermore such a model also requires parametric calibration which cannot be achieved at large scale… Due to this main limitation, the applicability of such models in karst is quite restricted.

4.5.2.2.2.2 Double Continuum models (DC)

This type of model presented by Teutsch [1988] is well described in Mohrlok and Teutsch [1995] and later in Cornaton and Perrochet [2002]. When applied in karst aquifer, the **DC model** (also called **dual-porosity model**) considers two distinct overlapped continuums; one reflecting the matrix flows and the other one representing the fissured or conduit flows. Both continuums are hydraulically connected as a transfer function (Equation 4—3) makes it possible the water exchange between these two media according to their respective hydraulic heads (resp. H_m and H_f) and an exchange coefficient α.

$$q_{Ex} = \pm \propto (H_m - H_f)$$

Equation 4—3. Transfer function of water exchange between continuums in a dual-porosity model (Barenblatt et al. [1960])

Matrix and fissured/conduits porosities are respectively expressed by the ratio between volumetric density of the continuum to the apparent total volume of the system. Evaluation of the exchange coefficient requires to know the hydraulic properties of the matrix and those of the karst conduits as well as the global geometry of the aquifer.

DC models may be performed under steady-state conditions or transient ones. Such DC model may highlight relationships (i.e. the water exchange) between the matrix rocks of restricted permeability and the fissured or conduits features of high permeability and allows inferring the efficiency's degree of the karst conduit network for draining groundwater.

4.5.2.2.2.3 Combined Discrete-Continuum models (CDC)

Starting from the observation that EPM models cannot reproduce the measured hydraulic heads within the karst system without extrapolating high hydraulic conductivities to the fissured/conduit continuum (even out of the range of realistic values, compromising the validity of the hydraulic equations), **CDC models** implement karst conduits in a Darcian **continuum as discrete elements** (Kiraly and Morel [1976a]). Conduits flows could be simulated using one-dimensional finite element (using Poiseuille Formula in laminar case, cf. Equation 2—3) while the matrix flows are represented by three-dimensional finite elements (Kovács and Sauter [2007]). As for EPM model, a linear or a N-order exchange coefficient is computed to perform the coupling between the discrete conduits and the continuum via a Barenblatt-type relation (Equation 4—3). This remains a challenging parameter to assess as it depends on the conduits geometry and the hydraulic properties at the interface with the matrix.

A detailed description about CDC models has been produced by Kovács [2003b]. Since 2008, the CDC approach has been implemented in the MODFLOW package as MODFLOW-CFP (Reimann [2009]) and widely tested in karst aquifer (Hill et al. [2010]; Saller et al. [2013], etc.).

It should be kept in mind that CDC models are among the first "commercial" models dedicated to karst hydrology which may take into account realistic hydraulic parameters. This model requires to explicitly consider the geometry of the fracture / conduit network as well as the hydraulic properties of the matrix, resp. the conduits.

In parallel to the hydrological simulation, such CDC models have been also used to simulate as well (i) karst conduits genesis by coupling flows and calcite dissolution model (Clemens et al. [1996]; Sauter and Liedl [2000]) as (ii) hydrochemistry and solute/particle transport (Birk et al. [2005]).

4.5.2.2.2.4 Discrete Fracture Network models (DFN)

DFN models are introduced by Long et al. [1982]. They were initially developed for fissured aquifers. Models consist in the discretization of a set of fractures or equivalent 2D plans assumed to be the permeable structures in which the groundwater flows. The motivation for DFN model development started form the observation that, in fractured and karst aquifers, groundwater flows and transport are dominated by a restricted number of discrete pathways (mainly open fractures, conduits or other features). Unlike previous distributed models, here the matrix permeability is assumed to be negligible (Kovács and Sauter [2007]). When introduced, the fundaments of this approach have been long discussed compared to existing continuum approach. The controversy was mainly related to the lack of **representative elementary volume** in the DFN approach, which makes it difficult to opt for a conceptual model.

The **transmissivity** along the features is usually computed by the “cubic-law” (Snow [1969], Equation 4—4) which is function of their aperture. Discrete features and their hydraulic properties (mainly aperture) may be deterministically (using field investigations, geophysics, boreholes tests, etc. which remains challenging to perform) or stochastically (using a Monte-Carlo process) implemented.

$$T = \frac{a^3 \rho g}{12\mu}$$

Equation 4—4. Expression of the Cubic-law formula (Snow [1969]); ***T*** *is transmissivity [L2T-1],* ***a*** *is the fracture aperture [L],* $\boldsymbol{\mu}$ *is the fluid viscosity [ML-1T-1],* $\boldsymbol{\rho}$ *is the fluid density [ML-3] and* ***g*** *is the gravitational acceleration [LT-2].*

According to Kovács and Sauter [2007], limits of DFN models are (i) the high requirement of data related to fractures properties and (ii) the underestimated capacity of the matrix for storage processes. Characteristics and advantages of this approach have also been discussed by Dershowitz et al. [2004] who made an excellent review about advances in DFN modelling. As presented by the authors, recent coupled DFN/EPM models have been developed first in order to introduce continuum elements and representative elementary volume and secondly to assess the hydrological functioning of the groundwater flowing through the matrix. Three types of hybrid EPM/DFN models have been developed, mostly for fractured aquifers:

- **The layered DFN/EPM models:** this hybrid model makes it possible to reproduce the evolution of the groundwater table using continuum EPM elements and the preferential flow circulation (features connectivity) and groundwater discharge using DFN. DFN nodes (intersection between and edges of polygonal features) are linked to EPM nodes defined at the corners of the continuum volumes.
- **The EPM implementation of DFN hydro-structural models:** EPM models of discrete features are implemented using finite element, finite difference and finite volume methods. EPM grid obtained by finite element method may depict the discrete features geometry while the finite difference method induces a coarser approximation of the discrete features (stair-stepped shape). In this approach, geostatistical simulation of discrete features using krigging variograms, numerical inversion or Oda’s crack tensor (Oda [1985]) can derive properties of the DFN features to the EPM continuum volumes.
- **The nested DFN/EPM models:** these models are based on the EPM continuum approach and implement DFN features in locations of interests. These represent a compromise according to the scope of the model and the availability of the data.

Application of DFN models in karst is rare as Discrete Conduit Network models (DCN) are more appropriate for simulating flows in closed pipes using Darcy-Weisbach equation instead of the cubic-law (Equation 2—4).

4.5.2.2.2.5 Discrete Conduit Network models (DCN)

This approach inspired from the concept of the DFN approach in order to reproduce the **conduit-dominated flows**. Groundwater flows in 1D or 2D interconnected **pipes** (or conduits) developed in a 2D or 3D network (Ghasemizadeh et al. [2012]). Assuming 1D conduits, models are able to compute the propagation of laminar flows using the Hagen-Poiseuille law (Equation 2—3) or turbulent flows using the Darcy-Weisbach formula (Equation 2—4) depending on the Reynolds computed number.

As for the DFN approach, characteristics of the conduits (which are the hydrological parameters to take into account in the models) could be deterministically or stochastically determined.

Jeannin [1996] (and later Jeannin [2001]) established a **DCN model** of the downstream part of the Hölloch cave system in Central Switzerland with the aim to reproduce the observed discharge rate at different outlets and sections of the system. The determination of the hydrological parameters and the calibration processes have been deterministically implemented, as some sections of the cave are accessible to measurements.

The application of that type of model compared to measurement data-set highlights certain aspects of the system functioning which can be extrapolated to other sites:

i. Hydrological non-linear processes of the system may be explained by the presence of perched conduits and overflow outlets that are successively activated by the rise of the hydraulic gradient within the system. The activation of these additional flow-paths considerably modify the hydrological functioning of the system which becomes non-linear;
ii. The groundwater storage in the epiphreatic conduits and in the fissured matrix surrounding conduits may a priori be neglected;
iii. The use of the Louis Formula for the head-losses evaluation within the conduits system by using the Darcy-Weisbach equation seems appropriate.

In spite of these encouraging results, it should be observed that few advances have been performed in the field of DCN models compared to CDC models (Wu et al. [2009], Hill et al. [2010]; Reimann et al. [2014]; , etc.). However, recent applications should be mentioned as innovative in the field of DCN (Peterson and Wicks [2006] Gill et al. [2013]; Chen and Goldscheider [2014];) and engineering commercial solutions are now available : SWMM (Rossman [2010]), Infoworks® (Wallingford Software [2008]) facilitating the implementation of the models. DCN models will be further discussed in §. 6.3.4.1.1.

4.5.2.3. Synthesis, reliability and limitations

Hydrological simulation approaches in karst that are presented above may be synthetized in the following Figure 4—10 as extensions of the previous approaches diagram presented in Figure 4—1.

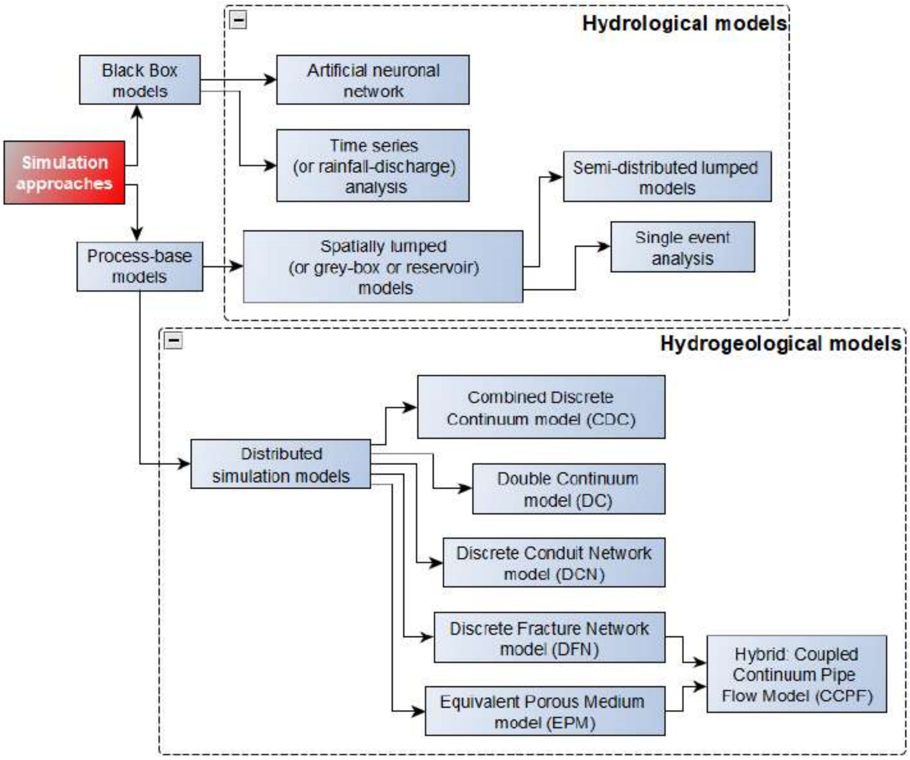


Figure 4—10. Hydrological and hydrogeological simulation models in karst; synthesis

As shown in Figure 4—10, various types of single or hybrid models do exist in karst hydrology. These may be implemented without any contextual data (black-box models), considering mainly temporal datasets (lumped or “grey-box” models) or considering physical parameters of the aquifers (distributed models). It’s surprising that there are so many types of simulation models to address both hydrological and hydrogeological issues. In fact, each type of simulation model has its own utility, depending on the hydrological addressed question, the nature of the system, the available data and the means and resources that could be allocated to the work. Main advantages and capabilities of the proposed simulation approaches are listed in Table 4—4.

Functionalities	**Black-box models**	**Spatially lumped models**	**Distributed simulation models**
Calibration	None or limited	Faster	Difficult
Reliability control	No	Impossible outside the range of the calibration conditions	Depends on the level of details of the data
Forecast	Using Artificial Neural Network models	No	Yes
Required data	Low	Relatively low	High
Inferred physical parameters from the aquifer	No	average	Yes
Validation with measured parameters in the field	No	No	Yes
Require	Times series data	Time series data	Spatial and time series data

Table 4—4. Advantages and disadvantages of the existing hydrological simulation approaches in karst

Then, according to the previous demonstration, the reliability of the proposed approaches to address the three types of hydrological questions (see §. 4.5.1) is displayed in Table 4—5.

Hydrological question \ Simulation approaches	**A: System recharge assessment**	**B: System discharge assessment**	**C: System outlets discharge assessment**
Black-box – time series analyses	☺(bivariate)	☺(bivariate)	😐
Black-box – Artificial Neural network	☺	☺	☺
Lumped models – single event analysis	☺	😐	☹
Lumped models – semi-distributed	☺	😐 (recharge-dominated system) ☹ (conduits-dominated system)	☹
Distributed models – EPM	☺	☹	☹
Distributed models – DC	☺	😐	☺
Distributed models – CDC	☺	☺	☺
Distributed models – DFN	☺	😐	😐
Distributed models – DCN	☺	☺	☺

Table 4—5. Reliability of the usual simulation approaches in karst to address the three types of hydrological questions. Depending on their specificities and capabilities, the above-presented models may be ☺ well adapted, 😐 partially adapted, or ☹ unadapted to address the issues.

According to the previous tables, all the proposed approaches present various advantages and disadvantages regarding the questions to address. Only **black-box**, **CDC** and **DCN** approaches may really answer the three types of hydrological questions even if black-box models cannot be a substitute for process-based (or conceptual) models since they do not integrate physically-based parameters. This clearly demonstrates that no one of these approaches may be considered as exclusive to address hydrological questions whatever the site, the available data and time.

Thus, approaches combination is still the most relevant way to address hydrological questions on a site, according to available data and time. In the frame of this thesis, an example of such combination of hydrological simulation approaches is provided §. 6.3.

4.6. Mismatches between existing approaches and needs for the practice

The previous demonstration focused on the different approaches that are applied in karst in order to address pragmatic issues related to hydrology, mapping, or 3D organization of the aquifer. It appears that although a multitude of approaches do exist; rare are those which provide a concrete and organized workflow leading to an explicit conceptual model of the system. Such a conceptual model is however a prerequisite for the description of the groundwater flow-system.

Regarding the hydrological, 3D modeling and mapping approaches, it seems obvious that most of them cannot be compared to each other as they do not explicitly present the same conceptual model of the system. Often the conceptual model assumed for a given approach is even not explicitly described. This is a real limitation for applying such approaches – especially regarding practical issues. It is therefore very difficult for the user to select a modelling approach according to a given hydrogeological question. Ideally, the user/modeler should provide an explicit and clear formulation of the hydrogeological question as well as a clear knowledge of the karst context. Based on that, he must explicitly describe the conceptual model of the system required to address the question. Finally the user/modeler should be convinced that the selected modelling approach addresses his hydrogeological question. One difficulty the karst hydrogeologist is to construct his conceptual model of the studied system as no approach does exist for this purpose.

For many practical questions, a good conceptual model is a 3D representation of the flow system. These are the motivations for elaborating KARSYS, which was developed for this purpose. The approach should further be compatible with mapping concepts, with conduits generation approaches and with hydrogeological simulation models. These are the specifications for developing KARSYS (§. 5) and its specific extensions (§. 6).

5. *The KARSYS approach*

5.1. Introduction

As described in the previous chapters, karst aquifers are of great significance in terms of groundwater resources, energy, natural hazards, etc. These chapters also point out that many methods do exist for assessing characteristics of karst aquifers.

These methods reveal accurate for depicting one or several characteristics of flow-systems for given conditions. However most of them do not explicitly present a **conceptual model** of the aquifer and of the flow-systems. They usually fail to provide concrete image which synthetizes existing data / observations and simple principles of karst hydrology. Different methods focusing on space or time are often combined but results are barely compared or even synthetized. This often leads to divers and sometimes contradictory interpretations for a same site.

The motivation for **KARSYS** was to develop a pragmatic **approach** for synthetizing data and few principles of karst hydrology in a **3D conceptual model**. It is expected that this **explicit 3D model** intends to document the main characteristics of karst aquifers and of flow-systems and will serve as a basis for further investigation or for designing numerical models.

The basic idea goes back to the work initiated by L. Kiraly in the beginning of the 1970's when the author established the 1/50'000 hydrogeological map of the canton Neuchâtel (Kiraly [1973a]). Unlike existing maps which are mostly based on geomorphological description, this document provides a systematic concept for documenting karst aquifers and their characteristics over a whole region. Thanks to geological and hydraulic principles, groundwater bodies were delineated and confined / unconfined parts were distinguished. Flows were not explicitly shown but users may infer the main flow-paths by themselves. Basically, the KARSYS approach combines and summarizes similar concepts and principles as those promoted by L. Kiraly. It also includes concepts and principles which have been developed by other authors such as Palmer [1986] or Jeannin 1996 regarding the development of the conduits and the organization of the flow-systems.

The development of KARSYS has been initiated before the thesis starts. Statement of the approach is presented in Jeannin et al. [2013]. The authors provide the main steps of the approach as well as a series of applications at global and regional scales. This paper gives the state of art. However, conditions for application, modus and limitations were not fully developed and clearly formalized. These are the main focus of this chapter.

As noticed in the description of the Swisskarst project at the beginning of the document; KARYS Original 3D has been applied in various geological and geomorphological contexts and for different issues. Indeed, between 2010 and 2014, the KARSYS Original 3D approach has been applied on the following tests sites (cf. Table 5—1). The application of KARSYS to these sites was highly instructive and made it possible in all cases to improve the hydrogeological knowledge of the considered aquifers (and flow-systems). These various applications were opportunities to test the developed approach and to improve it from a technical point of view: (i) to define conditions for applying the approach, (ii) to define validation procedures for resulting models and (iii) to asses advantages and limitations of the approach. Various processes of the approach have been made semi-automatic in order to optimize long and recurrent tasks. Scripts and other dedicated routines have been developed to make the routine faster; these have not been detailed here.

Test sites	Issues	Sites characteristics	References
Jura sites of the southern Jura (VD, CH)	Assessment of hydropower potential	Tectonic folded / thrusted setting, relevant geological and hydrological data	Jeannin et al. [2010a]
Jura part of the Bernese canton (BE, CH)	Assessment of karst groundwater aquifers and reserves	Tectonic folded / thrusted setting, relevant geological and hydrological data	Malard et al. [2012]
Beuchire-Creugenat and Voyeboeuf-Bonnefontaine karst flow-systems (JU, CH)	Assessment of karst flood-hazards	Tabular / horsts and grabens environment, relevant geological and hydrological data	Vouillamoz et al. [2013]
Picos de Europa (Spain)	Assessment of karst aquifers structuration and organization of the main flow-paths	Tectonic slices setting, poor geological and hydrological data	Ballesteros et al. [2013]
Trovsko-Banjška plateau (Slovenia)	Assessment of karst groundwater aquifers and reserves	High elevated thrusted plateau, poor and contradicting geological data, relevant hydrological data	Turk et al. [2013]
Kanin massif (Julian Alps, Slovenia)	Assessment of karst groundwater aquifers and reserves	Tectonic slices setting, poor and contradicting geological and hydrological data	Turk et al. [2014]
Hoch-Ybrig, Helvetic Alps (Schwyz, CH)	Assessment of the karst flow-systems organization and evaluation of tracing scenarios	Tectonic folded / thrusted setting, plastic deformation, relevant geological data, poor hydrological data	ISSKA [2013a]
Helvetic Alps, canton Sankt-Gallen (S Gallen, CH)	Assessment of karst aquifers organization in the perspective of geothermal probes regulation	Tectonic folded / thrusted setting, plastic deformation, relevant geological data, poor hydrological data	ISSKA [2013b]
Prealps, canton Fribourg (Fribourg, CH)	Assessment of karst aquifers organization in the perspective of geothermal probes regulation	Composite, tectonic folded / thrusted and slices setting, plastic and ductile deformation, relevant geological data, poor hydrological data	ISSKA and GeoAzimut [2014]

Table 5—1. Test sites where the KARSYS approach has been applied in the frame of the Swisskarst project

In addition to KARSYS Original 3D, different extensions have been realized in the frame of this thesis. These are presented in the next chapter (§. 6).

5.2. KARSYS Original 3D

KARSYS is a **3D geological-based approach** combining **geological**, **hydrological information** and **hydraulic principles** observed in karst media with the aim to provide a **3D conceptual model** of the aquifer and of the flow-system. In its basic form (KARSYS Original 3D) the approach is organized in **4 steps** and starts from available literature and/or field investigations on site. Each step provides a model using dedicated tools and by consideration of specific data and principles that are explicitly enounced step by step. The workflow of the approach is presented hereafter.

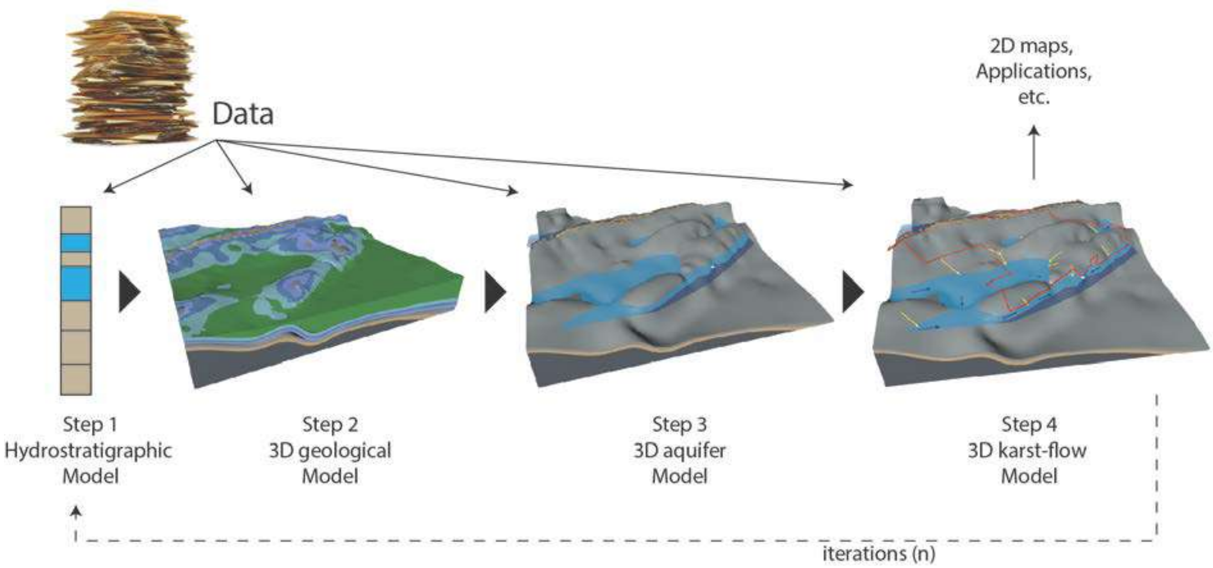


Figure 5—1. Workflow of KARSYS Original 3D (modified from Jeannin et al. [2013])

As KARSYS intends to be **systematic**, notions and terminologies have to be clearly defined to avoid any misinterpretation on the nature of the admitted principles and the outputs. In the formulation of the approach, notions and terminologies refer to those presented in §. 2. Conditions for application, reliability, validation processes, advantages and limitations of the approach are discussed after in order to indicate the applicability of KARSYS.

5.2.1. Steps in the application of KARSYS Original 3D

5.2.1.1. Step 1 - hydrostratigraphic model

5.2.1.1.1. Principles

The **karst hydrostratigraphic model** should distinguish the lithological formations that are sensitive to karstification from those which act as less permeable or as a strict aquiclude. The hydrostratigraphic model is built as a lithological log where the considered formations are explicitly considered as “**karst aquifer**” or as “**karst aquiclude**”.

Examples of karst hydrostratigraphic model are described in the literature, ex: Jeannin et al. [1995]; Kovács and Jeannin [2003], etc. All along the Swisskarst project, regional and local hydrostratigraphic models have been established in various parts of Switzerland.

The hydrostratigraphic model is established for a site. Depending (i) on the selected scale of the application and (ii) on the available data, it may be more or less detailed (Figure 5—2).

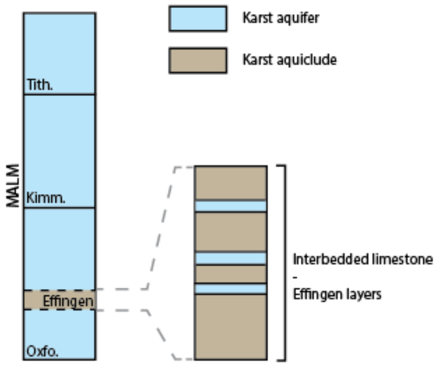


Figure 5—2. Example of hydrostratigraphic model for the Upper Jurassic limestone in the Swiss Jura (Malm); principles and criteria for the distinction between karst aquifers and karst aquicludes are presented here-after.

By principles, any exposed soluble rock (carbonate, gypsum, halite, etc.), what is more in a contrasted environment of permeabilities (by example interbedded limestone formations between two impervious formations like muds, marls or sandstones), has to be considered as **karstified** by meteoric water (= epigenic karst) unless further arguments do disprove it.

With the exception of places where the massifs / lithologies are undoubtedly considered as karstified, many other places (resp. lithologies) are still considered as **unclearly karstified** (example of the Drusberg-Kalk and the Kieselkalk in the Helvetic Alps, see Häuselmann [2002]). Due to uncertainties or to ambiguous observations, these formations may be characterized as potentially-karstified or pseudo-karstified as their sensitivity with respect to dissolution is almost equivalent to their hydrogeological drainage by fissures. In the example Figure 5—2, the Effingen formation (Oxfordian marls) lying close to the basement of the Malm formation (upper Jurassic) is considered as a regional aquiclude. These thick marls isolate the Malm (Upper Jurassic) karst aquifer from the lower one (Dogger aquifer). In detail, these are formed by an intercalation of marls and thin beds of limestone in which well-drained karst aquifers do also develop. Depending on the purpose, it appears obvious that considering Oxfordian marls as a strict aquiclude or aquifer may be contentious…

5.2.1.1.2. Recognition of karstic / non-karstic formations

Indices of karstification are of three types: **geomorphological** indices, **hydrological** indices and **physico-chemical** indices in groundwater. The combination of these indices attests of the karstification. Some authors already presented sets of indicators attesting a karst-like functioning of the aquifers. For Appalachian regions, Quinlan et al. [1992] presented a set of dedicated features that characterize a karst-like functioning. For alpine regions, the KarstALEA method (Filipponi et al. [2012]) also proposes a relevant index of hydrological indicators defining the karst-like functioning of the aquifer.

In most cases, simple observations on field and recognitions of the main springs may attest if the considered aquifer is karstified or not – especially from the geomorphological point of view. Additional data (hydrological measurements, chemical analyses, etc.) may also be useful to confirm the first appreciation.

5.2.1.1.2.1 Landforms: evidences of rock sensitivity to epigenic karstification

Karst landscapes are characterized by specific forms of carbonate rocks resulting from dissolution processes (Ford and Williams [2007]; Ginés et al. [2009]). The presence of caves, of point-concentrated springs, of karren felds, sinkholes, ponors, etc. are the most significant evidences. Depending on the geological context and on the climate, these forms may be divers and more or less pronounced (density and size). The Figure 5—3 synthesizes **geomorphological forms** of karst landscapes which undoubtedly reveal dissolution processes (net erosion zone) and attest the karst-like functioning of the underlying aquifer.

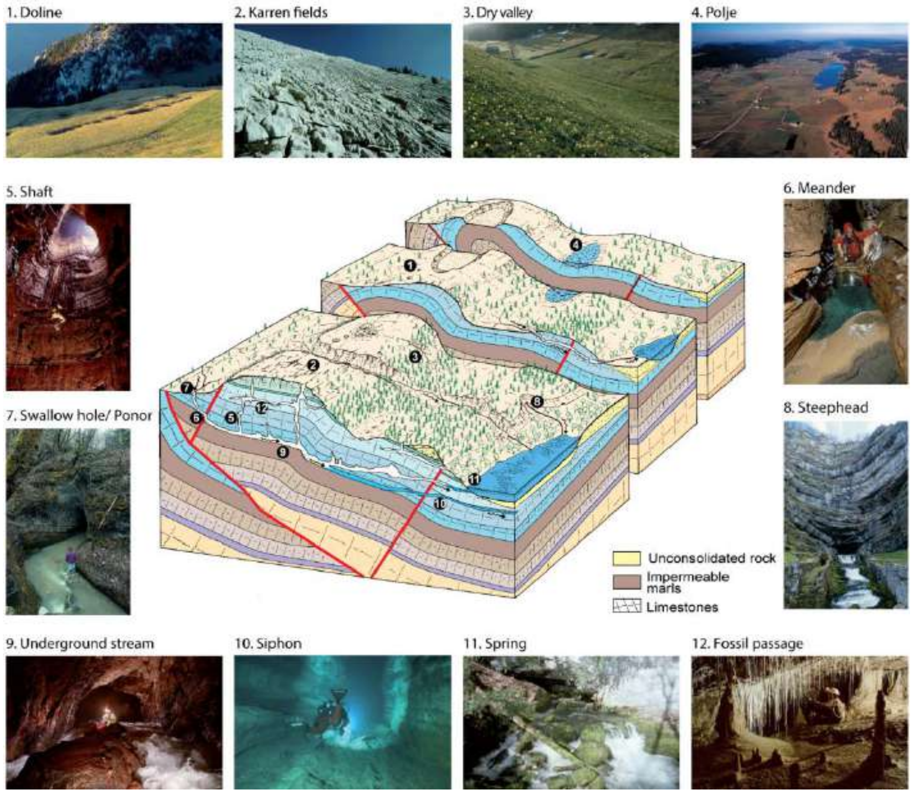


Figure 5—3. Typical forms of a karst landscape, all indicators for a karst-like hydrological behavior (Filipponi et al. [2012])

The fact that such landforms are present in the field a priori indicates a strong degree of karstification on the ground and by extension in depth. However, in some cases these typical landforms may be absent despite the presence of karstification at depth. This could appear in the following cases:

- **Overlaying covers** may hide these forms: soils, ice, quaternary deposits, lavas, geological strata, etc.
- **Recent erosion processes** may have eroded these forms: glaciers retreat, etc. The resulting landscape is waiting for being karstified again thanks to new climatic conditions.
- **Anthropic modifications** may have erased these forms: depressions infilling, quarries, etc.

On the opposite, geomorphological forms typical for karst environment may be present a land-surface without indicating a karst-like functioning at depth. These environment are called **pseudo-karst landscapes** and refer as karst geomorphological forms produced by some processes other than pure dissolution (ex: Grimes [1975]; Blancaneaux and Pouyllau [1977]; Waltham [2008]). Under specific climate conditions, denudation and longtime exposure, low soluble rocks and even non-soluble rocks (for instance indured sandstones or even granitic rocks) may form a karst-like landscape on surface due to a **long exposure to erosion**. They may even form caves locally. However these environments remain close to a fissured aquifer at depth.

Therefore, typical karst geomorphological forms on the ground are not exclusive indicators which suggest the presence / absence of karstification processes at depth. These indicators should be completed by evidences for karst hydrology.

5.2.1.1.2.2 Hydrological evidences of karst hydrology

Karst aquifers are characterized by specific **hydrological features / evidences** regarding surface and groundwater flows. Even in absence of karst geomorphological forms, hydrology may be considered as the most significant evidences attesting for karst hydrological processes.

5.2.1.1.2.2.1 Surface drainage density

As mentioned in §. 2.2.1.2, under specific climates, the relative deficit of **drainage density** on the surface is a clear indication for well-developed underground drainage capacity. Under temperate climate, an obvious deficit of surface streams is an indication of karstification underneath. The assessment of the surface drainage-density over the catchment may thus be considered as relevant criteria to assess if the massif is karstified or not. Interruption of surface streams, sudden increase (or resp. decrease) of discharge rate along the surface streams are also additional indicators.

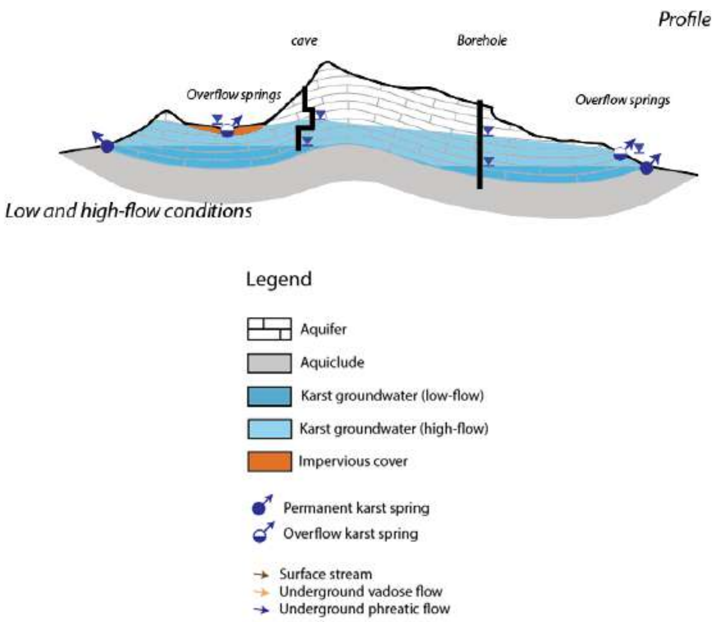
In theory, on the basis of a detailed Digital Elevation Model (DEM) and a precise survey of the permanent streams (i.e. the streams flowing for low-flow conditions), deficit areas may be distinguished from those presenting a denser drainage network on surface. Methods like IDPR (Mardhel et al. [2004]) or those presented before by Tucker et al. [2001] compare a computed stream network from the DEM with the surveyed one in order to point out zones of contrasted drainage density. In theory this method is relevant but in practice, even if DEM nowadays become of more larger resolution, existing information on the streams network (mainly vector lines extracted from topographic map) fail in documenting real permanent (at least active for low-flow conditions) and temporary streams. The reliability of the given channel network is the main limitation of the proposed approaches and often leads to misinterpretations on the drainage density for an area. However, when the data meet the required conditions of reliability, these methods may be applied with a high degree of confidence once the resolution of the DEM is comparable to those of the vectorized channel network.

5.2.1.1.2.2.2 Indications of unsaturated zone and groundwater

Karst aquifers in mountainous regions are characterized by a relative **thick unsaturated zone** in comparison with other aquifers. Groundwater bodies present a “water table” lying close to the hydraulic base level. The water table in karst aquifer is also often characterized by strong and fast **fluctuations** over short periods (several meters, dozens of meters or hundreds of meters over a few hours or days). Because of lower permeability, comparable magnitude and frequency of fluctuations could not be measured in a porous or fissured media – this feature is specific to karst aquifers.

Groundwater fluctuations could be measured in **boreholes** (piezometer) or in **caves** (cf. Figure 5—4) at the condition that measurement points intersect one or several active conduit(s) in the phreatic zone. These groundwater fluctuations may also be observed close to the outlets of the systems by the activation of overflow springs emerging several meters or dozens of meters above the baseflow spring.

Figure 5—4. Measurements of the water level in caves or in boreholes penetrating the (epi)phreatic zones bring relevant information on hydrology for low and high-flow conditions (Malard et al. [2014b]). Measurements of such large and fast fluctuations often attest that the aquifer is karstified.



5.2.1.1.2.2.3 Karst springs: outlets of flow-systems

As a basic principle, karst groundwater emerges from the lowest carbonate outcrop of the karst aquifer. The presence of **point-concentrated springs** with relative high discharge rate suggests the development of an extended catchment area (up to several hundreds of square kilometers) over the ground surface. This is usually a relevant **evidence for karstification**. The presence of **temporary springs** with relative high discharge rate (often exceeding those of the permanent spring for high-flows), and respectively, the presence of point-concentrated infiltration features (sinkholes, caves, etc.) are also seen as relevant indicators.

Indicators for karst springs recognition have been synthesized when formulating the KarstALEA approach Filipponi et al. [2012] ; the main ones are listed in the Table 5—2.

Karst springs indicators	Observations
Discharge rate > 30-50 L/s	Catchment area of large extension is rare in non-karst environment. However exceptions do exist as large and fast responsive springs have been identified downstream of unconsolidated rocks like for recent landslides deposits.
Surrounding rock	Does the spring emerge from a carbonate rocks? Are there any indices of groundwater flowing through carbonate rocks?
Discharge rate fluctuations max > 10 x min	High oscillations of the spring discharge rate are evidences for karstification. Nevertheless if an overflow spring does exist, fluctuations of the main and permanent base spring will be reduced…
Fast reaction to hydrological events	Karst springs usually react fast to hydrological events. This is not an exclusive indicator as springs emerging from unconsolidated rocks (like for recent landslides deposits) may also react fast, and some karst springs do not react quickly. This could be a source of confusion.
High-flow turbidity	Karst springs may be affected by high turbidity under high-flow conditions or after a storm event

Table 5—2. Main hydrological characteristics of karst springs as evidence for karst aquifers (adapted from Filipponi et al. [2012])

Dye tracer tests may prove connections between two points over a long distance (more than 1 km) and they often indicate fast circulation of the groundwater flows (several dozen of m/h). Fast and directed flows are characteristic for karst aquifers.

However many exceptions do exist – especially in recent geological environments – for example as a result of strong Quaternary modification. After the glaciers retreat or after a rapid falling or rising of the hydraulic base level or after catastrophic events (landslides, volcanic eruption, earthquake, etc.) karst springs may not be visible on the field, they may diffuse through recent deposits or emerge under seas or lake's level… Although the aquifer is karstified, time is required before base springs form again and be identifiable on site.

5.2.1.1.2.3 Groundwater physical and chemical signatures of karst hydrological processes

Depending on the geographical context, karst groundwater emerging from springs usually presents a specific **physico-chemical signature**, especially for the following parameters (temperature, dielectric conductivity, microbiology, oxygen isotopes, organic and inorganic carbon). Although these parameters and their evolution are strongly site-specific, observed fluctuations, especially regarding dielectric conductivity and temperature may be seen as a relevant evidence of karstification.

The observation of the **vertical gradient of temperature** in existing and relative deep boreholes (> 100 m) is an example of a good indicator. Null or low-elevated gradients are indicators of karst aquifers while normal-elevated gradients may rather indicated non-karst aquifers (§. 3.1.3.1.1). Once the hydrostratigraphic model has been established, the user is supposed to build the geological model of the area of interest.

5.2.1.1.3. Synthesis

Once geological, geomorphological and hydrological evidences have been identified through the literature or on the field, they should be compared with their respective formations. The Table 5—3 describe the procedure for a fictive case. Pro-karst aspects are tagged in green while Anti-karst aspects are in red. Based on the combination of these Pro- and Anti-karst aspects, the user assumes if the formation could be considered as karstified (i.e. aquifer), non-karstified (i.e. aquitard) or undefined.

Formations	Lithology	Landform evidences	Hydrological evidences	Physico-chemical evidences	Type
F1	Limestone	Caves, ponors, karren felds	Baseflow and overflow springs	Fast fluctuations of the groundwater dielectric conductivity at springs	Karst aquifer
F2	Dolostone	None	No unsaturated zones. Saturated zone with no relevant fluctuations	Moderate fluctuations of the groundwater temperature	Undefined
F3	Marly limestone	Caves, closed depressions	Baseflow springs	Fast fluctuations of the groundwater temperature	Karst aquifer
F4	Marls	None	None	None	Aquitard

Table 5—3. Based on lithology, landforms, hydrological or physico-chemical evidences, the user assumes if the formation could be considered as karst aquifer, aquitard or if it is still undefined at that stage (ex: F2).

5.2.1.2. Step 2 - 3D geological model

One of the major steps in the KARSYS approach is the establishment of a **3D geological model** of the site. The model is based on the formations that are defined on the hydrostratigraphic model. It and aims at depicting the organization of the lithological layers that form the karst aquifer (thickness and structural geometry). The model extends over a wider area than the strict karst outcrops in order to encompass all the supposed recharge areas over the ground surface (ex: allogenic ones). The construction requires essential knowledges in geology and tectonics that are not described here (superposition principle, principle of original horizontality, etc.).

There are no conceptual principles related to karst at that step as the geological structuration of the site is not controlled by karst processes. The model is built by the introduction and interpolation of existing geological data. Such data may be of two types:

- **Direct geological observations:** these refer to information on lithologies (nature, contacts, and orientations, etc.). Such consistent data are usually sparse and most of them come from field campaigns over the ground surface. Lithological data in-depth are exclusively concentrated along few boreholes, caves or underground constructions (ex: tunnels).
- **Interpreted geological data:** modeling geological structures in-depth requires the integration of interpreted data. Interpreted data may refer to the extrapolation of observed data (for instance on a map or on geological cross-sections) – meaning that these already correspond to a geological model established by the geologist who made the document. Other interpreted data may be obtained through geophysical investigations: micro-gravimetry, seismic refraction / reflection, georadar, electric resistivity, etc. in which identified interfaces may have been punctually verified by a drillhole.

Structural elements, e.g. folds, faults and thrusts have to be considered if they significantly modify the geometry of the aquifer. Such structural elements may be of major importance in highly folded/trusted environments such as the Alps or the Jura Mountains. In tabular environments, faults may also significantly compartmentalize the aquifers by forming a series of horsts and grabens. At that stage of the process, minor faults are not considered although they may influence the position and the organization of the karst conduit network. These faults will be later considered for generating the conduit network (see §. 6.1).

Various model builders do exist for the establishment of 3D geological models. Two types could be distinguished: **implicit modelers** based on a potential field method and **explicit modelers** based on a direct data interpolation. Implicit modelers require an extra computation while explicit modelers are often time consuming, hardly reproducible and highly subjective due to manual inputs from the user (Cowan et al. [2003]; Vollgger et al. [2012]). Implicit functions describe the shapes of any geometry, such as complex overturned folds or enclosed surfaces like spheres (for instance granitic intrusion) what is more tricky to implement in an explicit modeler (explicit modelers are usually not able to automatically built overfoldings which remain digitized by the programmer). On the opposite, implicit modelers are usually more unstable; they require extra computation and they may be quite difficult to parameterize (possible artifacts).

In this view, implicit modelers provide more functionalities than explicit ones. Due to these functionalities and the few external constraints (costs, material resources, etc.), Intrepid Geomodeller® software was the selected implicit geological modeler used for the Swisskarst project.

Besides being implicit or explicit, geological modelers provide two types of shapes: **volumetric shapes** (full 3D) or **layered shapes** (2.5D) reflecting the bottom or the top of the modeled formation. Regarding the applications of KARSYS, volumetric shapes must be preferred to the layered ones. One of the main significant differences lies in the outcropped zones of the aquiclude. Using the 2.5D layered shapes models these zones appear as a gap while using the volumetric shapes models, these zones appear as a formation, thus providing an indication for the water to flow across these zones or not (Figure 5—5).

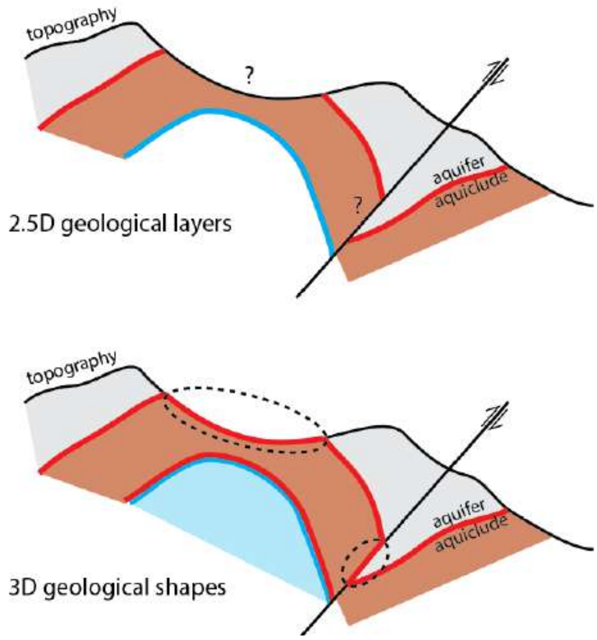


Figure 5—5. 2.5D geological layers only model surfaces of conformable contact between the formations. Eroded contacts (or surfaces of contact along faults) are not modeled. 3D geological shapes provide both normal and eroded contacts for each modeled formation.

3D geological models remain interpretative models of the geological reality as it is built using simplification and numeric constraints. Beside the resolution which is provided by the size of the resulting mesh, the **reliability** of the model depend on (i) the density and the accuracy of the data, (ii) the discretization of the geological units, (iii) the implementation of the visible structural features (folds, faults and thrusts), and (iv) the interpretation degree of the user and the invested time. These are further described in the §. 5.2.4 as parts of the KARSYS limitations. Several methods do exist to test the reliability of geological 3D models.

For indication, the establishment of a 3D geological model extending over 250 km^2 in an alpine context may represent about 100 hrs of work for an experienced user. The Figure 5—6 gives an example of a 3D geological model established on the indications provided by the hydrostratigraphic model.

One of the main problems in the elaboration of the 3D geological model refers to the drastic diminution of direct data in depth. More than 90% of the direct geological data comes from observations over the ground surface. With the exception of few boreholes and caves, direct observations in depth are extremely rare. These are mostly completed by interpreted geological data. Thus, uncertainties of 3D geological models are heterogeneous and significantly increase with the depth.

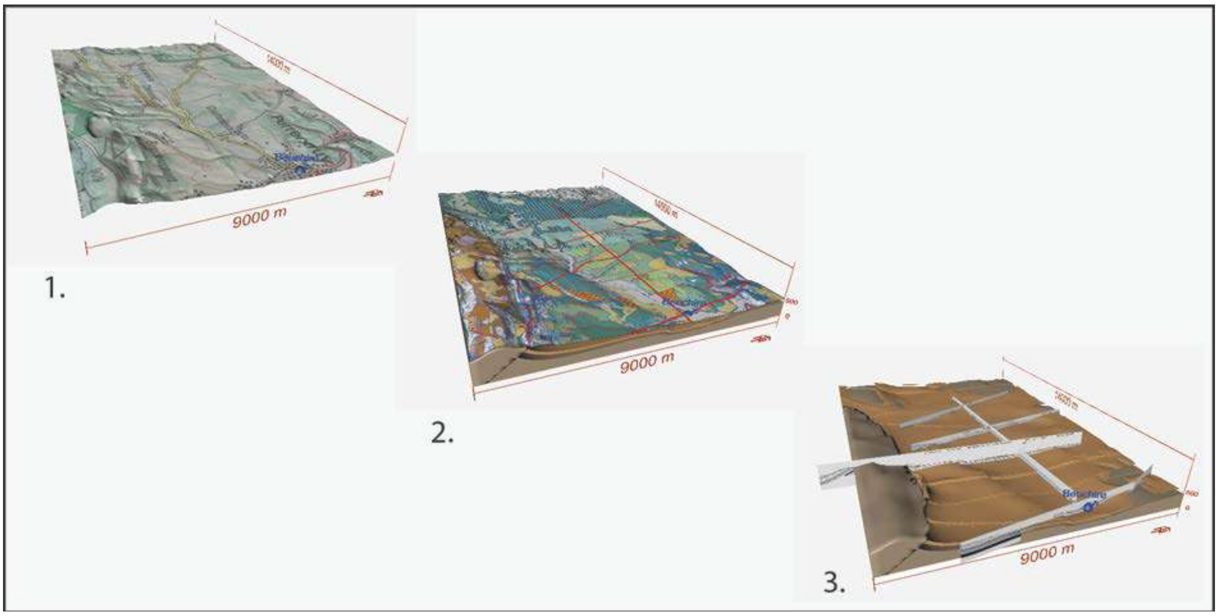


Figure 5—6. Example of a 3D geological model: the Beuchire-Creugenat karst aquifer (JU); 1. The model starts with the integration of the digital elevation model of the selected area, 2. 2D Geological information (i.e. maps, cross-sections, boreholes) are implemented, 3. The 3D geological units are processed based on the contact and orientations identified on the 2D geological information (focus is made on the impervious layers defined by the hydrostratigraphic profile).

Once the 3D geological model reaches a reasonable degree of precision, **3D meshes** (geological formations) and **2D shapes** (thrusts or faults) can be exported as .stl, .dxf or .wrl, or other 3D standard formats and imported into an explicit modeler software which supports 3D shapes (type Cinema 4D®, Blender, Solidworks®, etc.).

5.2.1.3. Step 3 - 3D aquifer model

The **3D aquifer model** aims at describing the aquifer properties (mainly the **geometry of the phreatic zones**) under low-flow conditions (i.e. the hydrological steady-state). The 3D aquifer model is built within a modeler software. At that step, KARSYS assumes three principles; these are considered as valid unless arguments in the field do disprove them:

1) The aquifer volume located below the elevation of the base hydraulic level is considered as full of water. Above the top of the phreatic zone, the aquifer is considered as unsaturated (with the exception of the epikarst).
2) The base hydraulic level of the karst aquifer is defined as the lowest place where carbonate formations outcrop at land-surface. Main springs are expected to emerge here. In case of under-flowing springs (sub-lakeside or submarine springs), the top of the phreatic zone lies at the level of the free surface water. Principle (2) assumes that the organization of the karst conduits is equilibrate with the prevailing base level conditions (both hypogenic and epigenic karsts).
3) Due to high hydraulic conductivity, the hydraulic gradient upstream from the main karst spring does not exceed 1‰ under low-flow conditions (see §. 2.2).

In these conditions, the hydraulic gradient may be inferred from the position of the main permanent springs by assuming a relative flat and horizontal plan crossing the spring and extending through the aquifer volume. This flat gradient is a **minimalist hypothesis**; it fixes the minimal extension of the phreatic zone. Hydrological data collected in the GIS database are integrated into the 3D modeler software. These consist in:

- **Karst springs:** these are integrated into the 3D modeler at their respective location (including elevation). Springs are distinguished between permanent and temporary ones.
- **Groundwater level indications (i.e. hydraulic-head measurements):** these indications come from boreholes or piezometers survey and from observations or measurements in caves after they have been analyzed and considered as representative of the groundwater fluctuations in the phreatic zone. Groundwater level indications are considered as representative if their fluctuations have a hydraulic relationship with those measured at the springs (see Figure 6—44).

In practice, depending on the existing data, there are three possible scenarios for delineating the geometry of the phreatic zone. These are described in Table 5—4 and the Figure 5—7 illustrates the description.

Availability of hydrological data	**Delineation process of the phreatic zone**
No hydrological data	If no hydrological data does exist (even locations of springs are not known), the extension of the phreatic zone is strictly conditioned by the geometry of the modeled geological units. "Perched" phreatic zones may be evidenced in the 3D model by directly pointing out disconnected compartments in the aquifer. For each of these disconnected compartment, the position of the hydraulic base level is fixed by the lowest position of the aquifer formation (or the "aquifer threshold"), for instance: - The lowest outcrop of the aquifer formation with the ground surface - The lowest contact with an adjacent aquifer formation (this case usually refers to compartmentalized aquifers in which the groundwater "cascades" from the upper compartment to the lower one) For each aquifer volume, a horizontal plan is added to the 3D scene at the presumed position of the hydraulic base level. The plan is stretched along the XY axes within the aquifer compartment until reaching the boundaries of the aquifer (cf. Figure 5—7a.). In this case, the presence of the phreatic zone remains a supposition until new indices confirm it.
Location of karst springs or other indications for the position of the hydraulic base level (sea, lake, etc.)	In this case, main permanent springs fix the position of the hydraulic base level. A horizontal plan is added to the 3D scene at the location of the spring and stretched along the XY axes within the aquifer, until it reaches the boundaries of the aquifer. This "hydraulic plan" symbolizes the minimal hydraulic gradient in the aquifer (cf. Figure 5—7b.).
Location of karst springs (or other indications for the position of the hydraulic base level) + additional hydraulic-head measurements	Main permanent springs fix the position of the hydraulic base level and additional measurements make it possible to adapt the geometry of the hydraulic gradient within the aquifer. Springs and low-flow measurements data are introduced into the 3D scene at their respective location. A plan is added to the scene at the location of the spring and stretched in the three directions in space in order to fit the hydraulic measurements until reaching the boundaries of the aquifer (cf. Figure 5—7c.). In case where the inclination of the hydraulic gradient seems to be higher than 1‰, it is supposed that a discontinuity in the aquifer acts as a hydraulic barrier. In this situation, the phreatic zone is expected to be hydraulically disconnected upstream from this point (cf. Figure 5—7d.). This hydraulic barrier may result from a misinterpretation in the geological modelling or from local discontinuities in the aquifer.

Table 5—4. Depending on the availability of the hydrological data, three possible scenarios for the delineation of the phreatic zone do exist

These three scenarios may be applied in the same 3D aquifer model as hydrological data may only exist for a part of the aquifer (usually the downstream part) and may be absent in the upstream part. The Figure 5—7e. gives an example of the conjunction of the three scenarios. The phreatic zone in "**block 1**" is deduced from the position of the spring. The phreatic zone in "**block 2**" is deduced from the position of the aquifer threshold. In "**block 3**" the phreatic zone has been deduced from the position of the aquifer threshold and the gradient has been adapted to hydraulic measurements in the borehole.

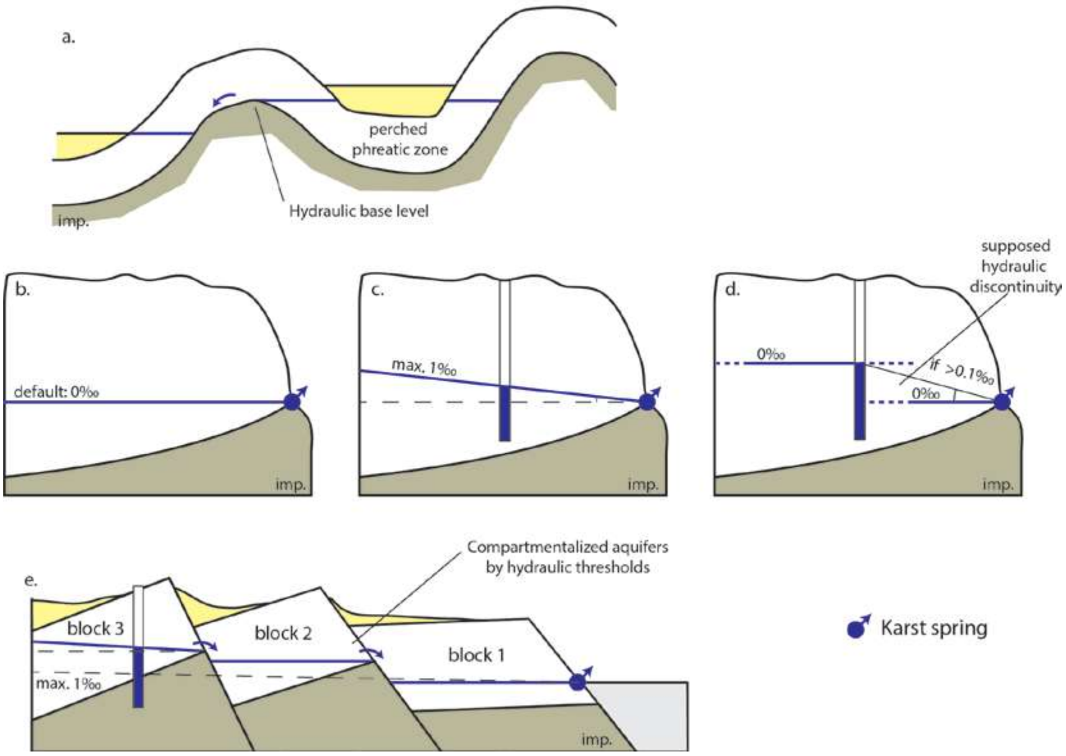


*Figure 5—7. Three types of scenarios do exist for delineating the extension of the phreatic zone in the aquifer; **a.)** no hydrological indication do exist to extrapolate the hydraulic gradient in the upper aquifer zone upstream, it is fixed by the position of the aquifer threshold; **b.)** the spring fixes the position of the hydraulic base level, by default the hydraulic gradient is 0‰; **c.)** additional low-flow indications do exist upstream the main spring to fix the inclination of the hydraulic gradient, the extrapolated gradient is lower than 1‰, c.) low-flow indications upstream from the main spring do exist but they suggest that the inclination of the hydraulic gradient exceeds 1‰. In this case, it is expected that a hydraulic barrier does exist and the phreatic zone is hydraulically disconnected upstream from this point. **d.)** depending on the structuration of the geological model and on the availability of hydrological data, the three scenarios may be applied for delineating the phreatic zones.*

In most cases – i.e. in intensive folded or thrusted environments where the dip of the formations is quite abrupt - the inclination of the hydraulic gradient up to 1‰ does not really change the geometry of the phreatic zone compared to a strictly flat gradient. On the opposite, in tabular environments where formations are gently sloping, a small inclination of the hydraulic gradient may significantly extend the boundaries of the phreatic zone.

In folded / thrusted environments, geological structure may host **perched groundwater bodies**. These develop in the aquifer at a higher elevation than the hydraulic base level and they usually feed the lower phreatic zone by overflowing **underground thresholds**. Perched groundwater bodies have been frequently evidenced in the Jura mountains (ex. Tripet [1972], Perrin and Luetscher [2008];). A recent application of KARSYS in the Bernese Jura (see Malard et al. [2012], Appendix 10.7) makes it possible to identify a perched groundwater body in the Tavannes syncline which overflows feed the northern and the southern low elevated phreatic zones. Application of KARSYS in Picos de Europa, Spain (Ballesteros et al. [2015b]) makes it possible to identify staged groundwater bodies cascading from about 900 m of elevation to 300 m.

Users should be very vigilant when considering **low-flow** and **high-flow indications**. These should be representative of the phreatic zone. In order to test the hydraulic relation with the main flow-system, data could be correlated with the discharge rates of the base spring. This implies that main springs and boreholes (or cave) should be monitored over a common period including high-flow events.

An example of a resulting 3D aquifer model is presented Figure 5—8.

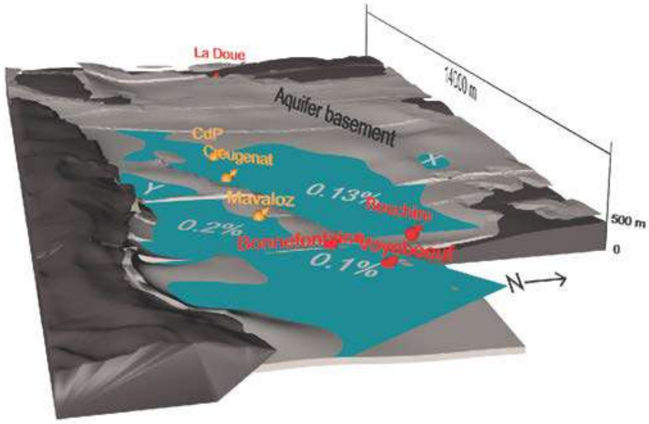


Figure 5—8. Example of a KARSYS 3D aquifer model (Malard et al. [2015a]) for low-flow conditions; permanent springs are displayed in red (Beuchire, Bonnefontaine and Voyeboeuf) while temporary springs are labelled in orange (CdP, Creugenat and Mavaloz). The hydraulic gradient is mentioned (in %). As low-flow gradient exceeds 1‰, hydraulic discontinuities are expected between the observation points (i.e. springs, boreholes or sumps in caves). A small perched groundwater body ("X") is supposed to develop in the northern part as a geological depression in the basement has been modeled.

Unconfined and confined parts of the phreatic zone may be distinguished by considering the intersection of the hydraulic gradient with an upper aquiclude (if such an aquiclude does exist in the perimeter of the modeled area, see Malard et al. [2014b]).

5.2.1.4. Step 4 - 3D model of the karst flow-system (low-flow conditions)

This step consists in positioning the **main drainage axes** of the aquifer in the vadose as well as in the phreatic zones. At that step, the approach assumes that:

1) The hydraulic gradient in the unsaturated zone is maximal. Vadose flows are mainly vertical (at least with an inclination up to 45° from the vertical).
2) In shallow karst - or when the vertical vadose flows reaches the top of the aquiclude before entering in the phreatic zone – water flow along the dip of the aquifer basement. Hydraulic gradients are fixed by the topography of the aquifer basement.
3) In the phreatic zone, the hydraulic gradient is directed towards the main outlet (i.e. the permanent spring) of the system. Phreatic conduits develop close to the top of the phreatic zone and are organized according to the "least hydraulic resistance" route towards the outlets.

These principles are further explained in Malard et al. [2015a] for the description of the conduits generator (see §. 6.1). These are considered as valid unless arguments do disprove them.

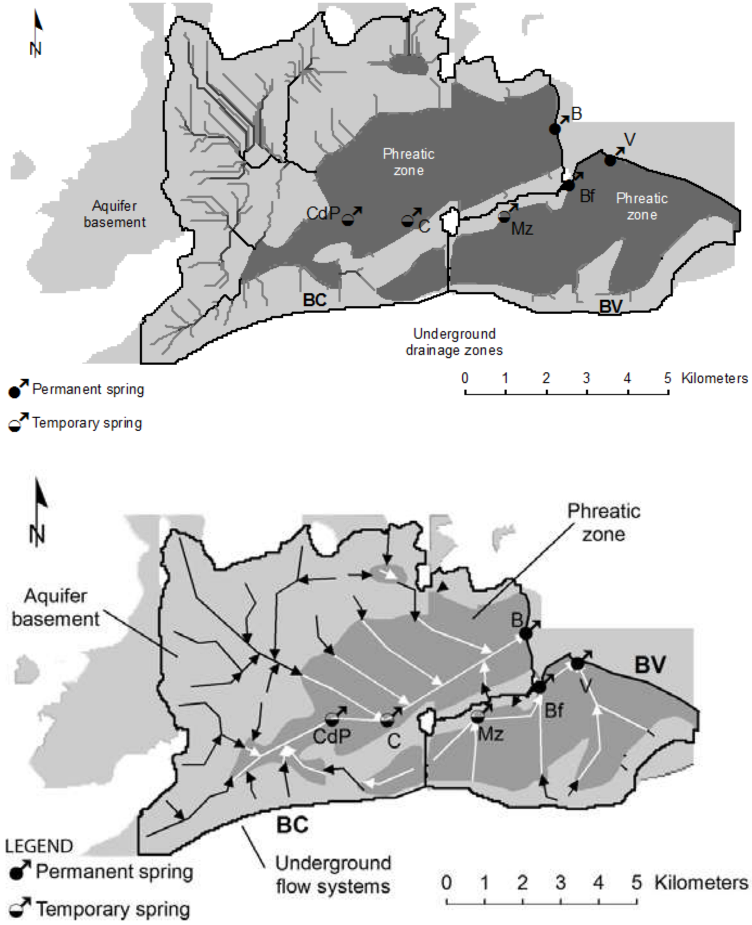
Application makes it possible to sketch the organization of the different flow-systems in the aquifer. Characteristics of the flow-systems - mainly their respective catchment area at land-surface - can thus be deduced. The sketched catchment is only valid for low-flow conditions (hydrological steady state) as no high-flow data have been yet considered.

5.2.1.4.1. Vadose flow

Vertical flows in the vadose zone are usually not sketched. With a few exceptions (large vertical conduit draining a swallow hole on surface), these **flow-paths** do not individually represent a significant component of the flow-system. As the density of vadose vertical conduits (or vadose vertical shafts) may be about 100 conduits per square kilometer in well karstified areas (see §. 2.2), it is basically not relevant to display all of them within the conceptual model.

The position and the orientation of the drainage axes can be processed in 2D using GIS for simple geological contexts. Flows in the vadose zones are then obtained by using Spatial Analyst tools (or the ArcHydro Tool, ESRI), which compute the expected drainage lines on the topography of the aquifer basement. Vadose flows stop when reaching the top of the saturated zone. Figure 5—9 illustrates the workflow for vadose flows delineation in the tabular Jura.

a.



b.

Figure 5—9. Principles of flows delineation in the vadose zone using GIS functionalities (ESRI, Spatial Analyst or ArcHydro Tools); ***a.****) the main vadose drainage axes (black lines) are automatically computed on the relief of the aquifer basement;* ***b.****) main axes are redrawn by hand. Here, vadose flows stop when reaching the phreatic zone. White arrows refer to the expected flow directions in the phreatic zone. The main permanent springs draining the aquifers are B, Bf and V (see Malard et al. [2015a]). Delineation of the upstream heads of the flow lines makes it possible to delineate limits of the underground flow-system, i.e. the projected parts (plan view) of the aquifer that feeds the flow-system.*

This procedure requires to convert 3D geological meshes of the aquiclude formations as 2D layers to be handled in a GIS. As long as the geometry of the 3D geological meshes remain simple (for instance in a monocline environment) the conversion remains workable. However for more complex geological contexts (for instance in a folded environment), the conversion fails in keeping the effective geometry. Drainage axes are then processed by hand within the 3D builder.

5.2.1.4.2. Phreatic flow

Since flows in the saturated zone are mainly horizontal, flow-paths toward the spring can be drawn, starting from the main inputs (basically the downstream ends of the vadose flows that have been previously sketched or any other significant inputs from the surface like swallow holes). Without any other indications, **phreatic flows** organize along the shortest hydraulic way between inputs and the main outlet. Faults or other discontinuities in the phreatic zone may provide additional indications for sketching phreatic flows.

Unlike vadose flows that are not supposed to change significantly between low- and high-flow conditions, phreatic flows may significantly changes by flooding perched conduits in the epiphreatic zone. Proposed phreatic flow-paths are thus strictly **restricted to low-flow conditions**. The organization of the epiphreatic flow-paths cannot be inferred from the actual phreatic flow-paths.

The delineation of the **underground flow-system** is an essential step for the delineation of their respective catchment areas at ground level. The underground flow-system is defined as the aquifer volume which is drained toward a specific spring or group of springs without considering flow mechanisms taking place at ground surface. The underground flow-system corresponds to the maximal extension of the underground drainage zone for a karst flow-system. The drainage zone may (i) be restricted to one single aquifer or (ii) drain several compartments of the same aquifer or (ii) drain distinct aquifers passing through hydraulic barriers (seepages, threshold zones, etc.). As the underground drainage zone is supposed to fluctuate depending on the rise of the hydraulic gradient in the saturated zone, boundaries of the underground catchment has usually to be distinguished between low- and high-flow conditions.

Finally, the resulting **KARSYS 3D conceptual model** of the aquifer and of the flow-system is displayed in Figure 5—10. The model provides an explicit "**image**" of the aquifer structure and of the groundwater flows during low-flow conditions (hydrological steady state).

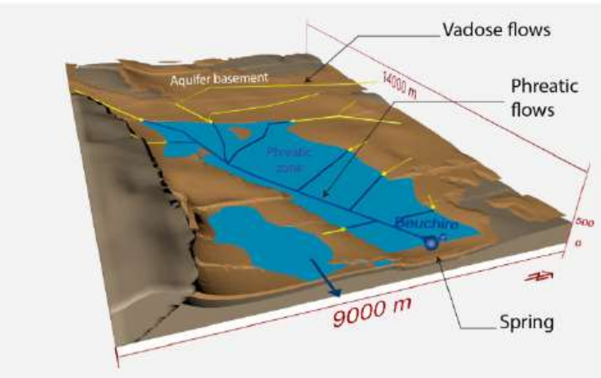


Figure 5—10. Example of a KARSYS 3D conceptual model of the karst-flow system (example of the Beuchire-Creugenat karst system adapted from Vouillamoz et al. [2013])

The catchment area of the flow-sytem may now be delineated. Procedures for karst conduits generation and catchment delineation based on KARSYS 3D models are described and formalized steps-by-steps in the §. 6.1. in a form of a published paper (Malard et al. [2015a]) as an extension of the KARSYS approach.

The here-above KARSYS model reflects low-flow conditions. As hydraulic gradient rises in the aquifer for **high-flow conditions**, the extension of the saturated zone is expected to change (usually to become larger), flooding cave passages located in the epiphreatic zones. According to mechanisms presented in section 2.2, the drainage of the phreatic zone may also change for high-flow conditions. Exchanges may appear with adjacent flow-systems which may capture (resp. which may loss) a part of the flows from/toward the main flow-system (**diffluences**). This usually modifies boundaries of the catchment areas at ground surface.

An example of KARSYS high-flow model of the Beuchire-Creugenat karst system is later presented in §. 6.3 (Figure 6—14). The final delineation of the systems catchment is then obtained once the KARSYS model has been established for low-flow and extended to high-flow conditions.

5.2.2. **Outputs**

Basically, the application of KARSYS on a site provides the **following outputs** as **spatial elements**:

1) Geometries of karst aquifers (and resp. karst aquicludes) as 3D meshes (see Figure 5—6);
2) Geometries of the phreatic zone(s) in the aquifer for low- and high-flow conditions as 3D meshes (see Figure 5—8). The volume of the groundwater reserve in phreatic zones may be assessed according to a value of effective porosity (see §. 2.1.3.2);
3) The distinction between unconfined and confined part(s) of the phreatic zone(s) for low- and high-flow conditions;
4) The position of the main flow-paths in the vadose zone(s) and in the phreatic zone(s) of the aquifer and an indication of their relative significance in terms of flows (see Figure 5—10);
5) An indication on the possible exchanges of flows from a flow-system to another one(s) for high-flow conditions;
6) An indication on the possible locations where groundwater overflows may occur. Respectively, KARSYS gives a zonation where infiltration are possible;
7) Finally KARSYS provides concrete elements for the delineation of the catchment area over the ground surface for low- but also for high-flow conditions – integrating autogenic and allogenic surfaces (see §. 6.1, Fig. 8).

These generic outputs are provided via the final KARSYS model and its associated documents, e.g: maps, sheets, 3D model, etc. (see Figure 5—11).

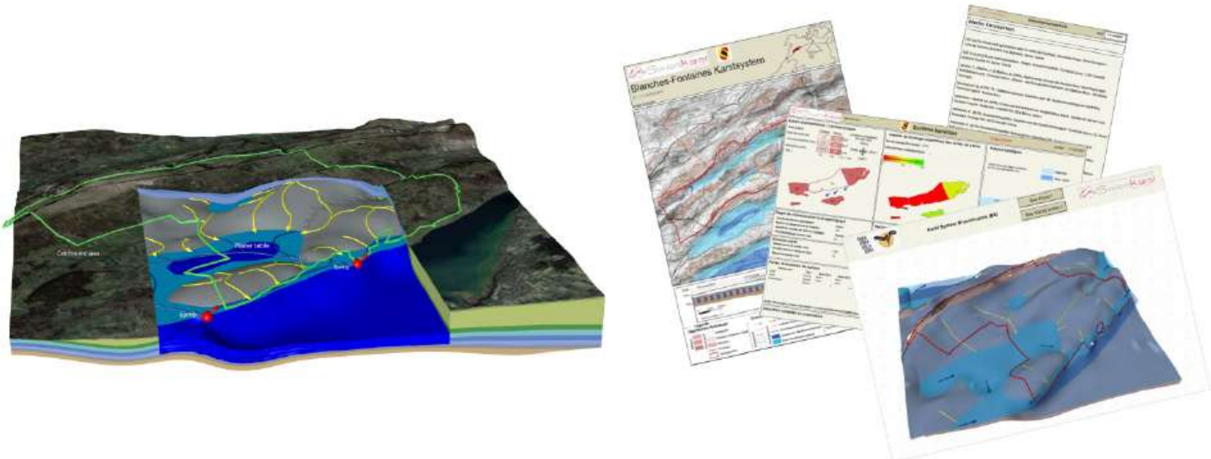


Figure 5—11. Generic outputs of KARSYS; left: final KARSYS model of a karst aquifer in the Swiss Jura, right: associated documentation provided by the application of KARSYS (2D hydrogeological map, hydrogeological sheet describing system and catchment properties, and portable 3D model, usualy as .pdf3D)

Aquifer and flow-systems characteristics may be transposed on KARSYS hydrogeological maps. Mapping principles and characteristics of these maps are presented in the two following publications: Malard et al. [2014b]; Malard et al. [2014c]. In the publication Malard et al. [2014b], a table summarizes all the relevant characteristics of the aquifer and of the flow-system which may be mapped.

5.2.3. **Advantages of KARSYS**

Main advantages of KARSYS compared to usual karst hydrogeological approach are:

1) KARSYS **may be applied in most karst regions** at the condition that geological maps, cross-sections and spring inventories are available. In its basic form, KARSYS does not require specific data which may

be difficult to obtain (for instance chemical or isotopic analyses) or those which takes a long time to acquire (for instance flow discharges, dye tracing campaigns, etc.). Unlike standard approaches, KARSYS may already provide suitable results with a few data and within a limited effort.

2) KARSYS **may be iterative**. Each new data / observation may be explicitly implemented in the conceptual 3D model and compared with modelled features. This is a significant difference with other approaches which usually require to restart analyses or modelling processes to take the new data / observation into account. Models are modified only if the new data / observation contradict the modelled features (for instance the extension / elevation of the phreatic zone, etc.).
3) KARSYS is a **systematic approach**. Whatever the site and whatever the purpose for which the model has been built, steps and application principles of KARSYS remain the same.
4) KARSYS steps are **explicit**. Unlike many standard approaches, KARSYS models may be compared on the same basis and they may be easily **understandable** by all users – even by persons with a limited knowledge in hydrogeology.
5) KARSYS **addresses most hydrogeological aspects in karst**. Usual methods and studies mainly focus on restricted aspects of the flow-system - without taking into account the surrounding aquifers or environments. As KARSYS addresses geological, geomorphological and hydrological aspects, all hydrogeological characteristics of the aquifer (and resp. of the flow-systems) are documented. Applying KARSYS may reveal significant inconsistencies in the pre-established interpretations as all existing data are synthetized and explicitly confronted in a same model. As KARSYS models usually cover a wider area than the strict supposed extension of the flow-system, possible hydrological relations with adjacent flow-systems may be pointed out. This is a real advantage that no other approach usually addresses.
6) Models obtained by KARSYS may be **validated independently** using additional data (for instance dye tracing tests) or hydraulic principles. This is a real advantage compared to other approaches in which most of the data are already used for modelling.
7) Incidentally, KARSYS requires to **organize all the relevant data** in a formal way. Geological, hydrological and other data are prepared, described and stored in a database including specific attributes and reference to the source document. This procedure makes it possible to recover metadata (author, form, etc.) and related source documents (.pdf form) from any KARSYS model.

5.2.4. Limitations

Different limitations may appear when applying KARSYS. These limitations are described in details in Appendix 10.8. They could be classified in several categories: limitations which are approach-independent (Human factor, DATA) and limitations which are approach-dependent (conceptual: principles, procedures or technical: processes and software).

The most relevant limitations specific to KARSYS are:

- The distinction between karstified and non-karstified formations is difficult to confirm. This distinction is mostly based on the relative contrast of permeability between the most permeable formation and the lowest permeable one. Regarding marly limestone or carbonated marls, the distinction could be uncertain.
- The accuracy of the 3D geological model. This is dependent on the quality and on the availability of the geological data but it also depends on the simplifications which are assumed when building the model.
- Hydraulic principles assumed in KARSYS are not valid in karst aquifers which are not equilibrated with the prevailing base-level conditions. These are valid only for mature aquifers which are equilibrated with the prevailing base-level conditions.

These limitations restrict the applicability of KARSYS to particular contexts and to particular conditions of data to be respected for a given resolution of the results.

5.2.5. **Conditions for application**

5.2.5.1. Contexts

KARSYS has been developed for karst environments. Presence of karst is the first condition to check before applying KARSYS. Although the question seems trivial, it may be difficult to directly address it on the field. The experience gained with the applications shows the most **appropriate karst contexts** for applying KARSYS (Figure 5—12).

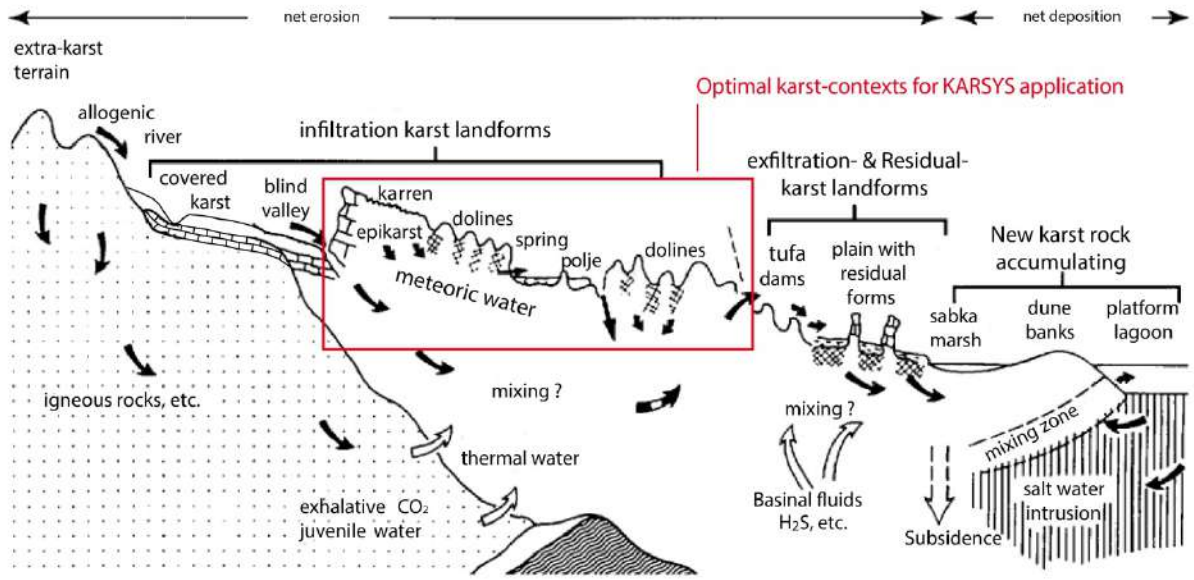


Figure 5—12. Optimal karst-contexts for the application of the KARSYS approach (Ford and Williams [2007], modified). Optimal contexts entail: Alpine karst (Turk et al. [2014], Ballesteros et al. [2015b];), high karst plateau (Turk et al. [2013]), lowland karst plateau (Malard et al. [2015a])

Feedbacks of the Swisskarst project showed that KARSYS reveals more appropriate (and really fruitful) in alpine or plateau karst regions where:

(i) **Epigenic karsts dominate** compared to hypogenic processes. Principles of KARSYS have been mostly developed for the characterization of epigenic karst aquifers (§. 4.2.1). Applications in the field of hypogenic or pseudo-karst characterization have not been developed so far as only few aquifers of that type do exist in Switzerland. As presented in the §. 2.1, mechanisms controlling the development and the organization of the drainage network in the aquifer are different from the epigenic one as they are independent from the meteoric water. In this type of karst aquifers, principles of the KARSYS approach have to be revised to include karstification processes due to upward thermal flow and deep CO_2 release. In its actual form, the KARSYS approach cannot be applied to these aquifers (about 10% of the known karst aquifers over the world);

(ii) **Lithological contrasts** between pervious and impervious rocks are strong and well defined. Basically, the approach provides a better characterization of the karst flow-systems in compartmentalized aquifers, where impervious layers develop up to the unsaturated zone (ex. Jura, Helvetic Alps, Julian Alps or even tabular Jura where horst and grabens tectonic settings develop). On the opposite, the characterization of flow systems that do not present clear impervious layers, whatever the tectonic setting, is more complex;

(iii) **Unsaturated zones are thick**; at least several dozens of meters

(iv) **Saturated zones are of moderate extension** or compartmentalized into several distinct units; for ex. separated by extensional or compressional patterns in order to identify upstream and downstream parts of the aquifer (see Figure 2—7). In such case, boundaries of the aquifer are much easier to delineate and flow-systems may be better documented;

(v) **Speleogenetic processes** may be considered as **equilibrated** to landscape evolution. This means that the actual phase of karstification is in equilibrium with the geomorphologic and bioclimatic conditions. A priori, karst aquifers are considered as **equilibrate** with the current base level conditions. This assumption is ordinarily respected but it may encounter exceptions; even if the karstification is a relative rapid process compared to geological timescale, it requires at least several thousands of years before the reorganization of the conduit network fits the new hydrological conditions. Mylroie and Carew [1987] or Ford [1988] argue for a minimum duration of 10’000 years (since the time the rock is exposed to erosion) until a karst aquifer develops to **maturity** (e.g. is in equilibrium with the current conditions regarding the hydraulic base-level and the hydrological regime).

At the opposite – even if the approach remains applicable and may bring additional and valuable information on the aquifer – KARSYS may be **less efficient in strictly confined** (and usually deep) karst aquifers where emerging zones are not identified. These refer to deep aquifers covered by relative thick and less pervious formations (ex. the Eocene-Oligocene limestone aquifer in the Aquitanian basin, southern France). These large-scale aquifers are presumably confined – even artesian. Even if these aquifers are considered as epigenic, the organization of the drainage remains complex compared to exhumed karsts, as most of the time, downstream outlets of the aquifer are not known. In such a context, the applicability of the KARSYS approach may be less fruitful even if no dedicated applications have been performed on this type of aquifers until now.

KARSYS may also be **less efficient in flat regions**, where tectonic evidences are scarce and where:

(i) lithological contrasts between pervious and impervious rocks are weak or difficult to identify,
(ii) Unsaturated zones are thin or do even not exist (for instance confined aquifers or low elevated plateaus). In this case, no impervious rocks are unsaturated, leading to a difficult lecture of the vadose flow-paths. Results of KARSYS will be limited in this case,
(iii) Large saturated zones with a really low gradient do develop. This may appear in large aquifers which present a continuous lithology without significant changes. In this case, the added-value of the KARSYS approach is not as beneficial as for a well compartmentalized aquifer;
(iv) Multiple speleogenetic phases have been identified and still condition the actual low-flow system from the expected one regarding actual geomorphologic and bioclimatic conditions (i.e. perched perennial springs above a karstified formation, etc.).

5.2.5.2. Data-condition

The application of KARSYS Original 3D requires the use of (i) **indispensable data** and (ii) **important but non-indispensable data** and (iii) **additional data** that could be used for validation. These data are presented in the Table 5—5. If conditions for the indispensable data are not fulfilled KARSYS cannot be applied. It should however be observed that indispensable data are nowadays supposed to be part of the standard information in a country. On the opposite, relevant and additional data result from specific surveys or experiments which are not included in the standard information of a country; especially the karst-related data. Besides this minimal data condition, it should be mentioned that the resolution of the KARSYS models is controlled by the data with the lowest resolution.

	Indispensable data	Relevant but non-indispensable data	Additional data (and/or validation data)
Hydrostratigraphic model	- Lithostratigraphic units	- Geomorphological map - Caves inventory and caves survey	- Surface streams network map
3D geological model	- Digital elevation model or elevation map - Lithologic or geological maps	- Tectonic or structural maps - Lithologic or geological cross-sections - Borehole logs - Lithologic or geological surveys in caves	- Detailed hillshade or aerial photos of the site - Geophysical measurements
3D aquifer model	- Main karst springs location (permanent springs, overflow ones and estavelles)		- Karst piezometric data (boreholes, caves, overflow springs)
3D karst-flow model	- Land-use maps	- Speleogenetic analysis - Inception horizons - Caves network surveys	- Results of dye tracing tests - Spring discharge data - Results of pumping tests

Table 5—5. Data-condition for the applicability of KARSYS Original 3D

Regarding extensions of the KARSYS approach (cf. §. 6), additional data may be required, especially regarding hydrology (ex. hydro-meteorological parameters).

5.2.5.3. Spatial resolution

KARSYS may be equally applied on a small flow-system or on a large region including several significant springs. In any case, the resolution of the KARSYS models is fixed by the **resolution of the spatial data** which are considered in the modelling process – mostly geological maps and cross-sections. Indeed, uncertainties concern more the geological interpretation than the hydrological data, especially along the vertical dimension. Indeed, due to low gradients, hydraulic indications can be fixed with a precision of one meter while geological interfaces are positioned within several meters of uncertainties. As a consequence, a few meters of differences in the geological model may have a significant impact on the interpretation of the flow-system (for instance the elevation of an underground threshold).

Before applying KARSYS, users should decide which resolution they work – especially for the discretization of the hydrostratigraphic model and for building the 3D geological model. Then, they must select input data for which resolution matches with those of the resulting model. The Figure 5—13 provides an indication of the expected resolution of the model depending on the size of the site and on the resolution of the input data.

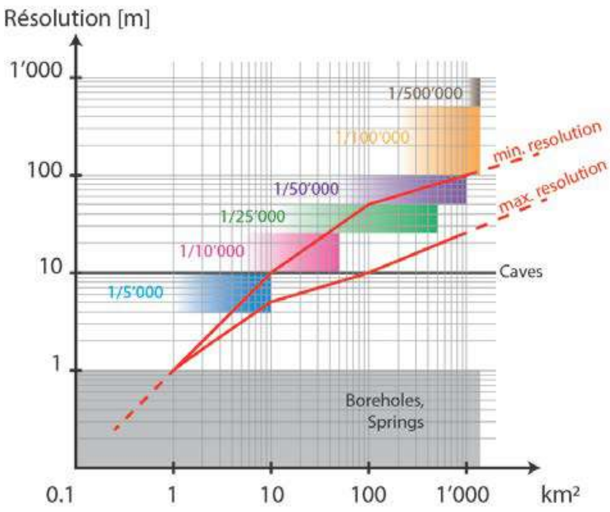


Figure 5—13. Expected resolution of KARSYS models according to the size of the model [km^2] and to the resolution of the input data. The resolution of geological data coming from boreholes or from hydrological data (i.e. springs) is about 1 m, whatever the size of the model. On the contrary, users are supposed to use geological maps of lower precision as the size of the model increases. This reduces the resolution of the resulting KARSYS model. Depending on the size of the model and on the resolution of the input data, users can expect a minimal resolution (the upper red curve) if they do not consider additional data of higher resolution. Considering a model of 100 km^2, users may expect a minimal resolution of 50 m.

Depending on the purpose for which the model is built, users may decide for the resolution of the input data. Regarding groundwater mapping (see §. 4.3), KARSYS may be applied on a large area (several thousands of km^2). At that scale, KARSYS makes it possible to distinct unsaturated and saturated zones and to locate unconfined and confined zones. For a smaller model (up to several hundreds to thousands of km^2), KARSYS makes it possible to infer vadose and phreatic flows. Regarding questions that require the location of the conduit network (i.e. of the voids), by example: location of a groundwater intake, assessment of collapses of flood hazards, prevention of construction from karst hazards, the approach should be applied with a resolution of 5 to 10 m, i.e. with a model which does not exceed 10 km^2.

5.2.5.4. Data structure

The application of KARSYS requires the development of a **GIS database** in order to store data and results of the application. A dedicated database has been designed for the Swisskarst project. The conceptual architecture of the database is synthetized in the Figure 5—14. Two classes of objects do exist: **DATA** (elements coming from existing literature or inventories) and **RESULTS** (elements resulting from the approach). Each object of the database is identified by a code. This code makes it possible to create relations between the objects (for instance between a spring and its related catchment, or between a tracer test and the associated injection point).

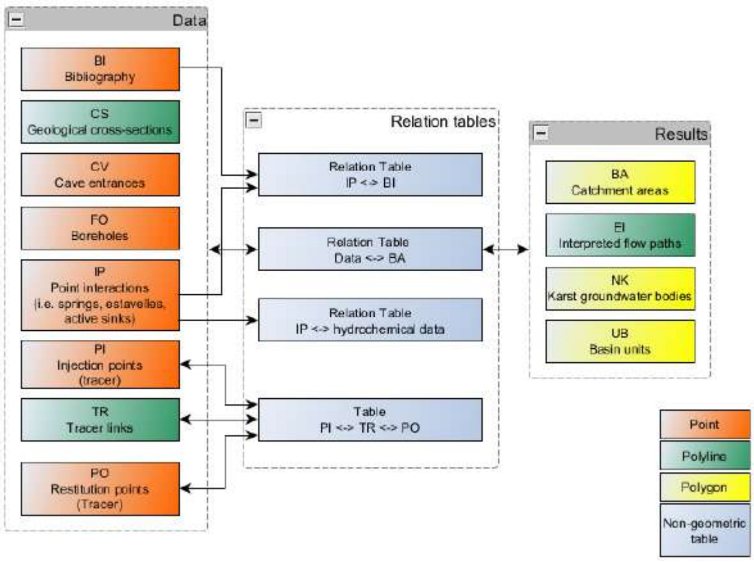


Figure 5—14. Architecture and content of the GIS database which has been developed for KARSYS; the relation tables make it possible to link the objects inside a class (DATA) or between the two existing classes ("DATA" and "RESULTS")

As usual for GIS, objects are of two types: geometric or non-geometric. Non-geometric objects reflect to the relation tables that link objects from different classes and sources. Geometric objects are of three types: points, polylines and polygons. Each object displays specific attributes which may be normalized under domains (for example for the regime of the springs: “permanent”, “temporary”, “unidentified”), or for the reliability of the data (e.g. of a tracer test): “highly-reliable”, “moderately-reliable”, “unreliable”), or for introducing complementary text for description. The catchment area is defined as the reference element of the karst system (one karst flow-system = one catchment area but one karst flow-system may be associated to several permanent and overflow springs).

5.2.6. **Validation procedures**

As KARSYS works on the combination of spatial 3D models, it seems obvious that each model has to be controlled and validated before being combined with the one of the next step.

As for numerical models, conceptual models should be **validated by observations** or independent datasets which were not considered for the establishment of the models. Thus, the reliability of the models could be documented and even précised if new data have been collected.

The validation of a conceptual model consists in checking that the deviation between spatial characteristics of a resulting model vs observed (or inferred) spatial characteristics on field are minimized.

KARSYS models may be checked and validated according to the following principles (Figure 5—15): Model (n) may be tested through a set of data (n+1, n+2, etc.) or through the model (n+1) as the data (n+1, n+2, etc.) were not used for the establishment of the model (n). As far as the data (n) are not used as direct parameter(s) for building the interpretations, they may be used several times for validation (for instance Data 3 is used for validating Model 1 and Model 2). Once the data (n) have been integrated as inputs in the model (n), they cannot be further considered for validation.

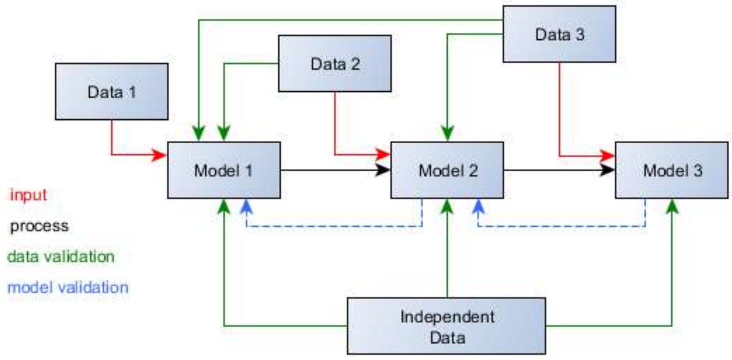


Figure 5—15. Principles of the validation process; resulting Model (n) is compared with validation Data (n+1), with independent data, principles or methods, and finally with the resulting Model (n+1).

The next sections present the step-by-step validation of the KARSYS models.

5.2.6.1. <u>Validation of the 3D geological model</u>

Interpretations of the 3D geological model, i.e. the structural interpretations (faults displacement, deposit thickness) or the position of geological contacts between two formations, etc. may be tested and validated by using independent data or data (n+1), by checking geological principles, by applying additional methods (mainly investigation methods, see §. 4.2.3), and/or by comparing with the 3D aquifer model. These are discussed in Table 5—6.

Validation means	Structural interpretation	Boundaries of geological formations
Independent dataset or Data (n+1)	Geological observations in caves may be compared to the geological interpretations. Idem for all geological data which were not explicitly considered in the construction of the 3D model.	
Geological principles	Tectonics principles: Geometries of strike faults, faults and thrusts have to be compared with the expected direction of the shift. Balancing principles: 2D kinematic modelling may be undertaken. Kinematic algorithms are able to restore deformation in geological cross-sections in order to test and validate the reliability of the geological structures. Various geological builder programs (MOVE, Petrel, GoCAD, etc.) propose such functions. These are usually complex and time-consuming tasks, which cannot be applied as easily. For instance, kinematic modelling may provide strong argument to decide which structure in Figure 5—16 is the most conceivable.	Conservation or non-conservation of the layers thickness: According to the depositional environmental and to the tectonic effects, the modeled sedimentary layers may (or not) laterally keep their respective thickness. In a conservative geological environment (uniform depositional environment and rigid deformation), checking thicknesses of the formations is a relevant constrain to validate the model.
Additional investigation methods	Geophysical methods: They may be used to validate both tectonic structures and geological boundaries in the 3D model. These are mainly ground-surface methods (non-reactive or reactive) or remote sensing methods. The most frequent methods are: seismic or resistivity soundings, Ground penetrating Rada (ground-surface reactive methods), microgravimetry or electromagnetic prospecting (ground-surface non-reactive methods). Forward modelling and inversion: These may improve structural interpretations and geometries of the geological formations. The gravity field control is an example of such inversion. This method consists in the comparison between the measured and corrected gravity-fields values and the values obtained by inverse computation of the gravity-fields using the respective rocks density (see by example Li and Oldenburg [1998]). Actually, most of the 3D geological modelers are able to infer equivalent gravity-fields values from elaborated models. Considering that the gravity-fields strictly result from the 3D geological structure of the site (assumption), mismatches between these two sets of values inform on a misinterpretation of the geological structures. Anyway, even if the gravity-fields control points out places where the geological structure is questionable, it does not really suggest a better interpretation. Moreover, uncertainties of this method are usually significant as the assumption that gravity-fields values only reflect the rock density may be discussed. In carbonates by example, depending on the karstification degree, the rock density may really vary a lot depending on places. The presence / location of groundwater may also have a significant effect on the gravity field (see the studies related to the NASA's Gravity Recovery and Climate Experiment (GRACE) mission: Swenson et al. [2006]; Tregoning and McClusky [2011]). Statistic methods: Statistical methods do also exist to assess the uncertainties of 3D geological models (see: Wellmann et al. [2010], Lindsay et al. [2012];). These methods are not turnkey solutions and they often remain complex to apply.	
Model (n+1)	Hydrological interpretations – mainly the position and extension of the saturated zones – may question the reliability of the 3D geological model. In case of mismatches, formations and/or structural interpretations may be adapted to improve the consistency of the 3D aquifer model. This last comparison is of great interest as hydraulic principles may be implemented independently from the geological interpretations and they often brings valuable indications on the reliability of the geological model.	

Table 5—6. Validation means of the KARSYS geological 3D model

As mentioned above, the reliability of the 3D geological model may be validated by the karst aquifer model. In a first instance, location and the extension of the phreatic zone may be inferred from the geological structures (see Table 5—4, case "No hydrological data") and compared to the hydrological data which have been observed on site. Inferred phreatic zones should match with the observations on site; otherwise it may indicate **inconsistencies in the geological model**. The Figure 5—16 gives an illustration of this principle for a simple (but frequent) case of geological misinterpretation. Based on the syncline interpretation, KARSYS will provide a model of the aquifer where flanks of the central valley are mainly infiltrative (case **A.**). In this case, only temporary spring could emerge along both flanks, depending on the rise of the hydraulic head in this part of the aquifer. Nevertheless, if a permanent spring is observed along one flank of the valley (case **B.**) it may suggest a **compartmentalization** of the aquifer, and then a disruption of the aquifer between both sides of the valley.

The application of KARSYS at regional scale in the Bernese Jura (see Appendix 10.7) was the opportunity to identify and to position specific places where the interpreted geological structure does not agree with the expected organization of the karst aquifers. Most of these inconsistencies appear to be related to the modeled elevation of the aquiclude crest along the anticlines (= thresholds).

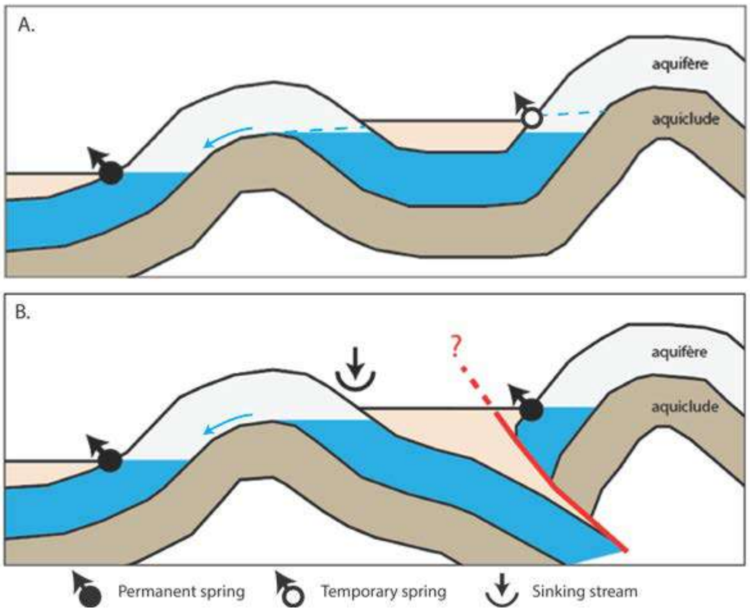


Figure 5—16. Hydrological information observed on a site and combined with the KARSYS principles may control the reliability of the interpreted geological structure on a site. ***A.*** *No permanent springs do exist in the central valley; a syncline structure with an underground threshold may explain the situation.* ***B.*** *A permanent spring does emerge along the flank of the valley and a sinkhole lies on the other flank; a geological discontinuities (here a thrust) may explain the compartmentalization of the phreatic zones.*

In this view, KARSYS may be seen as a validation approach and may be applied to other 3D geological models in karst regions for testing the reliability of the geological structures.

5.2.6.2. Validation of the 3D aquifer model

Hydrogeological low-flow interpretations are based on the 3D geological model and hydraulic principles combining a few hydrological data. The model may often be partially validated due to the usual **lack of independent data** (most of the hydrological data are used as inputs). The main interpretations to be validated are the location and extension of the phreatic zones under low-flow conditions. In a first instance, a consistent fit between the proposed aquifer geometry (resulting from the geological 3D model) and the delineated phreatic zones attests from a reliability of the proposed model. Other data and methods may be considered for validation (Table 5—7). At last, the reliability of this model may be further discussed as the flow-systems are delineated.

Validation means	Extension of the phreatic zones
Independent dataset or Data (n+1)	If speleological surveys and boreholes indications were not considered in the establishment of the aquifer model, these may be used to validate the extension of the phreatic zone.
Methods	Geophysical methods: A few geophysical methods sensitive to ground water molecules may be used for validating the position of the saturated zones in karst aquifers. Two of these geophysical methods may be cited: the magnetic resonance sounding (Vouillamoz et al. [2003]) and the spontaneous polarization "SP" (Boulding and Ginn [2003]; Gan et al. [2013]), which can be efficient for locating groundwater under certain conditions (depth, quantity, etc.). These methods are often limited in depth and the quality of the interpretations may also be disturbed by various interfering parameters (soils water content, soils heterogeneities…)
Model (n+1)	Interpretations of the resulting final KARSYS conceptual 3D model – especially the position of the main drainage axes may be compared with the 3D aquifer model. The reliability of vadose and phreatic zones may be compared and improved if they do not support demonstrated groundwater connections (for instance flow connections which have been clearly demonstrated by dye tracing tests).

Table 5—7. Validation means of the KARSYS 3D aquifer model

5.2.6.3. Validation of the 3D model of the flow-system

Interpretations of the final KARSYS conceptual 3D model are based on the resulting geological and hydrogeological 3D models. These interpretations do not require additional data - except cave surveys which may be used as input or as validation mean. Additional data and methods for the validation of the model are presented in Table 5—8.

Validation	Location and nature of the main drainage axes	Geometry of the catchment area
Independent dataset or Data (n+1)	Dye tracer tests: Parts of catchment area and/or direction of the main drainage axes may be validated by comparing with demonstrated connections by tracer tests (for low- or high-flow conditions). Examples of such validation are described in §. 6.1. Cave surveys: Cave surveys may be used as validation as far as these indications were not previously used to determine the location and flow-direction of the main drainage axes. Surveys of well-developed caves system may confirm the location of phreatic conduits and the delineation of parts of the catchment area. Examples of such validation are described in §. 6.1. Water chemical analyses: Analyses of particular groundwater compounds may attest from a specific source of infiltration (for instance specific compounds coming from well-defined industries or waste-deposits). They may validate parts of the delineated catchment area. Groundwater compounds may also attest from flow route through specific formations (for instance sulfate may attest from circulation in gypsum, etc.). These may validate supposed flow-routes.	
Principles or methods	Geophysical methods: A few geophysical methods may be applied on the site and focused along the modeled flow-paths in order to validate their existence: i.e. ground penetrating radar, resistivity profiles, acoustic sounding, etc. (see Chalikakis et al. [2011]). Hydraulic model: Position and organization of the drainage axes may be validated by establishing a hydraulic simulation model (see §. 6.3.4.1.1)	Recharge model: The computation of a "simple" recharge model may compare the proposed dimension of the catchment area with the dimension of the delineated one.

Table 5—8. Validation means of the conceptual KARSYS 3D model

5.3. Conclusion

KARSYS is a 3D-based approach for synthetizing data and few hydraulic principles in a 3D conceptual model which could be later used for further investigations or for designing numerical models. KARSYS has been developed for being applied at the scale of the aquifer or of the flow-system. It is a systematic approach composed of formal steps which may be iterated several times until conceptual models reach the expected accuracy. All spatial data that are relevant can be considered in an explicit way and compared to other data / observation. KARSYS may be applied in most karst regions and provide significant elements of understanding with a few data and within a limited effort.

KARSYS reveals extremely efficient for documenting epigenic karst aquifers of mountainous or tabular regions where (i) karst processes are in equilibrium with hydrological base levels, (i) contrasts of lithologies make it possible to identify karstified rocks from non-karstified rocks and (iii) phreatic zones are of moderate extension or compartmentalized into several distinct units. For pure confined aquifers (or even artesian ones) or where lithological contrasts make difficult to distinguish karstified from non-karstified rocks, KARSYS remains applicable but less fruitful. Idem for juvenile flow-systems which formed recently and which are not in equilibrium with the local base level. In that case, hydraulic principles admitted in KARSYS fail to describe the natural system. When applying KARSYS, the lack of geological data and of hydrological indications regarding karst springs (activity, mean discharge, etc.) are often the main limitations as well as the experience of the user.

Each step in the construction of KARSYS models may be validated by additional data or observations which have not been integrated in the construction process (results of dye tracing tests, cave data, etc.). The coherence of the geological 3D model may be tested by modeling the extension of the supposed phreatic zones. This often reveals a reliable test. It should be kept in mind that whatever the issues and the size of models, the resolution of KARSYS depends on the data with the lowest resolution – especially regarding geological data.

6. *KARSYS extensions*

The KARSYS approach provides an explicit conceptual 3D model of the karst aquifer and of the flow-system. This model already provides a clear image of the aquifer and of the flow-sytem but some specific issues may require additional information to be correctly addressed: the position of the conduits, details on the delineation of the catchment areas, assessment of the groundwater recharge, etc. Extensions have thus been developed on KARSYS to address such specific issues (Figure 6—1). They take into account additional data, concepts and models that are compatible with KARSYS (inception horizons, speleogenesis, etc.).

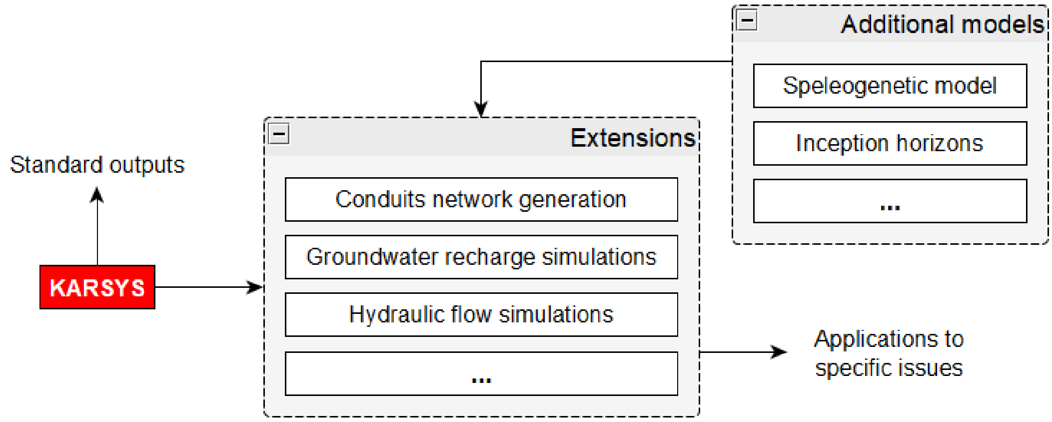


Figure 6—1. Examples of extensions to KARSYS; speleogenetic and inception-horizons models are presented in Filipponi et al. [2012]; they are not further discussed here.

The following sections focus on four extensions, which are mainly dedicated to flood-hazards assessment. Two extensions are presented in section 6.2: the **delineation of the flow-system catchment area** and the **generation of the low-flow karst-conduit network.** The two other extensions are presented in section 6.3: **hydrological simulation model** and **hydraulic simulation model.** As those chapters are long a summary of both sections is presented in section 6.1.

6.1. Summary

The aim of KARSYS extensions presented in chapters 6.2 and 6.3 was to characterize the hydrological (**recharge**) and the hydraulic (**flows**) functioning of the **Beuchire-Creugenat (BC)** and of the **Bonnefontaine-Voyeboeuf (BV)** flow-systems (JU, Switzerland) in order to be able to reproduce flood events.

The application of KARSYS presented in chapter 5 provided a description of the aquifer boundaries and of the **low-flow catchment areas** for BC and BV. The section 6.2 describes how the geometry of the low-flow conduit network draining the aquifer was generated. Characteristics of the generated conduit network were adjusted

for high-flow conditions in order to be compatible with **observed hydraulic relationships** between springs, caves and boreholes. Observed heads and discharge rates led to implement different thresholds, pipe narrowing and by-pass conduits into the conduit network. For instance, a long by-pass conduit (of about 2.5 km) with an average diameter of 3 meters was introduced downstream of Creugenat in the epiphreatic zone at 443 m of elevation.

Flood-peak simulation requires recharge to be modelled. The **RS3.0** simulation tool, developed for surface hydrology, was first used for this purpose. As the calibration was not optimal due to weaknesses in the computation of the evapotranspiration process, the alternative **KRM_1** tool was developed and applied instead. The calibration procedure implied to slightly enlarge the boundaries of the BV catchment area (southward and eastward, but still respecting geological constraints imposed by the KARSYS model) in order to reduce deviations between simulated and expected recharge. After these boundaries have been adjusted, simulation results with KRM_1 became consistent with the observed signal of BC and BV flow-systems and with supposed/observed values of RET, storage, etc.

The assessment of heads in the aquifer was necessary to assess flooding. This required flow hydraulics to be considered. Therefore, a pipe-flow model (SWMM) was used to simulate the hydraulics of flow through the generated conduit network. About 400 **distributed recharge files are used as inputs** for each of the discretized conduit branches. As lengths and geometries of the conduit network are fixed by the 3D model, the calibration procedure made it possible to **adjust diameters of the conduits**. Finally, simulation results show that **activation periods** of overflow springs and **discharge rates** of perennial and overflow springs are well reproduced as well as the variations of the hydraulic heads in different places of the systems. Simulations of the **flood event of August 2007** successfully reproduced the activation as well as the expected regime of the overflow springs while respecting the observed regimes for the other springs during this short period.

The application of these extensions to this case study shows that KARSYS can be integrated in the workflow for designing flow simulation models. Information and parameters provided by KARSYS (catchment areas, 3D model of the conduit network, etc.) can be directly transposed into recharge and hydraulic simulation models. Finally, the combination of KARSYS with recharge and/or hydraulic models proved to be really efficient for **addressing many issues in karst environments** such as flood-hazards as presented here or in published papers (Malard et al. [2014a], Jeannin et al. [2015a]).

6.2. Catchment delineation and conduit modelling based on the KARSYS approach (peer-reviewed paper, Hydrogeology journal 2015)

This section is made of the reproduction of a paper published in Hydrogeology Journal in June 2015. It shows how KARSYS was extended in order to delineate catchments areas according to characteristics of land-surface and how a conduit network could be generated in 3D through the whole aquifer. These two extensions are considered as a prerequisite for further flow simulations presented in section 6.3.

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An integrated approach for catchment delineation and conduit-network modeling in karst aquifers:

application to a site in the Swiss tabular Jura

Arnauld Malard & Pierre-Yves Jeannin & Jonathan Vouillamoz & Eric Weber

Abstract An essential issue in karst hydrology is the characterization of the hydrogeological flow systems, i.e., the delineation of catchment areas and the organization of the main flow paths (conduit network) feeding one or several outlets. The proposed approach provides an explicit way to sketch catchment areas, and to generate karst conduits on the basis of a three-dimensional (3D) conceptual model of the aquifer (KARSYS approach). The approach follows three main principles: (1) conduits develop according to the hydraulic gradient, which depends on the aquifer zonation, (2) conduits are guided by preferential guidance features (or inception horizons) prevailing in the unsaturated and saturated zones of the aquifer, and (3) conduits initiate on a regular basis below the autogenic zone of the catchment area. This approach was applied to a site in the Swiss Jura as a base for the assessment of flood-hazard risks. The resulting model proposes a new delineation of the system catchment area and appears fairer regarding hydrological measurements than previous interpretations, which under-estimated the catchment area by about 20 %. Furthermore, the proposed conduit network for the whole aquifer is also consistent with local cave surveys and dye-tracing observations. These interesting results demonstrate that the combination of this approach with the KARSYS 3D model provides an integrated and effective way for the characterization of karst-flow systems.

Keywords Karst · Conduits generation · Groundwater hydraulics · 3D model · Switzerland

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Introduction

Delineation of catchment areas and assessment of the conduit-network organization are essential for understanding and reproducing the hydrological functioning of karst-flow systems (Goldscheider and Drew 2007), for exploiting groundwater resources (Plagnes and Bakalowicz 2002), for delineating protection zones or mapping vulnerability (Doerfliger et al. 1999) or for preventing flood hazards (Maréchal et al. 2008). Catchment boundaries are required for assessing recharge processes while geometry and organization of the conduit network are required for explaining circulation or discharge processes. Consistent rules for the delineation of karst groundwater catchment areas and the generation of active conduit networks are then of great interest, especially for managers and stakeholders responsible for groundwater management, as well as for engineers searching for a pragmatic way to prevent or solve karst-related problems. Nevertheless, it should be observed that only a few methods have been proposed regarding spring catchment delineation and conduit-network modelling, and none of these really provides systematic guidelines which could be generalized.

Catchment delineations are usually mainly based on the interpretation of various investigation methods: tracer tests, hydrogram analysis and geophysics. Unfortunately such interpretations are often site-dependent, restricted to specific hydrological conditions, and could rarely be extrapolated or even reliably reproduced. Beside a series of artificial tracer tests, which ideally requires a high number of tests (not feasible in practice), no other method has proved to be effective for systematically delineating catchment and sub-catchment areas in karst regions (Käss 1998; Meiman et al. 2001). Consequently, catchment areas in karst regions are still very speculative and even poorly defined from a conceptual point of view.

Bonacci (1988, 1999) suggested a conceptual model for characterizing boundaries of catchment areas, as well as their variation depending on flow conditions, by defining general principles based on a structural approach. Unfortunately Bonacci did not formalize the way these boundaries should be assessed. Ginsberg and Palmer

(2002) wrote a series of original and pragmatic rules of thumb for estimating capture zones of karst springs, applicable to supply wells, based on systematic and "low-effort" principles of groundwater circulation, and inferred a conceptual model of karst aquifers which is applicable to all major systems of the Appalachian Plateau provinces. Their approach distinguishes systems devel- oped in a gently dipping (<5°) environment from those located in a steeply dipping (>5°) monocline environment. The approach also distinguishes dominantly fractured and bedded media. Even if this approach respects consistent geological and hydraulic assumptions, its application in thrusted and folded environments is questionable. Ginsberg and Palmer (2002) also mention mechanisms that are responsible for changing system boundaries under low/high flow conditions; unfortunately, they do not present a practical way to assess these variations. Recently, using 3D tools, Butscher and Huggenberger (2007) has offered a pragmatic approach for delineating spring catchment areas in mature, unconfined, shallow karst aquifers. The "aquifer base gradient" approach considers that groundwater flows toward the main spring depending on the topography of the aquifer basement. Even if this approach may be effective in shallow karst (Ford and Williams 2007), it does not consider the phreatic zone, which considerably restricts its applicabil- ity. In addition, no guidelines have been clearly delineated for a systematic application.

The assessment of the conduit-network geometry and organization is essential in karst. Indeed, White and White (2003), Worthington et al. (2000), and Jeannin (2001) demonstrated the significance of assessing conduit geom- etry in the phreatic and epiphreatic zones for reproducing the hydrology of karst flow systems. Nevertheless, it should be observed that in spite of a widespread theoretical consensus on the organization of the conduit's network, no real guidelines or tools exist in practice to model these networks.

Conceptual ideas about the genesis of karst conduit networks were summarized in the early 1970s in the "four state model" (Ford and Ewers 1978) and further devel- oped by Palmer (1991) and Worthington (1991). Two main approaches were used concerning the modelling (generation) of karst conduits: a deterministic (direct or inverse) and a statistic (or geostatistic) approach. The deterministic direct approach (e.g., Dreybrodt and Siemers 1997) includes a complete description of the physical processes governing the genesis of karst conduits (rela- tionships linking the distribution and characteristics of voids, of flow processes and of limestone dissolution processes). Such models showed the positive feedback existing between voids, flow and dissolution, and the way hydraulic gradients change along the karstification pro- cess. They also evidenced the initial slow development of karstification until the breakthrough of turbulent flow throughout the flow system and the (geologically) "short time" required to form large conduits after the break- through. This approach was very useful for the under- standing of theoretical processes, but is hardly applicable in practice because it requires a huge amount of data to parameterize the models and needs long computation time (Jaquet et al. 2004).

On the other hand, in inverse approaches, an attempt is made to infer characteristics of karst conduits from the system's global (spring) response (hydraulic or chemical) using more or less deterministic interpretation models. These were introduced by Mangin (1984) who defined very global characteristics, e.g., "well karstified" or "poorly karstified", terms which were neither well physically defined, nor really applicable. Various interpre- tation models have been proposed based on hydrograms, chemograms and isotope records using times-series analyses, principal component analysis (PCA) or spectral analyses (Aquilina et al. 2006; Lakey and Krothe 1996, etc.). For example, Grasso et al. (2003) intended to infer the dimensions of the flooded-conduit network ("karstification index") by expressing the ratio (carbonate concentration)/(flow rate) as a quantitative indicator of the length of the flooded conduits where the water came through. Kovács (2003a, b) proposed to infer the karst hydraulic parameters by comparing spring recession hydrograms with analytic formulae deduced from numer- ical models of simplified conceptual models of karst systems. Recently, Mayaud et al. (2014) proposed to elucidate the hydrological functioning in thresholds of an Austrian karst site by applying time-series analyses on the spring's signal and by establishing a finite elements simulation model in order to interpret hydrological analogies as physical properties of the conduits. Even if these methods are still widely applied (Bonacci 1995; Jeannin 1992) most of them remain very "global" and in most cases do not provide any clear spatial idea of the karst flow system.

Geostatistical approaches have been developed as an alternative to these non-spatialized methods. They provide probability fields showing where the conduits are sup- posed to develop. They are based on the relationships linking geometric characteristics of the conduits (orienta- tion, segmentation, connectivity, etc.) with other parame- ters (fractures, bedding planes, hydraulic gradient, outlet positions, etc.), according to statistical rules. In this field, various statistical methods were tested (Jeannin 1996) such as simple statistical approaches, cross methods or random walk methods (Jaquet 1995). In the last decade, the stochastic approach has developed substantially (Henrion 2011; Collon-Drouaillet et al. 2012; Pardo- Igúzquiza et al. 2012; Borghi 2013), and is based on the probabilistic interpolation of spatially distributed vari- ables. Conduits are generated according to a discrete fracture network where additional properties may be associated with each fracture set. A multitude of possible conduit models are generated based on the same initial set of conditions, which provides a view of the supposed spatial distribution of karst conduits; however, because stochastic simulation processes are based on geostatistical laws, and on simplified hypotheses and characteristics of the karst medium, the simulated models often fail to become integrated in the real geological context (Henrion

2011). In other cases, the generated conduit network can hardly be constrained by reasonable data and by general characteristics of karst conduit networks (e.g., Borghi 2013). Nowadays, knowing this limitation, hybrid approaches, combining deterministic and stochastic approaches, are performed.

Experimental approaches in the field should also be mentioned as alternatives to the deterministic and statistical approaches as they intend to infer the characteristics of the conduit network (connectivity, thresholds, bypasses, and conduit size) by performing a series of artificial in-situ tracer tests in order to characterize the flow system under various hydrological conditions. Smart (1988), Goldscheider et al. (2008) and Lauber et al. (2014) are the main authors promoting this approach. The stochastic approach is effective as it may provide the characteristics of the conduit network (geometry, size, tributaries, etc.) but it requires (1) access to the caves and (2) performance of long and repeated tests in order to distinguish parameters related to the physical properties of the conduits from those related to hydrological conditions.

Catchment delineation in karst and conduit-network modeling are, thus, usually conducted in a separate way. The aim of the present paper is to present an approach providing an explicit delineation of the catchment area(s) of a karst hydrogeological system, as well as a karst conduit network, whereby everything is consistent with each other and with the hydrogeological setting. Very few authors have tried to combine these parameters at the scale of a system. Among the previous authors, Borghi (2013) developed a geostatistical approach which is close to the approach presented here; however, it does not properly addresses the development of a conduit network below areas of diffuse recharge, and some aspects of his approach are too complex (too detailed) to be considered pragmatic or applicable to other sites. In the framework of the Swisskarst project (2010–2013), a pragmatic and systematic 3D-based approach called KARSYS (Jeannin et al. 2013; Malard et al. 2014) was developed for the characterization of karst aquifers. The approach, mainly developed for Switzerland, aims to, among other out- comes, explicitly define a conceptual 3D model of karst aquifers and systems. This model is a prerequisite for the here-proposed approach regarding catchment delineation and karst conduit modeling.

Study site

Geological context

The study site is located in the tabular part of the Jura in northwestern Switzerland, upstream from the town of Porrentruy (Fig. 1). A detailed geological, geomorphological and hydrogeological description of the site is given by Grétillat (1998) and Kovács and Jeannin (2003). The surrounding landscape shows low-elevated plateaus (~500 m a.s.l) crisscrossed by numerous dendritic valleys which are dry or active only in very high water conditions, indicating that most of the drainage is performed by efficient underground karst-flow systems. The geological context is characterized by a succession of NS and NW–SE normal faults, leading to a structuration of the karst aquifer in horsts and grabens (Kovács and Jeannin 2003). The main aquifers develop in the Jurassic limestone interbedded by thin layers of marls. Astartes marls (~30 m thick) act as the first aquitard. A second lower aquitard is formed by the lower Oxfordian marls with a thickness exceeding 80 m (Laubscher 1963). Pterocera and Exogyra Virgula marls can be considered as local aquitards as they are only a few meters thick.

Hydrological functioning

The Beuchire-Creugenat (BC) karst system represents a recurrent risk of flooding for Porrentruy as evidenced by serious inundation reports in the past. The flood event of 1 August 1804 is the largest known report of a flashy karst inundation with associated discharges reaching the order of 100 m^3/s. The Beuchire spring (B), emerging in the city, is considered to be the baseflow spring of the Jurassic karst aquifer. Its annual mean discharge is about 800 L/s and it may discharge up to 3.5 m^3/s. The Creugenat overflow spring (C) lies upstream of the city and activates only for high flows (13 times per year on average between 2002 and 2010). It usually discharges ~10 m^3/s, but it may exceed 30 m^3/s for an extreme event (Grétillat 1996). Upstream from Creugenat, the Creux-des-Prés (CdP) is a second overflow spring which may discharge ~1–4 m^3/s every ~30 years on average (no real measurements). Karst conduits of the C cave extend for at least 1.5 km (Gigon and Wenger 1986). Passages were surveyed by cave- divers but the downstream connection with the B spring and the upstream connection with the CdP have not been established yet. The Bonnefontaine-Voyeboeuf (BV) karst system is located south of Porrentruy. Voyeboeuf (V) is a baseflow spring, while Bonnefontaine (Bf) may be seen as an overflow spring even if it is active all year. Each spring may discharge up to 3–4 m^3/s under usual high-flow. The characteristics of the springs are displayed in Table 1.

Despite numerous hydrological studies carried out for a long time (Lièvre 1915; Schweizer 1970; Grétillat 1998 and Kovács 2003a, b), flow modalities as well as relationships between permanent and overflow springs of these two systems are not completely understood. Based on geomorphology, structural observations and tracer tests, the BC and BV catchment areas have been delineated by Grétillat (1998) and are displayed in Fig. 2.

Schweizer (1970) suggested a hydrological connection linking the BC and the BV karst systems based on a tracer test injected within the supposed BV catchment area but apparently reaching the B spring for low-flow conditions. As the tracer recovery is questionable, this connection remains hypothetical. Anyway, under high-flow conditions, variations of the hydraulic heads seem to rise by about 30 m and to activate overflow conduits, diverting flows from one system to the other. Later, Grétillat (1998) demonstrated a connection with the Dou spring system located in the western part of the area.

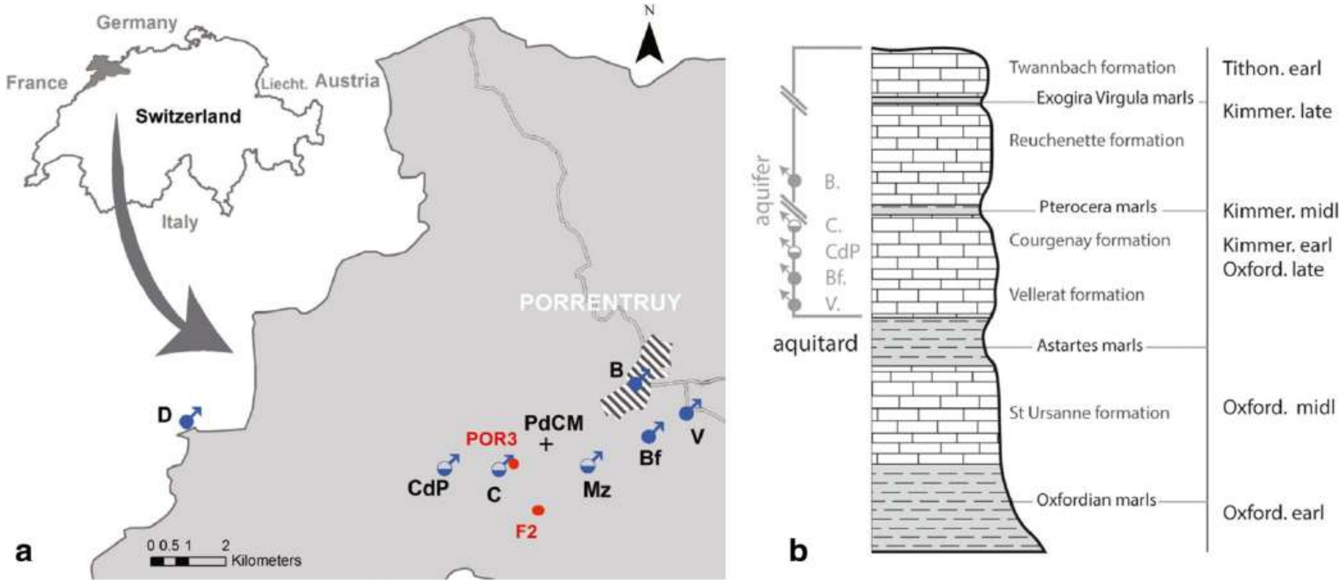

Fig. 1 **a** Overview of the study site and location of the investigated permanent springs: B Beuchire , V Voyeboeuf, Bf Bonnefontaine , D La Doue; temporary springs: C Creugenat, CdP Creux-des-Près and Mz Mavaloz ; collapsed cave (PdCm), boreholes (POR3, F2) and **b** main geological formations of the Jurassic aquifer

Approach

The proposed approach has three steps: (1) application of the KARSYS approach, (2) delineation of the catchment area and (3) generation of the karst conduit network.

The KARSYS 3D conceptual model

The application of KARSYS provides an explicit 3D conceptual model of the aquifer: delineation of the unsaturated (vadose) and saturated zones, characterization of the underground flow paths and assessment of the respective recharge area under low-flow conditions. Principles of KARSYS are described in Jeannin et al. (2013) and Malard et al. (2014) and are not repeated in detail here. KARSYS combines four standard steps: (1) identification of aquifer and aquitard formations, (2) establishment of a geological three-dimensional (3D) model of the aquifer, (3) integration of hydrological data into the 3D model and aquifer zonation, (4) sketch of the hydrogeological 3D model (karst flow systems).

Based on the geometry of the aquifer basement(s), on the delineation of the saturated zone(s) and on the location of the low-flow outlets (springs), the hydrogeological model is set up through the three following sub-steps: (1) the sketch of the main vadose and phreatic flow paths, (2) the delineation of the "underground flow system", i.e., the part of the aquifer that flows toward the system outlets

Table 1 Description of the main karst hydrological features of the site, coordinates X and Y (Swiss grid LV CH1903) and elevation

Spring name	Abbreviation	Type	X (m)	Y (m)	Elevation (m a.s.l)
Beuchire	B	Base-flow spring	572,590	251,860	Outlet: 423
Creugenat	C	Cave/overflow spring	568,950	249,575	Cave entrance: 451 Bottom: 436 Low-water level: 438
Creux des Prés	CdP	Cave/overflow spring	567,500	249,600	Cave entrance: 465 Bottom: 444 Low-water level: 444
Champs Montant	CM	Collapsed cave	570,213	250,253	Cave entrance: 443 Bottom: 436 Low-water level: dry
POR 3	P3	Borehole	569,345	249,730	Top: 450 Bottom: 431 Low-water level: dry
Voyeboeuf	V	Base-flow spring	573,950	251,070	Outlet: 439
Bonnefontaine	Bf	Permanent and overflow spring	572,950	250,450	Outlet: 439
Mavaloz	Mz	Emissive cave/overflow spring	571,325	249,675	Cave entrance: 471 Bottom: 443 Low-water level: 443
F2	F2	Borehole (150 m)	570,030	248,492	Top: 512.5 Bottom: 362.5 Low-water level: 450.5

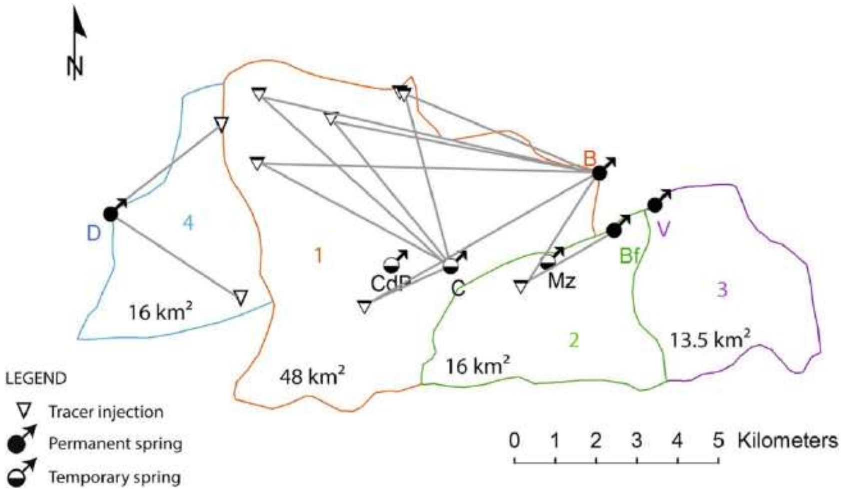

Fig. 2 Existing catchment delineation of the Beuchire-Creugenat (1), the Bonnefontaine (2), the Voyeboeuf (3) and La Dou (4) karst systems proposed by Grétillat (1998). Gretillat considers that Bonnefontaine and Voyeboeuf are two separate systems

and, (3) the delineation of the catchment area, i.e., the part of the ground surface feeding the underground flow system, including allogenic sources.

Delineation of the underground flow system and the catchment area

The underground flow system is defined as the part of the aquifer (saturated and vadose zones) which is drained towards one spring or a group of springs. Boundaries are obtained by contouring the volume of rock that is expected to feed the spring(s). Parts of the phreatic zone feeding the spring(s) are first evaluated, and then extrapolated further upstream through the vadose zone. These parts are merged and provide the boundaries of the whole underground flow system for a given hydrological condition (low flow first).

The catchment area of a karst system is defined as parts of the ground surface from where the entire or part of the diffuse and concentrated recharge is driven to the permanent or temporary outlet(s) of the system. Unlike catchment areas in surface hydrology, parts of the karst catchment area can only partially feed the karst flow system (e.g., because one part may run off at land-surface or because underground flows may be diverted towards two or more systems depending on flow conditions). Consequently, one piece of land can be common to several systems. Therefore, one catchment area may enclose three types of surfaces: (1) karst surfaces (K, “autogenic”) where the water is assumed to percolate vertically through the soil and the vadose zone, (2) non-karst surfaces (NK, “allogenic”) from which the runoff may be discharged to autogenic zones where it infiltrates, and (3) covered-karst surfaces (CK) where only a part of the runoff infiltrates, while the other part may be diverted outside of the catchment. Principles of catchment delineation are presented in Fig. 3. If the downstream end of the non-karst surface drainage network lies within the boundaries of the underground flow system, the NK sub-catchment is considered to belong to the catchment area. On the other hand, non-karst surfaces which are drained outside of the boundaries of the underground flow system are excluded, which provides a delineation of the non-karst (allogenic) catchment. CK zones located outside of the borders of the underground flow system but having their runoff reaching a downstream K surface located within the perimeter of the underground flow system are inscribed within the catchment. As these zones also infiltrate upstream of the system catchment area, they may also be inscribed in the catchment area of another karst system. Such sub-catchments are classified as “divergent” since the water may feed several systems.

As a prerequisite, a map of land-surface properties has to be drawn. This must at least distinguish the following categories: karst (K) where infiltration reaches nearly 100 % under low to middle-flow conditions; covered karst (CK) where infiltration is of a same order of magnitude as surface runoff; and non-karst (NK) where the runoff is close to 100 %.

Generation of the karst conduit network

Principles

The proposed process for conduit modelling does not aim to model the whole conduit network, often resulting from complex and multiphase speleogenetic processes; it only sketches the expected conduits that are required to drain the groundwater according to actual low- to moderate-flow conditions. It is based on two general principles: (1) conduits develop according to the hydraulic gradient, which depends on the aquifer zonation, and (2) conduits are guided by preferential guidance features (or inception horizons, Filipponi et al. 2009).

The hydraulic gradient in the vadose zone is vertical, i.e., conduits mainly develop vertically. The guidance effect of inception horizons is weak excepting for vertical or highly inclined features (faults, vertical beddings, etc.).

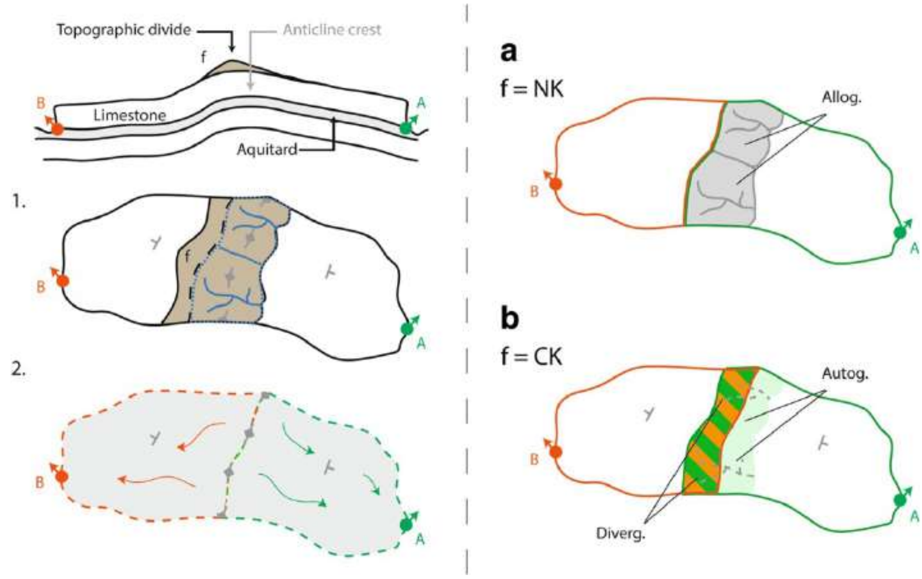

Fig. 3 Principles of spring catchment delineation: Principle (1) springs A and B emerge on both extremities of the limestone plateau. Stream networks develop on the surficial formation "f" and flow toward the A spring. Principle (2): the underground flow systems A and B are separated by the anticline crest which does not match the topographic divide. Principle (3a): if "f" is impervious (NK), stream catchments are considered as allogenic and are inscribed within the catchment area of the A spring. Principle (3b): if "f" is a semi-pervious formation (CK), stream catchments are divided according to the delineation of the underground flow systems. Parts of the CK sub- catchments, which are inscribed within the boundaries of the A underground flow system belong to the catchment area of the A spring; parts of the CK sub-catchment located upstream but outside of the A underground flow system are considered as divergent as they may feed both A and B systems.

The so-called "vertically controlled vadose conduits" end by either reaching the phreatic zone or the top of the aquifer basement (aquitard). Vertical conduits reaching the aquifer basement develop down-dip until reaching the phreatic zone (so-called "basement-controlled vadose conduits"). The main guiding feature is the top of the impervious layer, but inception features such as fractures, may divert the conduit development apart from the down- dip direction. Such diversion is supposed to develop for a few tens of meters, possibly one or two hundred. In general, at the scale of the system, such diversion of the flows would be considered as negligible.

In the phreatic zone, conduit development is also controlled by the hydraulic gradient, which is mainly conditioned by the position and elevation of the spring or of an underground threshold. Conduits are assumed to develop more or less horizontally and close to the top of the saturated zone. Phreatic conduits may develop loops with an extension reaching tens to hundreds of meters (Gabrovšek et al. 2014); this is not yet considered in the presented model. Phreatic conduits are assumed to start from all significant input points into the phreatic zone, i.e., from the downstream end of a vadose conduit (vertically or basement controlled). From these points, phreatic conduits develop and organize according to the "least hydraulic resistance" principle towards the outlet. In this zone, the guidance effect of inception horizons (e.g., bedding planes) is more pronounced than in the vadose zones. If inception horizons (bedding planes or fractures) do not directly link the input to the output point, conduits may divert from the shortest pathway by several hundreds of meters or even kilometers. At the scale of the aquifer, such influence may be of relative great importance.

In many cases, conduits in the epiphreatic zone result from a paleo-phase of karstification when geological or geographic conditions were different. In practice, paleo-conditions could be considered and integrated in the present model by iterating different models that reflect the successive paleo-conditions. It is however not discussed here.

The conduit development in the epikarst zone may be considered somehow as similar to that of the vadose and phreatic zones because epikarst entails a vadose zone on top of a saturated one. The scale is different, rather in the range of decameters than in kilometers. Here also, the guidance effect of inception horizons may be more pronounced in the saturated zone than in the vadose zone. Modeling conduits in the epikarst does not appear to be relevant at the scale of the whole flow system; thus, it will not be further discussed.

The approach assumes that the guidance effect of inception horizons is related to their "efficiency" (projection of the regional hydraulic gradient vector on the inception horizon planes). The Table 2 summarizes general principles regarding hydraulic and guidance effects.

Vadose conduits are modelled first as they are completely defined by infiltration nodes at ground surface and by the shape of the aquifer basement. Then, the downstream ends of the generated vadose conduits can be used as upstream ends of conduits of the phreatic zone. Springs are usually considered as the downstream ends of the phreatic conduits. Figure 4 shows the principles of the

Table 2 Considerations about the conduit generation in the different zones of the aquifer (hydraulic control and guidance)

Aquifer zone	Hydraulic gradient	Modeling principle	Main guidance effects (inception horizons)
Epikarst (vadose zone)	Vertical, maximum	Conduits develop vertically	Vertical features
Epikarst (saturated)	Sub-horizontal, low	Conduits develop and organize following the "least hydraulic resistance" principle	Sub-horizontal and vertical features
Vadose (vertically controlled)	Vertical, maximum	Conduits develop vertically	Vertical features
Vadose (basement controlled)	Vertical, projection moderate to high	Conduits develop and organize down the slope of the aquifer basement	Vertical features
Epiphreatic, phreatic	Sub-horizontal, low to high	Conduits develop and organize following the "least hydraulic Resistance" principle	Sub-horizontal and vertical features

conduit-network generation, which entails four main sub-models which are detailed in the following.

Infiltration (or capture) points and vertically controlled conduits

The infiltration sub-model is based on the following assumptions: (1) infiltration exclusively occurs in autogenic parts of the catchment area (K and CK terranes) and, (2) non-karst terranes (NK) are assumed to feed the karst aquifer by sinking into a karst (K) or covered-karst (CK) terrane in their downstream section (even though no visible sinking stream is documented). Autogenic zones of the catchment area are discretized in regular cells reflecting the infiltration density. Experience and cave observations in Switzerland provided estimates of the drainage density below the epikarst; the expected value is one vertical pitch every 20–50 m draining the epikarst. These pitches are expected to converge within the first 30–50 m below the epikarst (Filipponi et al. 2012). At greater depth in the vadose zone, the density is probably in the range of one pitch every 100–200 m. The expected density of the vertical conduits in the vadose zone fixes the size of the autogenic cells. Each autogenic cell provides one vertically controlled vadose conduit which is a priori randomly distributed inside the cell. If visible karst features are identified in the cell (doline, sinking stream, etc.), the infiltration node in this cell is snapped on the closest one. Then allogenic sub-catchments are linked to autogenic cells where the allogenic outlet reaches the K or CK cell. Vertically controlled vadose conduits are generated from each infiltration node down to the top of the aquifer basement or the top of the saturated zone. Such intersections are called "pitch base node" (PbN).

Basement-controlled vadose conduits

The development of the basement-controlled vadose conduits is guided by the topography of the aquifer basement and obtained using some utilities of the geographic information system (GIS) Toolbox Arc Hydro (ESRI) and stand-alone scripts. The generation starts from the PbN and/or from outlets of existing perched groundwater bodies above the main phreatic zone (i.e., the outlet node, Fig. 4). Basement- controlled vadose conduits

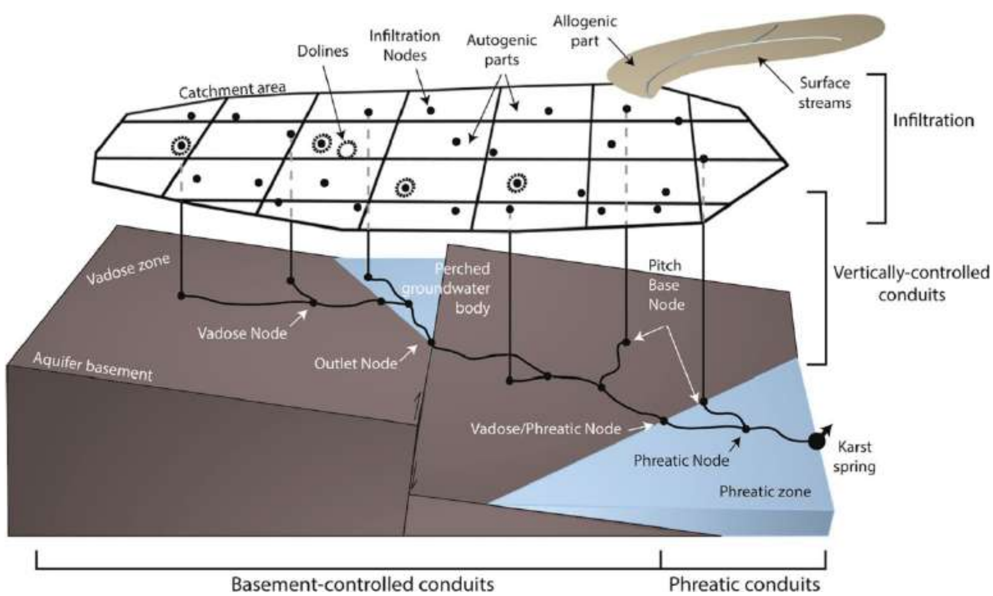

Fig. 4 Principles of the karst conduit network generator. The model is divided into four parts: the infiltration sub-model, the vertically controlled conduits sub-model, the basement-controlled conduits sub-model, and the phreatic conduits sub-model. Depending on the issue and the system, additional sub-models may be integrated to complete the network: epikarst, inception, and speleogenetic

develop down-dip until reaching the phreatic zone or the outlet of the system for “free draining systems” (Ford and Williams 2007, p. 122). Locations where vadose flow paths reach the phreatic zone of the aquifer are designed as “vadose/phreatic nodes” (VPN). These points are considered as major input points for the generation of the conduits in the phreatic zone. When VPN are processed, they integrate the size of the upstream drained area (including allogenic ones) as a weighting factor, which makes it possible to influence the organization of the phreatic conduits according to the significance of the upstream vadose conduits.

Phreatic conduits

The construction of the main supposed phreatic conduits depends first on the geometry of the saturated part of the aquifer. Then the process looks for the “least hydraulic resistance” flow path, i.e., the shortest network of conduits linking all VPNs to the main permanent karst spring. As the development of the phreatic conduits may be strongly influenced by inception horizons (Table 2), these are taken into account. The organization of the phreatic network is further influenced by the respective significance of the conduit upstream of each VPN, depending on their respective drainage areas. It is assumed that conduits developing from a VPN draining a significant recharge area developed first, with larger-sized conduits, attracting the branching of the nearby phreatic conduits towards the main drainage axes. Drainage is then organized towards these main conduits, forming a network of a lower order. The principles applied for the generation of the phreatic conduits are based on the combination of four parameters (Fig. 5): (1) the delineation of the phreatic zone in which the conduits develop, (2) the location of the outlet (spring zones or underground threshold) and the intensity of the hydraulic gradient; (3) the location of the inlet points (VPNs and PbNs) and their respective weight; (4) the intersection lines of the inception horizons with the top of the phreatic zone. Intersections are obtained from the KARSYS 3D model.A relative weighting factor is attributed to three of these parameters: O (outlet position and strength of the hydraulic gradient), I (significance of the input points VPN+PbN) and F (guidance effect of the inception horizons), which can be adjusted from 1 (low weight) to 10 (high weight). Considering the boundary conditions, these parameters are combined into a unique “least hydraulic resistance” grid. Once the grid is defined, the “least hydraulic resistance” paths are computed linking VPN and PbN to the main outlet.

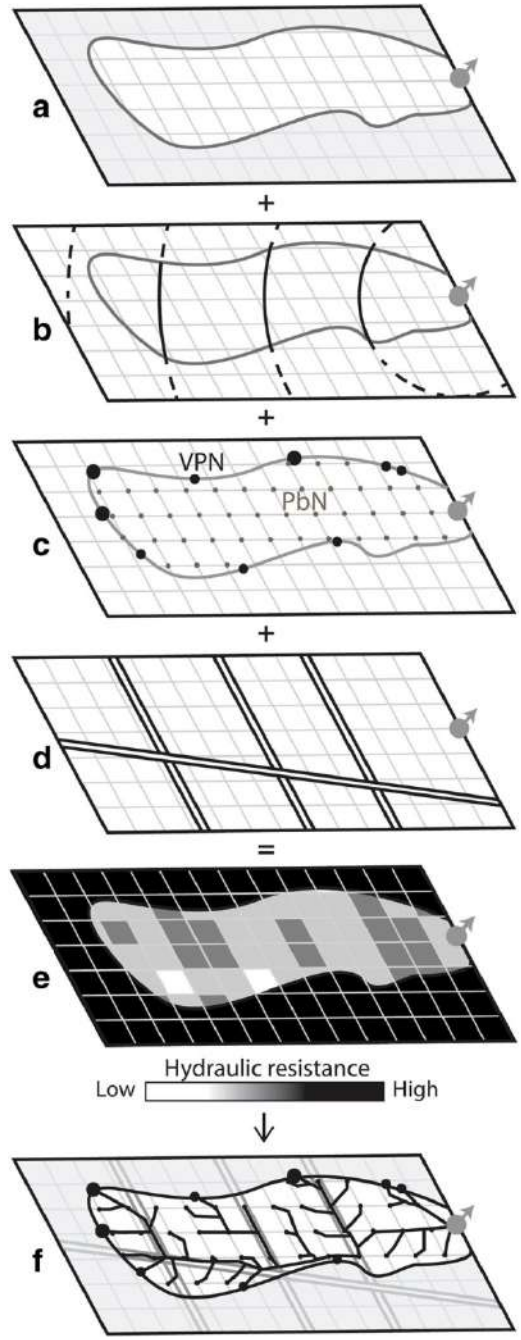

Fig. 5 Parameters controlling the development of phreatic conduits: **a** extension of the phreatic zone; **b** mimic of the radial hydraulic gradient to the main spring (orientation and intensity, O); **c** vadose inputs (VPNs and PbNs) and their respective weight (I); **d** intersection of inception features with the top of the phreatic zone and their relative significance (F); **e** combination of a, b, c and d parameters into a unique “least hydraulic resistance” grid. The flow paths, linking VPNs and PbNs to the main outlet of the phreatic zone, can thus be calculated (**f**)

Application to the test site

BC and BV KARSYS 3D model

The 3D geological model (Fig. 6) is built using the geological information from previous studies (mainly Grétillat 1996; Laubscher 1963 and Kovács and Jeannin 2003) and established with Geomodeller (release 2013). Some non-karst formations have been simplified to exclusively focus on the aquifer units (Kimmeridgian and Tithonian limestone). Astartes marls are here considered as the main aquitard forming

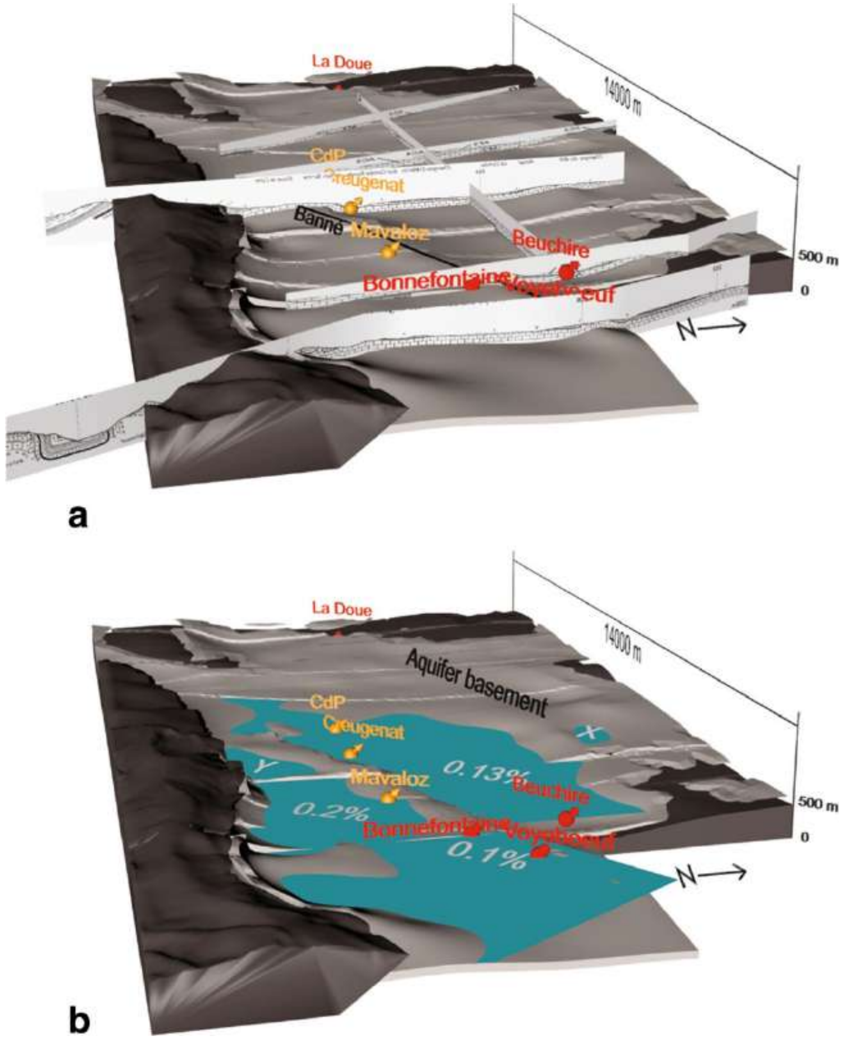

Fig. 6 a Perspective view of the 3D geological model of the aquifer basement; the model shows a series of horsts and grabens along a NS axis. A NW–SE anticline (Banné) crosses the model. b Delineation of the BC and the BV saturated zones and their respective maximum hydraulic gradients for low-flow conditions; the Creugenat, the Creux-des-Prés (CdP) and the Mavaloz overflow springs (in orange) are not active at low-water conditions

the bottom of the aquifer although water exchanges with the lower layer have been demonstrated (Kovács 2003a). Pteroceras and Exogyra Virgula marls are not considered as impervious at the regional scale and were not computed; however, it must be kept in mind that locally they could influence the flow direction. Major faults were introduced into the model as long as they shift the aquifer basement (especially SW–NE and NS faults), whereas minor faults were not introduced. The resulting mesh has a resolution of 50×50 m in the XY axis and 25 m in the Z axis. Even if the precision of the model is heterogeneous due to unequal data density and decreases from land surface to depth, it is assumed that hydrological features at the scale of the system may be inferred from this model. Usually, during the construction process, if geological informa- tion may contradict each other, the most recent ones are considered as valid unless other arguments exist. The hydrological 3D model is computed based on the position of the main permanent springs (Fig. 6) and the assessment of the hydraulic gradient fixed by additional hydrological features (boreholes and caves). Hydraulic gradients in the BC and BV systems are discussed separately.

Beuchire-Creugenat (BC) karst system

The elevation of the water table is set at the aquifer's downstream end according to the elevation of the B spring (423 m a.s.l). In the upstream direction, the water table clearly remains below the bottom of Champ-Montant pit (436 m a.s.l) and below the POR3 borehole (431 m a.s.l), as both are dry under low-flow conditions. As a result, the inclination of the hydraulic gradient is less than 0.13 %. The water level in the C spring, which is located less than 500 m upstream of the POR3 borehole, stands at 438 m a.s.l. As the apparent gradient between these two stations rises up to 2.3 %, the hydraulic continuity of the saturated zone cannot be assumed; therefore, a threshold at 438 m is supposed to disconnect C from the lower active phreatic conduits. It may result from a NS fault which shifts the aquifer layers between these two stations; thus, assuming a 0.13 % gradient, the geometry of the saturated zone feeding the system can be extrapolated across the aquifer until reaching the basement (Fig. 6).

Upstream from the Creugenat, the CdP cave (elevation ~465 m a.s.l) provides another access to flooded conduits (Gigon and Wenger 1986) lying at 444 m a.s.l for low- flow conditions. As the distance between the upstream passage of the Creugenat and the entrance of the CdP is roughly 600 m, the calculated hydraulic gradient exceeds 1.3 %, which also suggests the presence of a threshold at 444 m a.s.l., probably related to a minor fault which is not visible in the model. This hypothesis is supported by the fact that waterfalls are observed along the underground stream in the CdP cave; thus, hydraulic disconnections are frequent. It must also be mentioned that uncertainties in the cave surveys may lead to a few meters of difference compared to the real elevations. Two secondary ground- water bodies were identified, "X" and "Y". Their existences are not yet proven and may be the result of artefacts or imprecisions in the geological model; howev- er, nothing contradicts their presence. Obviously, accord- ing to the 3D model, they must overflow toward the BC flow system. Their outlet will be used to initiate the conduit-network generation.

Bonnefontaine-Voyeboeuf (BV) karst system

Both Bf and V springs are located at a comparable elevation (439 m a.s.l). Discharge measurements of these springs (2001–2004) and common oscillations due to withdrawals from a pumping well for the next community evidence a hydraulic connection at low flow (ISSKA 2010). The hydraulic gradient between them remains lower than 0.1 %. In the upstream portion of the aquifer, the hydraulic gradient is given by the emissive cave of Mavaloz in which the terminal sump lies at the elevation of 443 m and never dries up. This gives an indication of the maximum hydraulic gradient upstream from the Bf spring: 0.2 %. This gradient is rather high, and could be related to a threshold(s) between these two points. In the most upstream portion of the aquifer, the hydraulic gradient is assessed from measurements in F2 borehole as it is connected to the karst network. The water table lies at 450.5 m a.s.l., giving a gradient of 0.38 % upstream from the Mz cave. This high gradient also strongly suggests a threshold(s) between Mz and F2, which disconnects the groundwater, probably along a N–S fault. Continuous head measurements in F2 would make it possible to confirm or not the presence of a threshold, but were not carried out. As evidence for thresholds is not clearly established, the value of 0.2 % was considered in the model to sketch the shape of the phreatic zone in the whole area.

The resulting picture of both BC and BV systems includes two major groundwater bodies (basal phreatic zones of BV and BC) and two minor ones (X and Y) for low-flow conditions. Their extents are shown in Fig. 6.

BC and BV catchment delineation

The main flow paths of the BC and BV systems may be sketched in the 3D model. Vadose flow paths are based on the topography of the aquifer basement while phreatic flow paths draw the shortest mutual way to the main perennial spring. Most parts of the vadose zone are drained toward the phreatic zone which feeds the B, C and CdP springs. Bf and V springs drain only the south-eastern part of the aquifer area while the western part is supposed to be drained towards France. This may contribute to partially feed La Doue spring which emerges from the lower aquifer (Fig. 7). The two systems are separated by Le Banné anticline along which the aquifer basement emerges. BC and BV underground flow systems can be drawn accordingly. The process of catchment delineation for BC and BV karst systems is displayed in Fig. 8 and the characteristics are provided in Table 3.

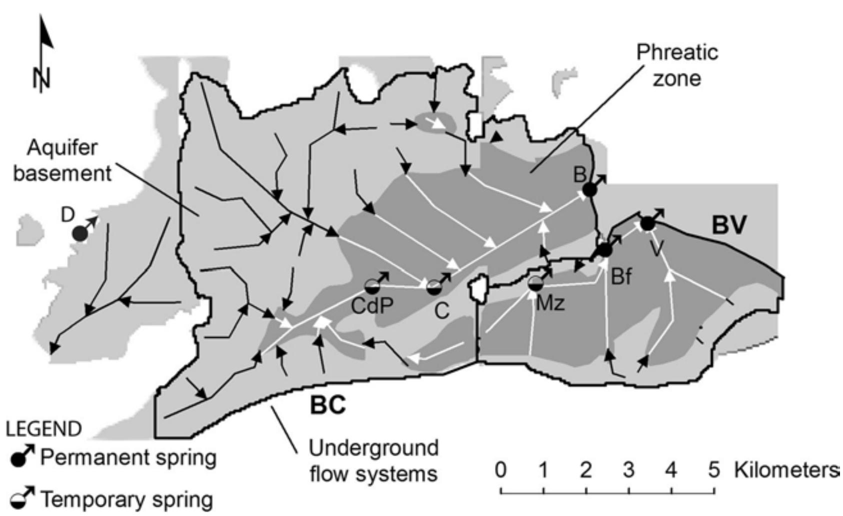

Fig. 7 Sketch of the main supposed vadose (black arrows) and phreatic (white arrows) flow paths of the BC and BV karst systems and delineation of the underground flow systems by assembling all vadose parts feeding the saturated zones drained by the springs

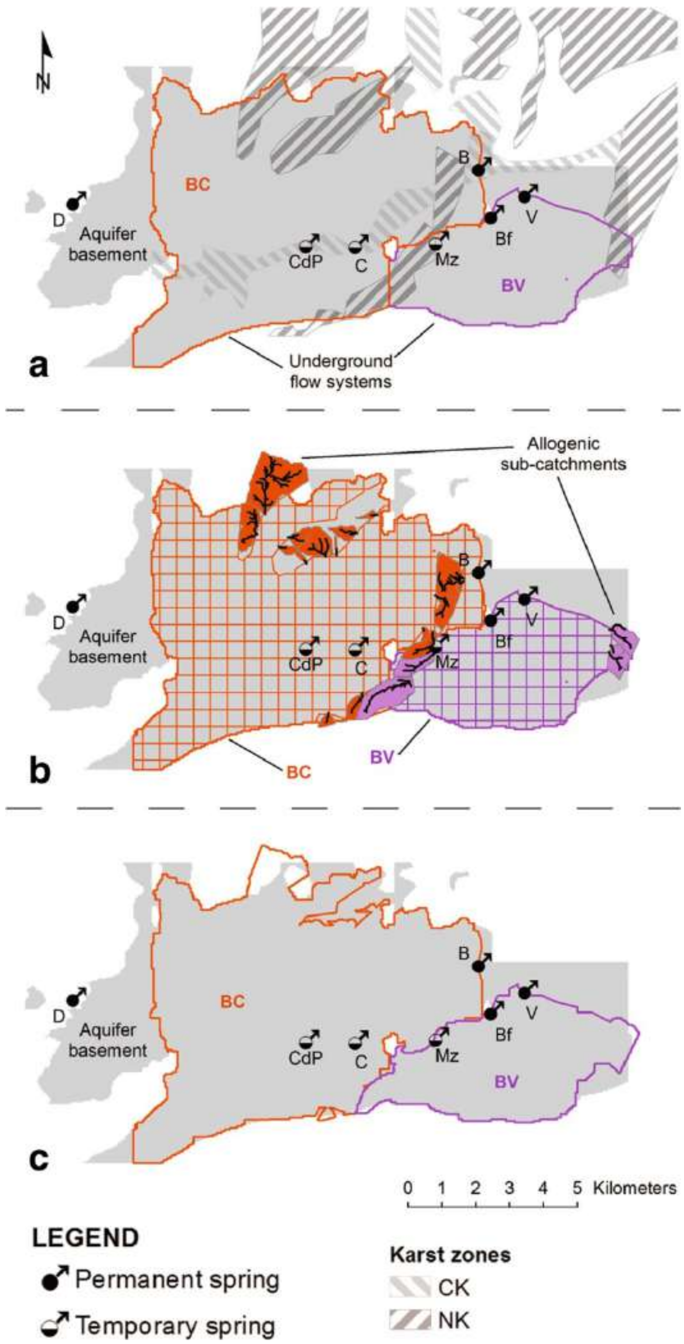

Fig. 8 Delineation process of catchment areas of the BC and BV karst systems: **a** NK and CK surfaces are compared to the extension of the underground BC and BV flow systems. **b** Surface streams are computed on NK surfaces. In the case where these allogenic streams contribute to the underground flow system, the allogenic sub-catchment is integrated within the boundaries of the catchment areas. In the case where the allogenic streams divert outside of the underground flow system, the allogenic sub-catchment is removed from the catchment areas. CK surfaces are considered as the autogenic ones, with a direct infiltration. Orange allogenic catchments belong to the BC catchment while the purple allogenic catchments belong to the BV catchment. **c** Low-water delineation of the catchment areas of the two karst systems including the allogenic zones

Table 3 Characteristics of the BC and BV karst systems under low-flow conditions; for both systems, allogenic parts represent more than 10 % of the total catchment area

Karst system	Underground flow system (km^2)	Catchment area (autog. + allog.) (km^2)	Autogenic parts (km^2)	Allogenic parts (km^2)
Beuchire-Creugenat	58	57	50.5	6.5
Bonnefontaine-Voyeboeuf	19	19	16.5	2.5

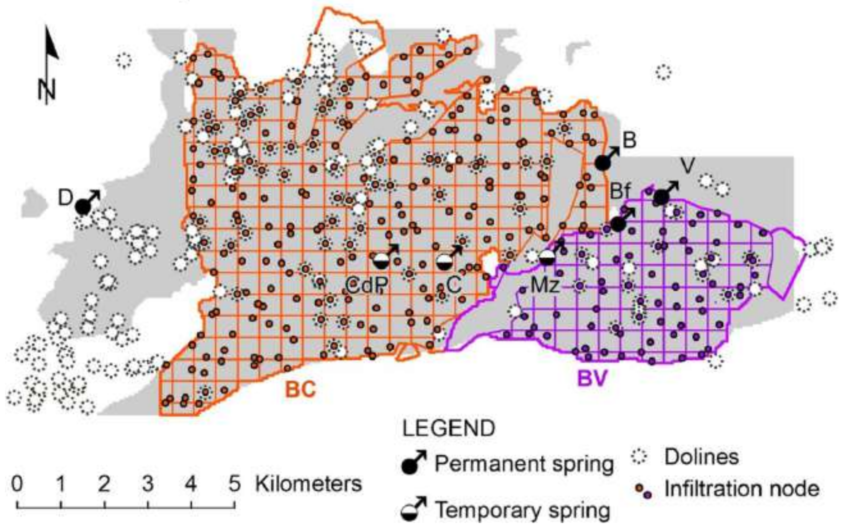

Fig. 9 Model of the distributed infiltration nodes in autogenic zones of the BC and BV karst systems; infiltration nodes are snapped to existing infiltration features within the cell (e.g., dolines) and randomly distributed where no infiltration features are known

BC and BV conduit-network model

In this paper, mainly because of representation problems due to the scale, the drainage density is assumed to be one vertical shaft every 500 m. The autogenic part of the catchment area is therefore subdivided into cells of 500 × 500 m. Infiltration nodes are computed based on the position of the cells and the observed infiltration features. It is assumed that each cell forms a main vertical conduit draining the area of the cell. The resulting infiltration model is displayed in Fig. 9.On the basis of the infiltration sub-model, the basement-controlled vadose conduits are generated for the BC and BV karst systems (Fig. 10) according to the shape of the top of the aquitard.

The BC karst system shows an extended vadose area and presumably numerous developed underground streams with significant discharge rates. For example, according to local values of specific discharge rate in this region (15–30 L/s/km^2, ISSKA 2013), the longest vadose conduit in the north-western part, reaching 5–6 km in length, should have an average discharge rate higher than 300 L/s. On the other hand, the BV karst system does not display long vadose conduits, as the saturated part extends almost below the whole catchment area.

Regarding the phreatic conduits, a relatively weak resistance was attached to the F parameter as it was observed that the existing phreatic caves (Creugenat and CdP) are strongly developed along faults. Application of these parameter weights to the BC and BV karst systems generated the phreatic conduit network given in Fig. 11.

Regarding the BC flow system, the generated network mostly develops along the NS faults and the south-eastern border of the phreatic zone, which is crossed by a SW–NE thrust-fault, until reaching the B spring. In this scenario, C and CdP caves are located close to the main generated conduits, draining a large part of the upstream aquifer as their respective regimes suggest. For the BV flow system, phreatic conduits mostly develop along the northern border of the phreatic zone until reaching the Bf spring.

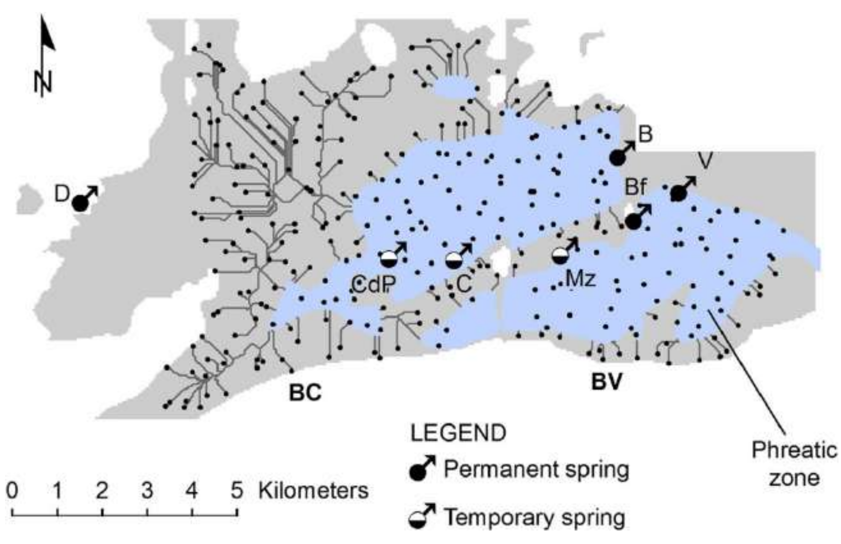

Fig. 10 Geometry of the modelled vadose conduit network for the BC and BV karst systems starting from the infiltration model (PbNs)

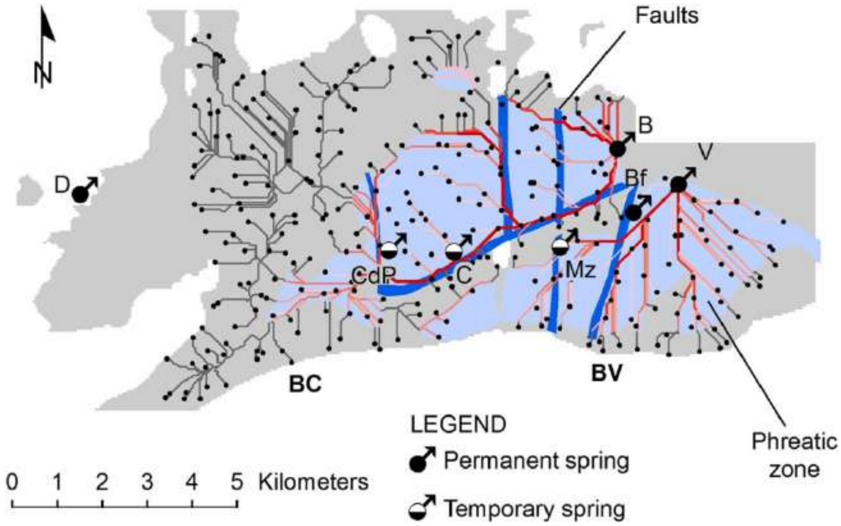

Fig. 11 Generated phreatic conduits of the BC and BV karst systems (red lines); the conduits are hierarchized according to the size of the drained area. The imprint of the NS faults and the SW–NE thrust considered as inception horizons are displayed (blue strips)

In the selected scenario, the V spring and the Mz cave are located close to the main conduits. The resulting BC and BV conduit network may then be integrated into the KARSYS 3D model, as represented in Fig. 12.

Discussion

Model validation

Delineation of the catchment area

Usually, two types of methods exist to validate the size of catchment areas, (1) those testing the spatial delineation of the catchment area, i.e., mainly tracer tests and (2) those testing the size of the area, mainly by comparing recharge assessments with the observed system discharge. Further methods such as time series analyses (hydrograms, chemograms, isotopes…) may also evidence potential changes (enlargement or reduction) in the catchment area. Compared to the catchment areas delineated by Grétillat (1998) (48 km^2 for BC, 29.5 km^2 for BV), BC is presently 10 km^2 larger, while BV is 10 km^2 smaller. This corresponds to the southern area where the Y phreatic discharge is to the BC system instead of the BV system. Gretillat (1998, p. 63) pointed out a surplus of water for the BC system by nearly 1/6. This probably corresponds to the additional 10 km^2 (nearly 1/6 of the total catchment area: 58 km^2) which were missing in his interpretation; furthermore, the boundaries of the proposed catchment areas are consistent with the existing tracer tests presented in Fig. 13.

Validation of the generated conduit network

The validation of the model proposed for the generation of conduit networks is slightly more complicated. The generated

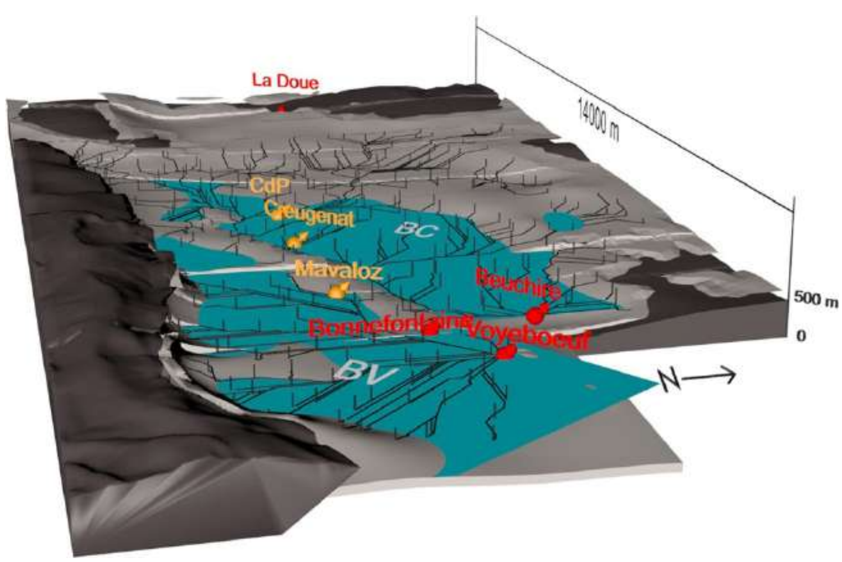

Fig. 12 Resulting 3D model of the generated conduit networks

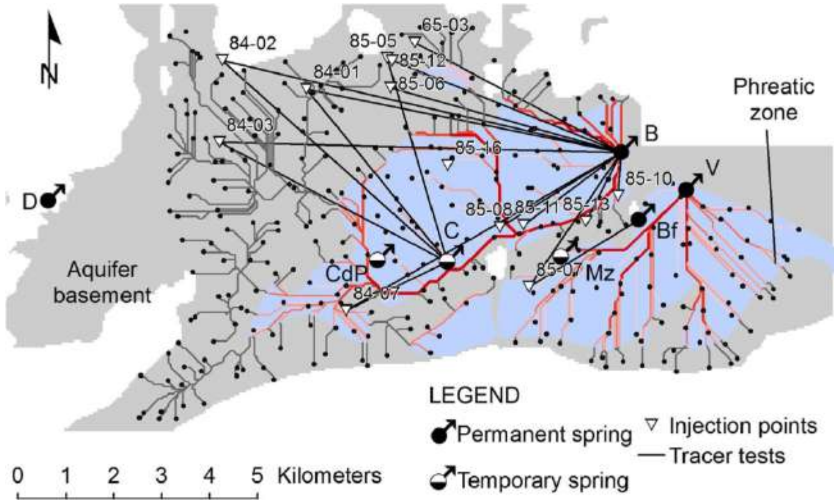

Fig. 13 Comparison between existing dye tracer connections (black lines) and the BC and BV karst conduit model (grey = vadose conduits, red = phreatic conduits). The numbers refer to the code of the tests which are further detailed in the text

network must be consistent with results of tracer tests, and of water budget and time series analyses, but ideally requires more direct data such as speleological observations, head and discharge measurements or geophysics. For shallow karst conduits, ground-penetrating radar may be undertaken in order to accredit the position of the supposed conduits (Collins et al. 1994). For conduits developing deeper than 15–20 m, microgravimetry or borehole seismic methods seem more appropriate, but still remain uncertain (Chalikakis et al. 2011). A more indirect way for validating the conduits model would be to apply a pipe-flow model and to compare with discharge and head measurements. Although this was also undertaken, it will not be presented here.

Firstly, the conduit model is compared to the existing results of dye tracer tests (Schweizer 1970; Favre 2001) especially in the northern part of the site where a lot of them have been performed (Fig. 13). Connections demonstrated by test Nos. 84-01, 84-02, 84-03 and 84-07 are consistent with the model as they indicate a connection with the C cave as well as with the B spring. Test No. 85-05 was found in the C cave, which is not consistent with the model; however, the tracer was injected very close to the boundary between two sub-catchments, one passing close to C, and the other flowing directly to B spring, which does not contradict the model. Test Nos. 85-06, 85-12, and 65-03 were found at B spring and not at C, which matches the model. Test Nos. 85-08, 85-10, 85-11, 85-13 and 85-16 are also consistent as they were injected downstream from C.

In contrast, test No. 85-07 was performed in the BV catchment area and obviously indicates a connection with the B spring. This corresponds to the questionable test described in the introduction (Schweizer 1970); if confirmed, this would imply an underground overflow over the anticline between the two systems. However, it may also result from the re-infiltration of water emerging at the Mz cave as the emerging stream flows toward the BC catchment.

Globally, the generated conduit network of the BC and BV karst systems appears consistent with the existing tracer test results. In addition, the sketch of the hydrogeological flow system clearly indicates regions where new tracer tests should be carried out in order to validate the model (for example S and SE parts of the BC karst system). This remark indicates that establishing such a model prior to performing a tracer test may be of great utility. Additional data or investigations may also contribute to validate the model (geophysics, hydrogram analysis, isotopes or chemogram, etc.) but often their interpretation does not bring unequivocal conclusions.

In a second step, the modelled network is compared with the existing cave surveys in the area. Maps of the CdP (550 m of length, Gigon and Wenger 1986) and the C caves (~2,000 m of length) are the unique available cave surveys exceeding 100 m of length. These cave passages are then compared to the generated conduit network (Fig. 14). Even though the existing caves do not overlap exactly with the generated conduits (~250 m of mismatch, i.e., less than the density of the infiltration nodes), the C conduits develop along an orientation SW–NE which is consistent with the model. The main tributaries come from the left bank for the real cave as well as in the model. Concerning CdP, the orientation of the generated conduit does not strictly match the surveyed passages, but the position does. The connection between the two caves is suggested by a dashed line for which orientation is quite close to the generated conduits.

Considering that the initial spacing of the infiltration nodes is 500 m, the modelled phreatic conduits globally match the caves surveys; the deviation between the surveyed conduit network and the modelled one is about 250–300 m, which is admissible regarding the density of the infiltration nodes. Regarding the BV conduits, the location of the temporary outlets (Mz, Bf) is really close to the main conduits of the generated network. This also indicates that the model matches the existing observations pretty well.

Strengths of the approach

The main strength of the approach is that it proposes a systematic way for delineating catchment areas and for

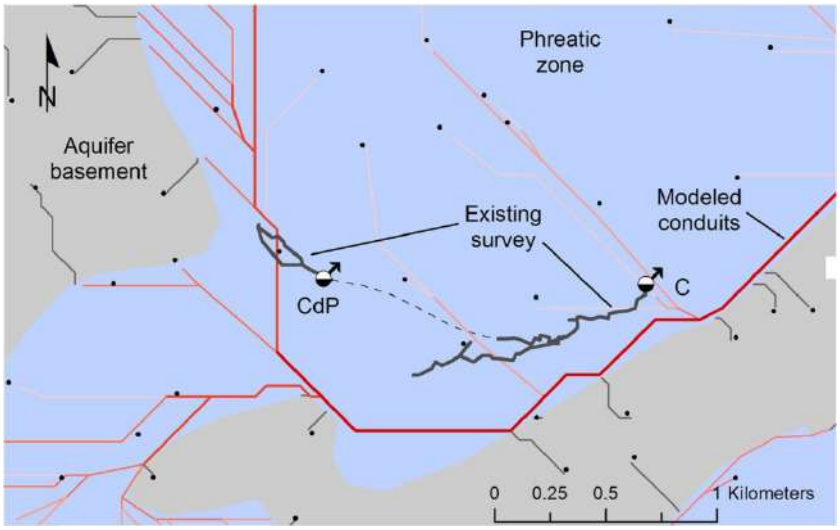

Fig. 14 Comparison between the existing cave surveys of the Creugenat (C) and Creux-des-Prés (CdP) and their supposed connection (respectively black plain and dashed lines) and the modeled conduit network (red lines)

modeling conduit networks on the basis of an explicit 3D conceptual model of the aquifer. In comparison with other modeling approaches, it explicitly takes into account the saturated and unsaturated zones of the aquifer and the guidance effects of the inception horizons for the conduit development. Moreover, it also takes into account an explicit infiltration model, making the generated conduit network consistent with the expected recharge areas. Outputs are directly usable for further simulation (flow and transport). For example, hydrological software can be applied in order to assess the recharge of the respective sub-catchments (e.g., RS3.0, e-dric.ch, application in Weber et al. 2011). Pipe-flow modelling (e.g., SWMM, EPA) can also be used directly to simulate flow in the generated conduit network. Such models make it possible to simulate the peculiar hydraulic processes taking place within the epiphreatic zone (example in Jeannin 2001). Other flow simulation approaches such as "hybrid" modelling (Schmidt et al. 2014) or "discrete conduits and matrix" (e.g., FEFLOW, Kresic 2013) could be applied as well.

Weaknesses of the approach

Although the approach reveals global efficiency and consistency, some weaknesses have to be mentioned. First, catchment areas have been delineated here, considering actual and low-flow conditions and do not assess possible lateral flows taking place in the epiphreatic or vadose zones which can transmit (or receive) flows over geological barriers at high-flow conditions. Thus, catchment areas of the systems only reproduce low- to moderate-flow conditions. Extension to high-flow conditions would require the assessment of the enlargement (or the reduction) of the underground flow system due to eventual divergences; however, although this was carried out, it is not presented here. Another limitation is the fact that the proposed model only generates "active" conduits in the phreatic zone. In reality, active conduits may also develop in the epiphreatic zone (up to dozens of meters above the saturated zone). Nevertheless, knowing the presence and location of the phreatic conduits, it seems possible to infer the presence and the location of additional and superimposed ones by testing the existing conduits model in pipe-flow simulation software. As the model does not take into account the previous phases of karstification, the generated conduits do not reflect the complete cave network, including fossil passages (as usually explored by speleologists). However, the model could be improved by successive applications of the approach on the same site and by modifying the hydrological conditions (base level, permanent springs, etc.).

Regarding the delineation of the boundaries between several systems draining the same phreatic zone, as it is often observed at the foothill of an elongated massif, in large valleys (Swiss Jura, Julian Alps, etc.) or along sea coasts, this is not (or not mainly) related to geological features. Data are often scarce for defining the position of the hydraulic boundary between the respective flow systems (i.e., "piezometric crest"). Furthermore, this boundary is expected to move according to flow conditions, which can hardly be assessed with precision. The KARSYS 3D conceptual model may help to make hypotheses about the expected boundaries but, in many cases, dedicated investigations are necessary to improve the reliability of the interpretation in this region (borehole and cave observations).

Conclusion

A systematic and reproducible approach to (1) delineate catchment areas of karst flow systems, and (2) to generate a conduit network in the vadose and phreatic zones for low-flow conditions based on the KARSYS 3D conceptual model of the aquifer is described. The approach is presented through an application in a Swiss Jura test site. Starting from the KARSYS 3D model under low-flow conditions, the delineation of the catchment areas at ground surface is obtained by extrapolation of the underground flow system boundaries and incorporates the potential allogenic zones feeding the flow system. The conduit modeling process is based on four distinct sub-models reflecting the infiltration processes (allogenic recharge or autogenic concentrated or diffuse recharge), the vertically controlled and the basement-controlled conduits in the vadose zone, and at least those in the phreatic zone. Conduits are modeled from the defined catchment area to the main baseflow outlet of the flow system by considering hydraulic principles and the expected guidance of inception horizons on the conduit development. The sub-model of phreatic conduits is adjusted by some empirical parameters, which have to be used by the modellers to adjust the generated network to their idea of the expected geometry. The model then ensures a sufficient drainage capacity of the aquifer and may be validated by using additional investigations, observations or data that were not integrated in the process (tracer test connections, cave surveys and geomorphological evidences). As with any other approach, parameters provided by KARSYS are approximate. Two main limitations have been identified so far. The first concerns the separation of two systems draining the same phreatic zone. This point can be clearly identified by the KARSYS 3D model, but cannot be solved without further hydraulic data. The second limitation is related to the modelling of the conduit network which considers low-flow conditions. The process does not consider previous phases of karstification resulting from paleo-conditions. This is first and mainly a problem for the generation of epiphreatic conduits, i.e., for simulating high-flows (e.g., the activation of intermittent perched outlet). It also clearly means that fossil caves cannot be generated directly with the current tool. Developments are ongoing in this respect. Regarding the Swiss test site, the proposed catchment areas seem more consistent with previous dye-tracer connections and hydrological budget than the previously existing delineation. The proposed conduit models are also consistent with the validation data (dye-tracer connections and cave surveys). These results indicate that the approach is pragmatic and may be applied systematically for low-flow conditions. It also provides a ready-to-use field of parameters, which can be used for flow simulation.

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6.3. Hydrological and hydraulic simulations in karst

Results presented in chapters 5 and in section 6.2 provide all geometrical characteristics of the karst flow-system. In this section we focus now on time variations. The aim is to link meteorological parameters (e.g. a storm event) to discharge rate and water heads within the aquifer as well as at its outlets (karst springs) model in order to address flood issues in a karst area. Technically, it consists in adding flow-simulation components (recharge, storage, hydraulic heads and discharge) to the existing KARSYS conceptual model. The next sections introduce the combined-use of hydrological and hydraulic models as extension to an existing KARSYS conceptual. After an introduction, this chapter is divided into three main parts: §.6.3.2 Test-site description, §. 6.3.3 Recharge simulation, § 6.3.4 Hydraulic simulations.

6.3.1. Introduction

The objective of this chapter consists in understanding and reproducing (i) **recharge** processes and (ii) **hydraulic** processes (i.e. the evolution of the hydraulic gradient v. discharge within the conduits) for two adjacent karst flow-systems in northern Switzerland (Ajoie, JU) which have been responsible several time for **floods**. Indeed, the city of Porrentruy has been frequently impacted in the past due to karst aquifers overflowing and especially through the overflow of the Creugenat temporary spring, for which discharge rates may exceed 20-30 m^3/s by extreme events. Depending on events' magnitude, some other permanent and overflow outlets may also become active and may contribute to the flooding (i.e. Creux-des-Prés, Mavaloz, etc.).

One objective of the simulations is to reproduce the extreme **flood event of August 2007** which is considered as being one of the biggest flood event of this last decades (OFEV [2010]).

Simulations are based on results obtained through the application of KARSYS and of the extension related to catchment delineation and conduits generation (§. 6.2). As the resulting model is only valid for low-flow conditions, characteristics of the conduits have been **adapted to high-flow conditions**. Observations and simulations make it possible to infer potential changes in the system properties. **Changes in hydrological properties** for instance may concern the enlargement (resp. the reduction) of the catchment areas by addition (resp. subtraction) of allogenic tributaries, etc. **Changes in hydraulic properties** are usually related to activation of thresholds or by-pass conduits in the conduit network.

Two recharge simulation models have been performed; one by using **RS3.0** (Simulation results are reported in Appendix 10.12) and one other by using **KRM_1** as results provided by RS3.0 did not match our expectation. The recharge model is calibrated over the period 2002-2004 and simulations cover the period of August 2007.

Distributed recharge files obtained with KRM_1 for the period 2002-2004 and for August 2007 are then transferred to **SWMM** in order to simulate the observed **activation** and the respective **discharge rates** of the six involved **outlets** (three permanent and three temporary springs).

The test-site and the available data are first described. These make possible to test various scenarios of hydraulic relationships for high-flows in order to determine hydraulic features which were not inferred for low-flow conditions. Then, the implementation, the calibration and the simulation results for the recharge and for the hydraulic models are discussed.

As discussed in §. 4.5, **flow simulation models** and their application to karst flow-systems points out that recharge processes are very significant in controlling the flow-system response. Various types of flows-simulation models do exist. The most appropriate type is chosen depending on issues to be addressed (Table 6—1). In many cases, it even seems that modeling recharge would be almost sufficient to reproduce the whole karst hydrological response. At the beginning of the Swisskarst project, it was thus decided to start from the simplest possible hydrological model, i.e. a pure recharge model and to progressively introduce **groundwater flow processes** (i.e. hydraulic processes), when the observed response could not be approached by simple models, especially in cases where conduits are supposed to strongly modify the recharge-simulated signal. The following section is thus organized according to this approach; it starts from simple **hydrological models** (recharge model) and then, **hydraulic models** are progressively introduced if issues required.

Issues	What should the model address?	Type of model
Groundwater resource management	- Annual and/or seasonal discharge rates - Storage - Low-flows (impacts of droughts, etc.)	Recharge
Flood-risks assessment, construction	- Peak flows - Hydraulic-head variations - Storage	Recharge & hydraulic
Effects of climate changes	- Storage - Annual and/or seasonal discharge rates - Low-flows (impacts of droughts, etc.) - Peak flows	Recharge
Hydropower potential assessment	- Annual and/or seasonal discharge rates - Hydraulic-head variations	Recharge & hydraulic

Table 6—1. Issues in flow simulation and criteria for choosing the most appropriate model

In details, the selection of the most appropriate flow simulation models (recharge or hydraulic) is also driven by the **karst context**. Indeed, as indicated §. 4.2.1, various types of karst aquifers do exist in Switzerland and abroad, for instance: (i) the low-land karst aquifers of the tabular Jura which are characterized by well-developed and cultivated soils, (ii) the elevated karst aquifers typical from the folded Jura or the Prealps characterized by few soils, forests and pastures, and (iii) more elevated karst aquifers, typically in the Alps. These last are characterized by the lack of soils and the presence of permanent glaciers. Each geographic context corresponds to a **hydroclimatic regime** (Köplin et al. [2012]). Regarding this diversity, selected models have to offer flexibility in order to be adapted to all the encountered karst contexts and/or hydroclimatic regimes.

The combination of these factors led us to select two types of flow simulation models at the beginning of the project:

- A semi-distributed model **RS3.0** for quantifying recharge processes (hydrological model),
- A pipe flow model **SWMM**, for assessing heads and discharge rates through storm water drainage, i.e. channels and pipes which could be likened to karst conduits (hydraulic model).

During the implementation of the project, it has been observed that the applicability of RS3.0 was restricted to alpine karst areas. Indeed, the Swisskarst intermediate report (ISSKA [2013c]) presents the different simulations which have been performed for different hydroclimatic regimes. Results show that the calibration of the RS3.0 model for the Milandre test site (Tabular Jura, jurassian pluvial) or for the Areuse one (Folded Jura, Jurassian pluvio-nival) was more difficult than for alpine karst systems of higher elevation. It has been supposed that effects of vegetation, of intermediate storage (in soils and epikarst) and of routing are more pronounced for these pluvial systems of lower elevation and should be addressed more precisely than alpine ones where snow-controls most of the recharge process. Then a third semi-distributed model called **KRM_1 ("Karst Recharge Model 1")** has been developed for quantifying recharge processes for these types of systems by taking into account additional components which are not computed in RS3.0.

6.3.2. Test-site description

Hydrological and hydraulic dynamics of the BC (Beuchire-Creugenat) and BV (Bonnefontaine-Voyeboeuf) karst flow-systems have been first studied in the frame of the Swisskarst project for which a KARSYS 3D model has been built (see Vouillamoz et al. [2013]). This KARSYS 3D model was subsequently taken over for the generation of the 3D conduit network (see §. 6.1, fig. 11). Two conduit networks have been generated (the BC and the BV ones). These are isolated under low-flow conditions due to the relief of le Banné anticline which acts as a hydraulic barrier. Low-flow catchment areas of BC and BV systems are about 19 km^2 and 57 km^2respectively. These enclose autogenic zones as well as allogenic ones for which runoff is driven to downstream autogenic zones where it infiltrates. These catchment areas are considered as basic prerequisites for the proposed approach.

6.3.2.1. Available measurements (times series)

Quantitative hydrological measurements of springs, boreholes and water levels in caves, as well as various meteorological data are available (Table 6—3). Measurements for the Beuchire spring and the Creugenat overflow (the main springs of the aquifer) show missing data and long periods of gaps - especially for the Beuchire spring as no data do exist between 2004 and 2011. Regarding the discharge rates of Creugenat, uncertainty on measurements may be considered as significant because measurements are not easy to achieve as: (i) the flow is temporary, (ii) the river-bed is large and changing, and (ii) fluctuations of the flows are high (e.g. more than 20 m^3/s).

Other minor springs do emerge from the same aquifer in the vicinity of Beuchire. Chaumont spring, Boucherie spring and Pont des Graviers spring are considered as permanent springs (see Schweizer [1970] and Grétillat [1996]), they also emerge at an elevation of ~423 m. Boucherie and Pont-des-Graviers springs are of diffuse type whereas Chaumont emerges directly from the bed-rock. Regarding these springs, only minimal, mean and maximal discharge rates have been reported in the above-cited documents (Table 6—2). Data are scarce and uncertain but it remains possible that max. discharge rates may have been underestimated (in Grétillat [1996], the max. discharge rate of the Beuchire spring is limited to 1.6 m^3/s although measurements since 2001 show values larger than 3.3 m^3/s…). Other minor overflow springs were also indicated in the stream-bed of the Creugenat. Unfortunately, their respective regimes are not known.

	X coord. (m)*	Y coord. (m)*	Elevation (m a.s.l)	Min. discharge rate (L/s)	Mean. discharge rate (L/s)	Max. discharge rate (L/s)	Refs.
Chaumont	572410	251856	~423	1	5-10	>80	Grétillat [1996]
Boucherie (or “Innovation spring”)	572590	251915	~423	1	2-3	>10	Schweizer [1970]

Table 6—2. Other minor springs emerging in the vicinity of the Beuchire spring and their respective min., mean and max. discharge rates.

Besides visible overflow springs, an underground connection has been suggested in the past between BC and BV systems. A tracing test realized by Schweizer [1970] evidenced that a part (a few percent as indicated by the author) of the BV groundwater may divert toward the BC one. This obviously occurs under middle-flow conditions. This result suggests that under such conditions and possibly for higher flows, the drainage area of the BC system may significantly enlarge due to the rise of the hydraulic gradient thus reinforcing the discharge. This connection should be confirmed and the contribution to the flooding process should be quantified.

	X coord. (m)*	Y coord. (m)*	Elevation (m a.s.l)	Data	Time step	Period	Abb.
Meteorological data							
Fahy	562458	252676	596	Rainfall	1 hour	01.01.1990 – 31.12.2012	FAH
Fahy	-	-	-	Temperature (+2 m/ground)	1 hour	01.01.2000 – 31.12.2011	FAH
Fahy	-	-	-	PET (computed)	Daily	01.01.2000 – 31.12.2012	FAH
Mormont	569675	254200	540	Rainfall	Daily	01.01.2000 – 31-12.2012	MMO
Montenol	578420	244825	692	Rainfall	Daily	01.01.2000 – 31-12.2012	MTO
Delémont	591840	245950	467	Rainfall	1 hour	29.08.2012 – 31.12.2012	DEM
Vacherie-Mouillard	574250	246950	810	Rainfall	Daily	01.01.2001 – 01.01.2013	VAC
Théodoncourt	566960	251660	579	Rainfall	Daily	01.01.2001 – 01.01.2013	THE
Bressaucourt	569370	248270	550	Rainfall	Daily	01.01.2001 – 01.01.2013	BRE
Hydrological data							
Beuchire	572590	251860	Outlet: 423	Spring discharge rate	Hourly 15 min	01.01.2002 – 31.12.2004, 01.01.2009 – 01.08.2012 (2010 shows missing data)	B
Creugenat	568950	249575	451	Hydraulic head	30 min	01.01.2002 – .31.12.2004	C
Creugenat	568950	249575	Entrance: 451 Bottom: 436	Spring discharge rate	30 min	01.01.2001 – 31.12.2011 (Station GNA)	C
Champ-Montant	570213	250253	Entrance: 443 Bottom: 432	Hydraulic head (>436 m)	10 min	18.06.2012 – 11.07.2012	PdCM
POR3	569345	249730	Top: 449 Bottom: 431	Hydraulic head	15 min	01.01.2001 – 31.12.2004, 10.04.2012 – 26.09.2012	POR3
Voyeboeuf	573950	251070	Outlet: 439	Spring discharge rate	1 hour	01.01.2001- 01.08.2013	V
Bonnefontaine	572950	250450	Outlet: 440	Spring discharge rate	1 hour	01.01.2001- 01.08.2013	Bf
Creux-des-Près	567500	249600	Entrance: 465 Bottom: 444	No data			CdP
Mavaloz	571325	249675	Entrance: 465 Bottom: 441	No data			Mz

*Table 6—3. Available measurements; meteorological data come from Meteosuisse, hydrological ones come from MFR, RWB or the Jura canton (*coordinate Swiss Grid CH 1903). No measurements are available for Mavaloz and Creux-des-Prés.*

6.3.2.2. High-flow characteristics of the BC and BV flow-systems

Upstream from the springs and depending on the recharge intensity, indications in the literature show that the hydraulic head in the aquifer may rise by several tens of meters for several days (Grétillat [1996]; Vouillamoz et al. [2013]). These rises obviously lead to significant enlargements of the saturated part of the aquifer and may activate overflow springs such as Creugenat, Creux-des-Prés or Mavaloz. Characteristics of the BC and BV flow-systems are discussed separately. The resulting high-flow 3D conceptual model is displayed Figure 6—14.

6.3.2.2.1. Beuchire-Creugenat (BC) karst flow-system

Figure 6—2 demonstrates the hydraulic connectivity between different stations of the BC flow-system: the Beuchire discharge rate, the hydraulic heads of the Creugenat overflow spring, hydraulic heads recorded in the Pit of Champs-Montant (PdCM) and those in the POR3 borehole are plotted in parallel for June 2012.

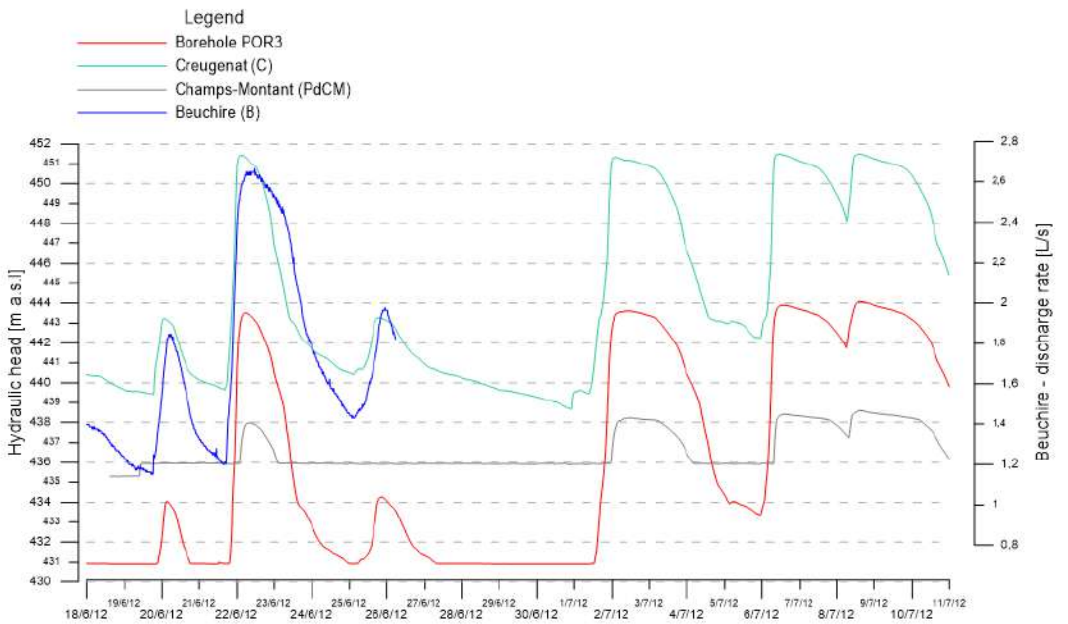


Figure 6—2. Superimposed head measurements of Beuchire (B), Creugenat (C), Champs-Montant (PdCM) and the POR3 borehole over June 2012 clearly evidence a hydraulic connection between these stations. The elevation for Creugenat and Beuchire is well measured while the precision of the altimetric leveling for PdCm and for POR3 is about 1 m.

6.3.2.2.1.1 Beuchire spring and Creugenat overflow

The Creugenat may overflow more than 10 times/year (max recorded discharge 20 m^3/s, see Hessenauer and Meury [2002]). Under usual high-flow conditions, correlated measurements of the Beuchire discharge and pressure data recorded in the Creugenat are displayed Figure 6—3. The curve evidences "linear" correlations and thresholds functioning which indicate that hydraulic obstacles are present in the system between these two outlets (Vouillamoz et al. [2013]). Globally the discharge rate of the Beuchire spring increases as the pressure head in the Creugenat raises. But in detail two main thresholds may be identified; one at 438 m and another one at 443 m a.s.l. These could be whether attributed to the emergence of an overflow spring (nevertheless no such springs are known) or to the activation of a perched conduit. As the discharge rate of the spring still rises although the water level in Creugenat remains stable, the best hypothesis is that a conduit acts as a by-pass with an overflow at 443 m. Such a conduit is assumed to be related to a paleolevel of the system. Figure 6—5 gives an illustration of the supposed organization of the conduits between Creugenat, and Beuchire according to observations for high-flow conditions.

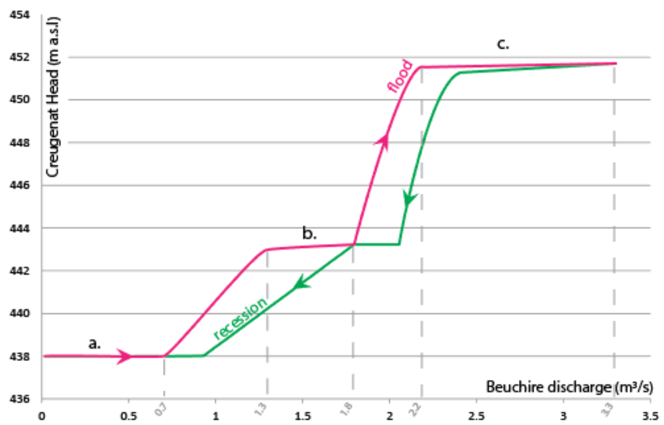


*Figure 6—3. **1)** As long as the Beuchire spring discharge rate remains lower than 700 L/s, the water level at Creugenat does not react (~438 m a.s.l): both emergences are disconnected by a threshold (a) situated at this elevation. **2)** As the Beuchire discharge rate exceeds 700 L/s the hydraulic head in Creugenat progressively rises up until reaching a threshold (b) at 443 m a.s.l. This threshold may correspond to a by-pass conduit diverting the flow to the Beuchire spring, **3)** as the discharge rate of the Beuchire spring increases from 1'500 L/s to 2'000 L/s the water level in Creugenat does not change (~443 m). **4)** As the discharge rate exceeds 2'000 L/s the water level in Creugenat rises up again until reaching the outlet elevation (c) at 451 m a.s.l.*

A zoom on the recession curves of Creugenat shows that the flood rising is extremely fast as well as the beginning of the recession. As the level falls below 443 m a.s.l. the velocity of the recession sharply decreases which denotes a reserve flushing ranging from 443 to 438 m a.s.l. This observation confirms that one or several additional conduit(s) with a significant storage capacity do(es) exist at the elevation of 443 m. These conduits are water-filled as the hydraulic gradient rises in the system and release the water once the flood decreases.

6.3.2.2.1.2 Borehole POR3

Measurements in POR3 indicate that the water level fluctuates between 431 m a.s.l (position of the sensor) and 447.5 m a.s.l at maximum (i.e. ~1 m below the surface). The correlation of POR3 head measurements with those recorded in the Creugenat (Figure 6—4) shows a direct hydraulic relationship. Headlosses between Creugenat and POR3 permanently range between 8 and 9 m for the rising and between 6 and 7 m for the recession. This suggests strong head-losses between these two stations.

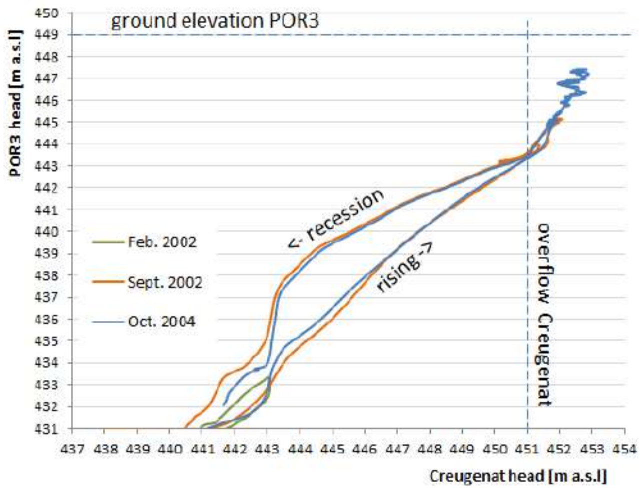
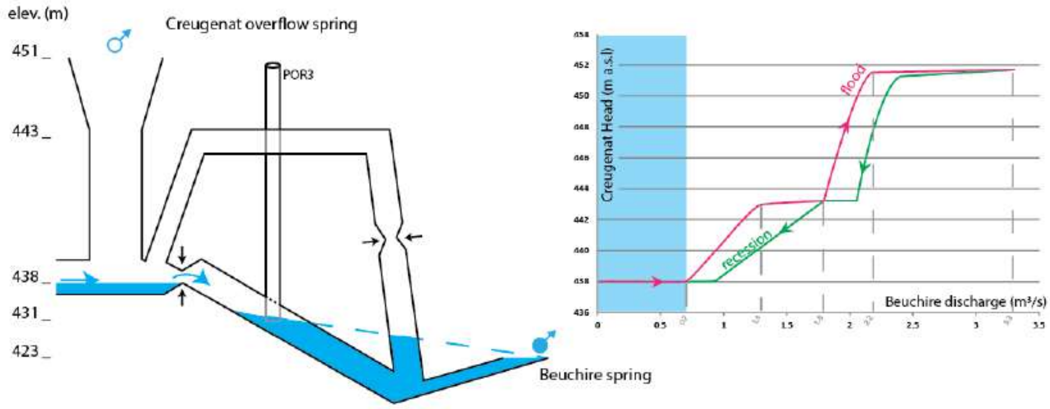
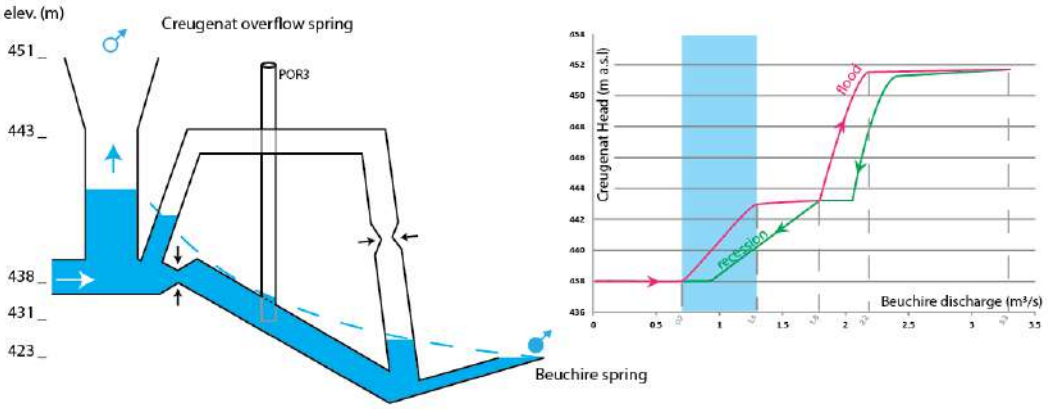


Figure 6—4. Hydraulic relationship between groundwater heads in POR3 and in Creugenat (for 3 selected flood events in 2002 and 2004); for a strong overflow event of Creugenat the water table in POR3 reaches a maximum at 447.5 m. The plateau at 443 m is clearly visible during the recession.

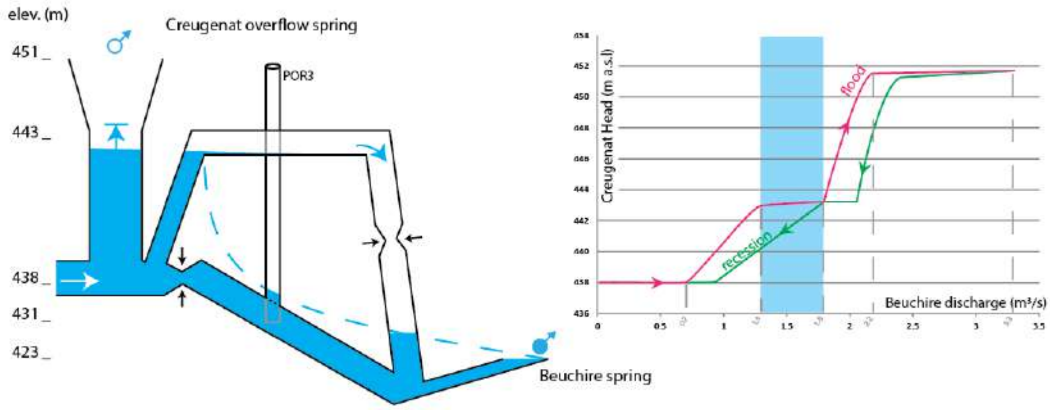
Finally, the Figure 6—5 shows the supposed functioning of the conduits in the vicinity of Creugenat, POR3 and Beuchire. This indication will be later used for adapting the geometry of the conduit network.


elev. (m)
451
443
438
431
423
Creugenat overflow spring
POR3
Beuchire spring
Creugenat Head (m a.s.l)
flood
recession
Beuchire discharge (m³/s)

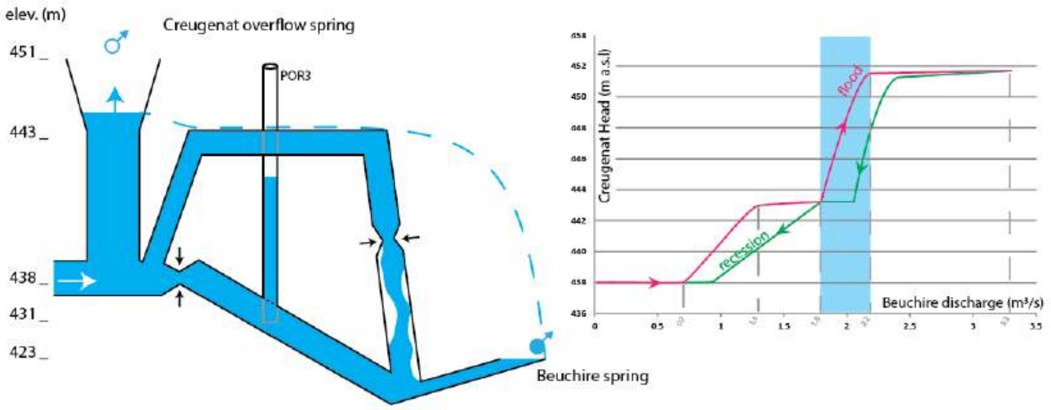
a.


elev. (m)
451
443
438
431
423
Creugenat overflow spring
POR3
Beuchire spring
Creugenat Head (m a.s.l)
flood
recession
Beuchire discharge (m³/s)

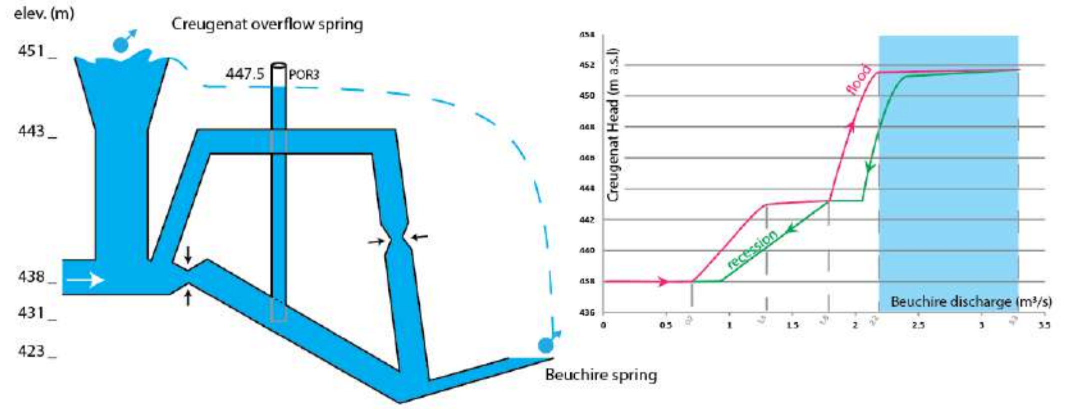
a.→b.


elev. (m)
451
443
438
431
423
Creugenat overflow spring
POR3
Beuchire spring
Creugenat Head (m a.s.l)
flood
recession
Beuchire discharge (m³/s)

b.


elev. (m)
451
443
438
431
423
Creugenat overflow spring
POR3
Beuchire spring
Creugenat Head (m a.s.l)
flood
recession
Beuchire discharge (m³/s)

b.→c.



c.

*Figure 6—5. Inferred evolution of hydraulic heads of the BC conduits-system for high-flow conditions (phases **a.**, **b.**, and **c.**) induces the addition of a first threshold at 438 m a.s.l. and the addition of a perched conduit at 443 m a.s.l. in order to explain that the discharge rate at the Beuchire spring increases while the hydraulic head in Creugenat does not rise anymore. Oscillations of the water table in POR3 act as an indicator of the hydraulic head evolution in the intermediate part of the conduit network.*

6.3.2.2.1.3 Pit of Champs-Montant (PdCM)

The bottom of PdCM (432 m) is dry most of the time (ISSKA [2012a]). This may be an artifact as the water table is only recorded if it exceeds the elevation of 436 m (the sensor is placed +4 m above the bottom).

Compared analyses between head-measurements in Creugenat and head-measurements in POR3 / PdCM have been made for 3 floods events of June and July 2012 (Figure 6—6). These indicate that while the water level in POR3 progressively rises until reaching a peak value of 443-444 m a.s.l. (which corresponds to the activation of the supposed by-pass conduit) the water level in PdCM does not react. The first recorded reaction at PdCM starts once the Creugenat overflows (at 451 m a.s.l), i.e. when the hydraulic gradient downstream the Creugenat is not supposed to increase anymore… This observation suggests that the pit of PdCM may progressively fill up once the threshold 443-444 m is reached or once the Creugenat starts overflowing as it is located downstream from the Creugenat… This remains a hypothesis as the quality of the data is not sufficient - but in such case the water level in the cave cannot be considered as an indication of the evolution of the hydraulic gradient in the system but as kind of local appendix storage. By precaution, the water level fluctuations in PdCM will not be further considered when designing the hydraulic model.

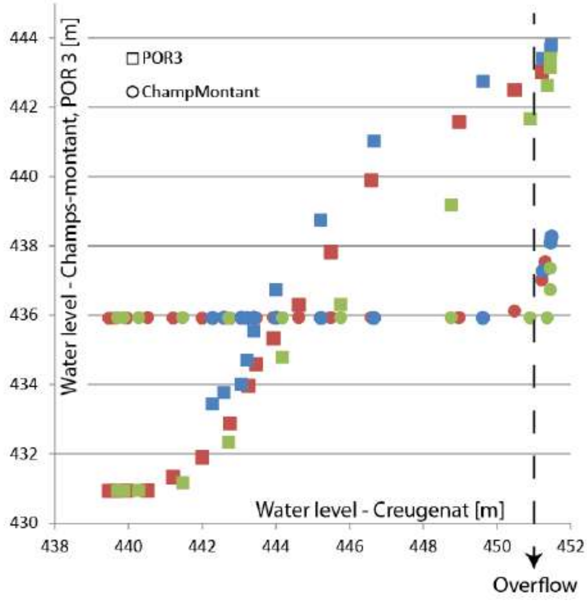


Figure 6—6. Observations from June to July 2012 (i.e. for three flood events of moderate intensity); the water level in the POR3 borehole started to rise simultaneously to the Creugenat flooding while the water table in PdCM does not start rising before the Creugenat overflows.

6.3.2.2.1.4 Creux-des-Prés overflow spring (CdP)

Creux-des-Prés is a cave described by Gigon and Wenger [1986]. Due to contamination in the 90ies, the cave is no longer accessible. Between the Creugenat and the Creux-des-Prés, the hydraulic gradient is estimated based on the elevation difference from the entrances of these two caves. The supposed gradient is close to 1% for high-flow conditions, and due to the lack of additional data, this value may be extrapolated until reaching the upstream boundaries of the aquifer basement from CdP. Based on this assumption, the hydraulic head at the upstream part of the phreatic zone may reach more than 530 m when CdP overflows. In the past, Monbaron and Bouvier [1999] indicate that CdP activated once the Creugenat overflow spring exceeded 10 m^3/s. This means that CdP would become active up to 5 times/year.

Nowadays it seems not to be no the case. Records of overflows do not exist but testimonies and oral discussion state that overflows appear every 10 years. Another source of information mentioned that CdP activates once the Creugenat overflow-spring exceeds 16 m^3/s, and the discharge rates would reach 2 to 4 m^3/s when Creugenat discharges about 18 m^3/s. This seems reasonable as activations of CdP are rare and 16 m^3/s refers to unusual peaks for the Creugenat overflow-spring. This value has been exceeded two times over the last 15 years; in March 2006 (16.1 m^3/s) and in August 2007 (18.8 m^3/s). The last known activations of CdP are: April 4th 1992, February 21 1999 and August 9th 2007 (Figure 6—7). For the latter the discharge rate ranged between 2 and 4 m^3/s.

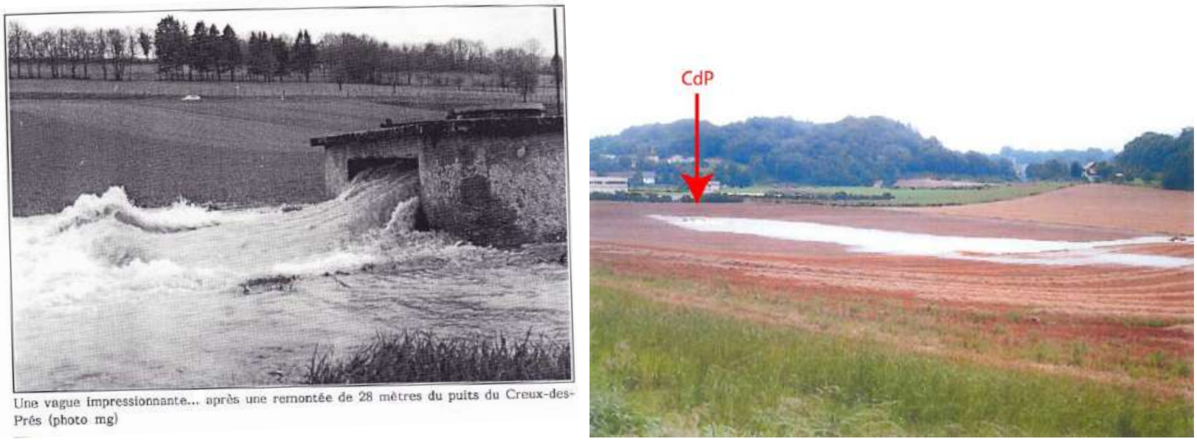


Figure 6—7. Right: overflow of CdP during the flood event of April 4th, 1992. The supposed discharge rate on the picture is about 3 m3/s, even more (Maurice [1993]). Left: overflow of CdP during the flood event of August 2007 (9th); order of magnitude of the estimated peak discharge rate was about 2 to 4 m^3/s (picture from J-.C Bouvier)

Regarding the event of August 2007, the recorded discharge rate of Creugenat exceeded 18 m^3/s. This makes it possible to infer the supposed discharge relationship between Creugenat and CdP (Figure 6—8).

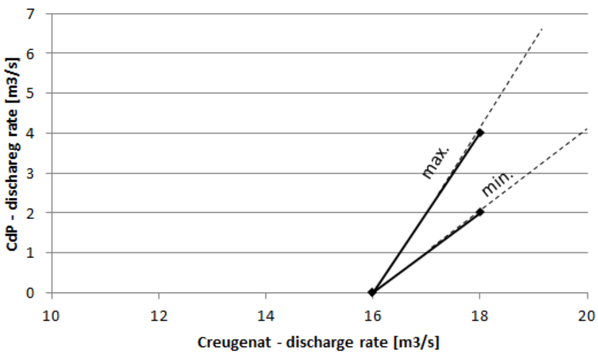


Figure 6—8. Supposed hydraulic relationships between the Creugenat discharge rate and the CdP discharge rate according to a min. and to a max. hypothesis.

Other caves - acting as small overflow springs - do exist upstream of Creux-des-Prés but they will not be explicitly considered in the model (see in Grétillat [1996]).

6.3.2.2.2. Bonnefontaine-Voyeboeuf (BV) karst system

6.3.2.2.2.1 Bonnefontaine (Bf) and Voyeboeuf (V) springs

Bf and V are permanent springs under usual flow conditions (Grétillat [1998]). Additional hydrological evidences in the field are necessary to assess the evolution of the hydraulic gradient upstream of these springs. Hydrograms of these springs have been analyzed by Jeannin (ISSKA [2010]) in order to address flood issues of the surficial streams which develop downstream of the springs. The author reevaluated the delineation of the catchment areas of these two springs and found respectively 11.7 km^2 and 10.7 km^2 for the Bonnefontaine and the Voyeboeuf karst flow-systems (at least 23 km^2 for the whole flow-system). The respective dynamic of Bf and V springs has been discussed according to the discharge rates and to visible thresholds on the flow duration curves (Figure 6—9). Profiles of the two springs are really similar, except for mid- to high-flow periods (0.75 to 2 m^3/s) when the discharge rate of Bf spring is higher and for low-flow periods when the discharge rate of Bf spring is lower. This analysis suggests that Bf spring partly acts as an overflow outlet. In details, several inflexions may be observed on the Bonnefontaine plot (for instance at 90, 150, 200, 350, 520, 700, 1’330, 1’800 and 2’300 L/s). These refer to hydraulic changes in the system (successive activation of underground thresholds) or to possible activation of higher overflow springs. Minor springs (or estavelles) have been observed in the vicinity of Bonnefontaine.

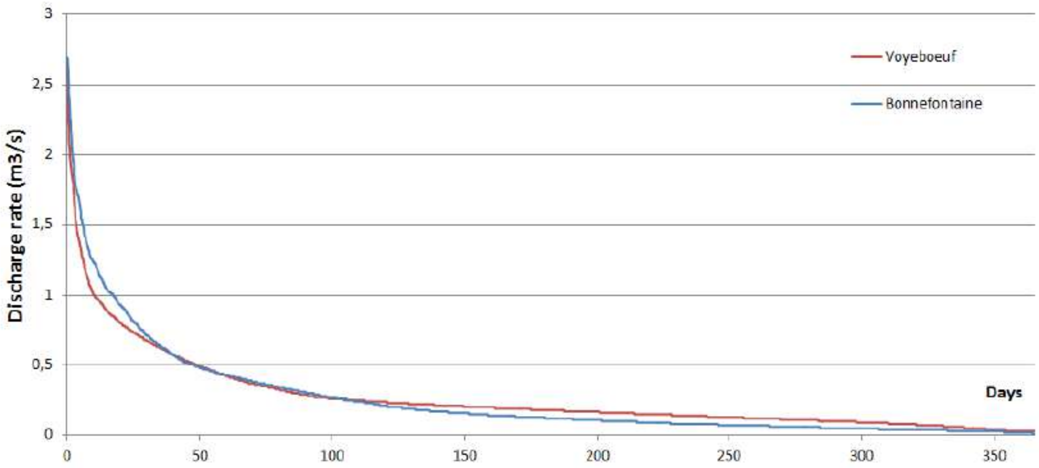


Figure 6—9. Flow-duration curves of Voyeboeuf and Bonnefontaine springs (2001-2013)

The analysis of the regime of Bf and V springs for high-flow conditions does not provide clear evidences of hydraulic relationship with the BC flow-system. Even if several plateaus may be observed on the Bf and V springs regime (for 2, 2.5, 5 and 6 m^3/s), they could not be correlated with the regime of Creugenat. These plateaus could then be related (i) to internal diffluences / bypasses within the BV conduits system, (ii) to diffluences with another karst system (not likely), or (iii) activation of outlets which could divert the water outside of the BV system or even toward the BC systems possibly by overflowing above ground and flowing to BC system. This last case should be carefully considered as when the Mavaloz cave (Mz) becomes emissive, the upstream stream draining the surface of the BV catchment is diverted to the BC catchment and the flow is gauged at the Creugenat measurement station (Figure 6—12). Consequently, the activation of the Mz overflow spring leads to an overestimation of the effective Creugenat discharge rate (+ 1 or 2 m^3/s max.).

The following Figure 6—10 displays the hydraulic relationships between the measured discharge rates at V and Bf springs for various periods in 2002 and 2004. Measurements show a good linear correlation. The dispersion is however quite significant for low to moderate discharge rates (lower than 1 m^3/s at V spring). For moderate discharge rates, i.e. ranging from 1 to 1.5 m^3/s for V spring, a plateau (or a break) is observed in the evolution of the regime for Bf spring. As the discharge rates of V spring exceeds 1.5 m^3/s, the relation is linear again and dispersion is lower.

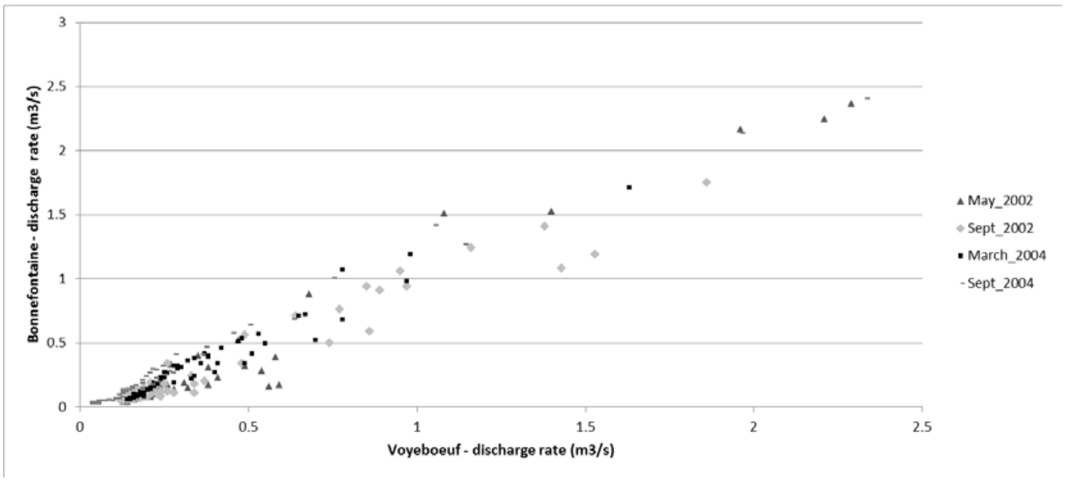


Figure 6—10. Hydraulic relationships between measured discharge rates at V and Bf springs for various periods in 2002 and 2004.

6.3.2.2.2.2 Mavaloz cave (Mz)

The cave of Mavaloz (Mz) is described by Gigon and Wenger [1986]. The estavelle lies at 471 m a.s.l and 2.9 km upstream from Bf spring, close to the village of Bressaucourt. The natural entrance has been enlarged at the beginning of the 20th century and partially refilled during the second part of the century with a conglomerate of boulders and gravels. The cave is no longer accessible.

The activation of this overflow spring is not frequent as related by Lièvre [1939] or Schweizer [1970]. It appears that Mz activates once the Creugenat (451 m) and the Creux-des-Prés (465 m) are both active (~one time / 10 years). However, Monbaron and Bouvier [1999] mentioned that the Mavaloz ephemeral stream activates once the Creugenat overflow exceeds 8 m^3/s (approximately two times a year), suggesting that other overflow springs may appear along the bed of the ephemeral stream… Recent discussions with the Service for Environment of the Jura Canton indicate that Mz activates one to two times per year. According to their comments, observations from Monbaron and Bouvier [1999] will be considered as true and it is postulated that Mz activates once the Creugenat overflow exceeds 8 m^3/s.

There is no information about the overflowing discharge rate. As the entrance of the cave has been partially obstructed, the potential overflowing discharge rate may be notably reduced in comparison with conditions described by L. Lièvre or by J. Schweizer. Then a maximum discharge rate of a few hundred of liters per second will be considered when flooding (max. ~300 to 500 L/s, see Figure 6—11).

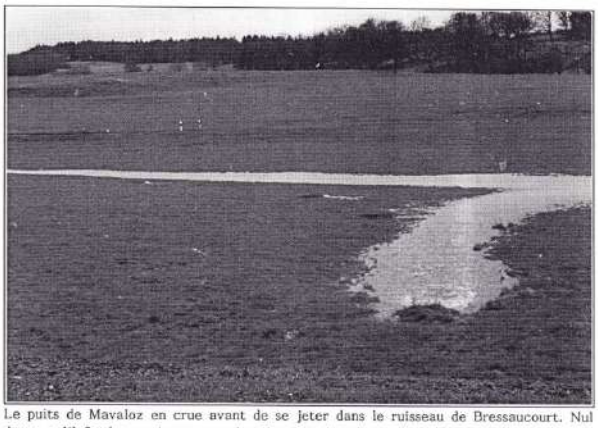


Figure 6—11. Overflow of Mz during the flood event of April 4th, 1992; the supposed discharge rate on the picture is in the order of a few hundreds of liters per second (Maurice [1993]). The discharge rate is small compared to the Creux-des-Près for the same event (see Figure 6—7).

For high-flow conditions, the water emerging from the cave is diverted from the BV system as the surface stream discharges toward the BC system (see Figure 6—12). Between the main permanent V and Bf springs and Mz cave, the hydraulic gradient is about 1.1%.

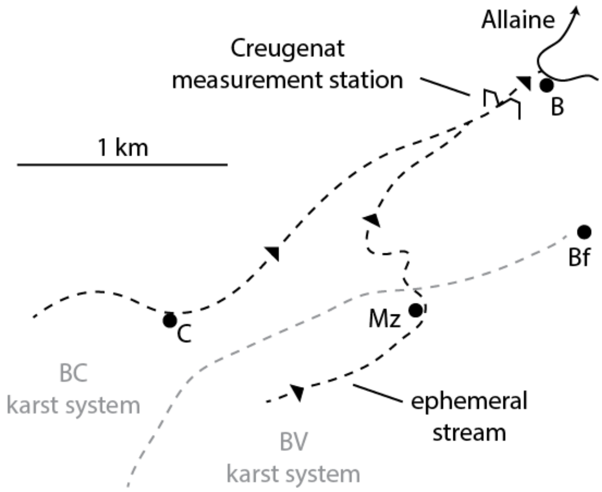


Figure 6—12. Mz cave acts as an estavelle. When the cave becomes emissive, the ephemeral stream and the overflowed water are routed toward the BC karst system (B = Beuchire, C = Creugenat)

Consequently the value of the calculated gradient 1.1% refers to normal high-flow conditions. There are unfortunately no available discharge measurements of this emissive cave or even an estimation of the related discharge rate or the modus of activation, excepting for the flood events of April 1992 and August 2007 where it has been observed that the cave was discharging several hundreds of liters per second (according to the Figure 6—11 and oral information from JC Bouvier).

6.3.2.2.3. Underground passes

Underground passes over the aquiclude have been identified at various locations of the 3D aquifer model, along the Banné anticline which separates BC and BV karst systems under low-flow conditions (Figure 6—13). They are mainly due to NS strike-slip faults that cross the anticline. Elevations of the passes range between 450 m and 480 m, i.e. close to the elevation of the Mz entrance located at 465 m a.s.l.

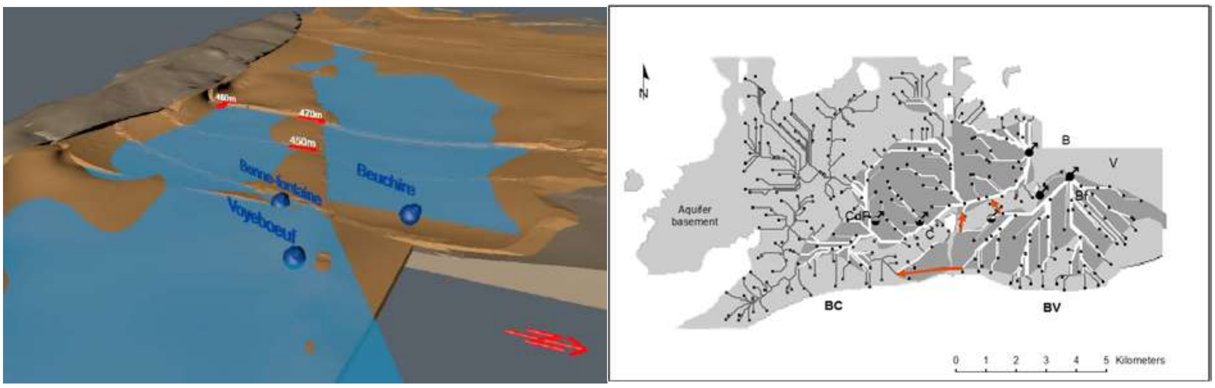


Figure 6—13. Three passes are evidenced through the aquiclude along the joint border of the BV and BC karst systems; at 450, 470 ("Le Banné" anticline) and at 480 m a.s.l. These passes may cause flow exchanges between these two systems depending on the fluctuations of the hydraulic gradient in the aquifer. According to this observation, the addition of three new hypothetic conduits could be suggested to the conduit network model (figure on the right, see §. 6.1)

Depending on the rise of the hydraulic gradient within the conduits system, groundwater flows may progressively cross these passes - especially the one located at 450 m, which may correspond to the connection pointed out by Schweizer [1970]. Indeed, in 1968 the author performed a tracing experiment in the upstream section of the stream sinking into the Mz cave for low-flows. A little quantity of tracer has been recovered at B spring compared to the quantity which has been recovered at Bf spring. Analyses indicated that only 45 g of tracer have been recovered at B spring while 865 g have been measured at the Bf spring (unfortunately, V spring was not monitored!). Based on these results and the recovery curve, it is possible to estimate that the quantity of diverted water toward the Beuchire spring is in the order of a few liters per second. Even if the results of this test appear incontrovertible, couple of comments could be addressed regarding the test modalities:

- The author apparently did not monitor the Voyeboeuf spring although it is the base-flow spring of the BV system… Tracer may have emerged at this outlet. Furthermore, the total recovery of the tracer has been estimated at 91%! Regarding the size of the systems and the fact that significant springs were not observed, this recovery rate seems questionable...
- The tracer has been injected in the stream nearly 1 km upstream of its sink into the cave. There is unfortunately no indication if the tracer completely sunk into the Mz cave or if a part could be diverted through other sinks or through surface streams toward the BC flow-system…

Therefore, considering the conditions of the test, it is not absolutely sure that a diffluence does exist for these flow conditions. However, under high-flow conditions, the hypothesis of a diffluence from BV to BC may be envisaged and should be tested.

6.3.2.2.4. Aquifer model of BC and BV for high-flow conditions

The high-flow hydraulic gradients of BC is displayed in Figure 6—14. The maximum gradient between B and POR3 is 0.54%. Between POR3 and Creugenat the hydraulic gradient is significantly steeper (1.85%). This evidences that the discharge capacities between these two stations is strongly reduced leading to the overflow of the Creugenat. In reality a collapsed handmade-wall partly obstructs the downstream conduit of Creugenat. As the equivalent-diameter of the conduit is punctually reduced head rises up to make Creugenat overflowing. Upstream of Creugenat, the hydraulic gradient rises up to 1% to activate CdP.

Regarding BV system and assuming that groundwater overflows over the underground pass located at 450 m, the hydraulic gradient for high-flow conditions may be first inferred from the elevation of the pass, i.e. 0.27% upstream from the Voyeboeuf spring. As the pass becomes active, the hydraulic gradient does not further increase between the springs and the pass. However, for higher flow conditions, the gradient can still increase upstream of the pass at 450 m, reaching 471 m (i.e. 1.54%) to activate Mz. Close to the pass at 450 m, the high-flow hydraulic gradient of BV system is probably higher than for BC system (as the hydraulic gradient of this area is controlled by the overflow of the Creugenat spring at 451 m), then the diffluence is expected to flow from BV system toward the BC one.

These related-information on the evolution of the hydraulic gradient within the systems make it possible to establish the following model of the aquifer for usual high-flow conditions (Figure 6—14). For these conditions, the phreatic zone of the aquifer considerably enlarges upward; the Creugenat activates as well as the identified pass crossing “Le Banné” anticline at the elevation of 450 m a.s.l. The Creux-des-Prés remains still inactive as it only activates for higher hydraulic gradients corresponding to extreme flood events (once every 10 years or more).

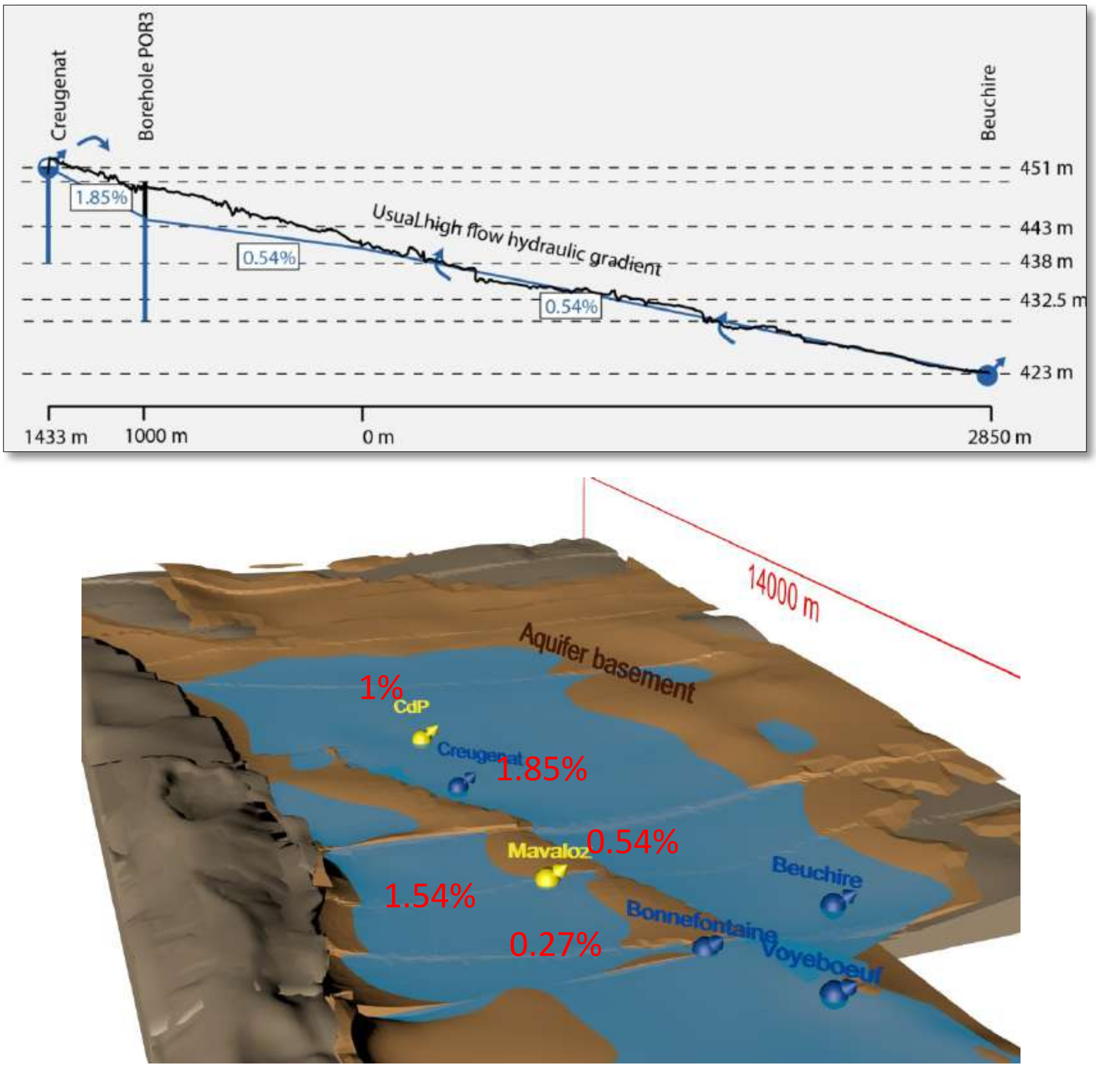


Figure 6—14. The shape of the hydraulic gradient for usual high-flow conditions can be sketched for BC and BV systems. CdP and Mz are still inactive for these conditions.

According to these indications for high-flow conditions, the low-flow conduit network model may be adjusted by the implementation of three supposed conduits crossing the Banné anticline at 450, 470 and 480 m connecting BC and BV karst systems (see Figure 6—13). These are supposed to by-pass a part of the BV groundwater toward the BC one. Thus, BC and BV karst systems are supposed to act as a single flow-system with multiple outlets. In addition to this supposed diffluence, it is also possible that the lower karst aquifer (early Sequanian, not depicted here) may contribute to feed the upper Malm aquifer as the increase of the hydraulic gradient in the lower Sequanian aquifer may exceed the hydraulic head in the upper Malm aquifer. In the western part of the site for instance, the Doue spring drains the lower aquifer (lower Sequanian) which is partly fed by the upper one. There are no clear evidences for this phenomenon but it has to be kept in mind for the interpretation of the simulation results.

6.3.3. Recharge simulations

*As mentioned in §. 6.3.1, the recharge (i.e. effective infiltration) of BC and BV flow-systems was first simulated with RS3.0. Several weeks have been dedicated to the calibration of the RS3.0 model by adjustment of the computation parameters. Unfortunately, results of the calibration were not satisfactory (see Appendix 10.12). Simulations show that **seasonal regimes cannot be well reproduced with RS3.0**. Indeed, for winter periods, simulated base-flows of the two systems are slightly underestimated compared to measurements and conversely base-flows for summer periods are overestimated. Underestimation in winter could be systematically observed between December and April (-50% of the measured base-flows) while the overestimation appears from May to November (+50% of the measured base-flows). In addition, it was observed that the intensity of flood-peaks is slightly underestimated in winter (January to February) compared to the observations, while in summer (August to November) the model slightly overestimates the flood-peaks intensity. Nevertheless, flood events are well reproduced for the autumn period (October to December). These seasonal misfits point out two deficiencies: the structuration of the **GR3 reservoir** which does not reproduce infiltration processes in karst, and the weakness of the **interception / evapotranspiration sub-model** which does not simulate very well seasonal water losses by the vegetation. The interception sub-model reveals to be **too simplified** to reproduce the expected effect of the vegetation (mainly forests and cultivated fields) over the catchment. RET is extracted from the upper first reservoir which empties fast. The upper reservoir is thus often empty and consequently RET is underestimated, and the seasonal hydrological balance is not respected. On the other hand, the model produces summer floods which are not observed in reality. This clearly evidences the deficiency of storage capacities of the model. This limitation influences the seasonal rate of the RET as the role of the vegetation cycles cannot be implemented.*

*As explained in §. 6.3.3.1.1.1, for assessing RET RS3.0 first considers the existing PET measurements. When such measurements do not exist, RS3.0 provides a simulated curve of PET using the Turc formula which is not the most appropriate formula for this context (and secondarily for the hourly time-step). This induces an additional bias in the computation of a realistic RET. Consequently, **RET is significantly underestimated** if we compare it to observations made by Jeannin and Grasso [1995a] on the adjacent test site of Milandre. These authors indicated that the real evapotranspiration (RET) reaches up to 50% of the raw rainfall (Jeannin and Grasso [1995a]) or even more. This is quite high compared to alpine flow-systems where RET is less than 300 mm for more than 1'500 mm of annual rainfall (i.e. 20%, in Weber et al. [2011], for a karst system in Flims, GR). The upper reservoir where RET is extracted is often empty and no more evapotranspiration is possible… We can try to force model parameters in order to reach a reasonable value of RET, by multiplying the rate of evaporation by 3 to 5, but this brings the model out of range. This clearly shows that the organization of the reservoirs is not appropriate for this type of low-land karst system where effects of soils and vegetation are dominant for recharge processes, which is the contrary of alpine karst system where soils and vegetation are scarce, and where snowmelt is the dominating factor.*

Then it was decided to leave RS3.0 for BC and BV systems. Simulation and results of the RS3.0 approach are however presented and discussed in Appendix 10.12 for information.

Another semi distributed model for aquifer recharge has thus been developed. KRM_1 focuses on refining interception and sub-soil processes in order to better estimate the RET. The consideration of land-uses and vegetation covers in the RET calculation implies to explicitly implement an appropriate interception sub-model. The organization of the model is described in the §. 6.3.3.1.1.2, and hereafter applied to BC and BV systems. It is partially based on previous works made by Sauter [1992] and by Jeannin and Grasso [1995a]

6.3.3.1. Introduction

Weber et al. [2011] shows the relevance of the **RS3.0** semi-distributed model (Dubois and Boillat [2000]) to assess the **effective infiltration** in **alpine karst aquifers**. Due to high infiltration rates, recharge processes in alpine karst aquifers are mainly dominated by (i) **snow-melting processes**, (ii) **contrasted distribution of rainfalls with the elevation** and (iii) **glacier-melting processes**. As a consequence, a fine discretization of these three processes makes it possible to properly assess groundwater recharge for these aquifers. The most important parameters of the model are the gradient of the rainfall intensity with the elevation and the rate of snow/ice-melt depending on simulated variations of temperature. Flanks exposure may also be discretized as the evolution of the temperature may also strongly differ, delaying snow/ice-melt if flanks which are exposed northward or southward respectively.

Attempts to apply RS3.0 to **low-elevation karst environments**, such as those of the Swiss tabular Jura, provide unreliable recharge assessment. It seems that in **absence of snow and relief**, parameters related to **soils, sub-soils and vegetation** become **dominant** in controlling **recharge processes** (see Sauter [1992] or Jeannin and Grasso [1995a]). Unfortunately, in its actual form, the RS3.0 infiltration sub-model (i.e. the GR3 reservoir, see §. 6.3.3.1.1.1) cannot reproduce soils and sub-soils (or epikarst) mechanisms which are mainly responsible for the **interception** and the **RET production**. Design, calibration and simulations of the RS3.0 model is presented in Appendix 10.12. As results were not satisfactory, **KRM_1** was developed to better assess soil and sub-soil reservoirs, and thus better simulate (i) interception mechanisms depending on land-uses and vegetation cover, (ii) real evapotranspiration processes and (ii) storage capacities of the aquifer which are supposed to change with seasons.

As measurements of the Beuchire and the Creugenat springs only overlap over the period from Dec. 2001 to Dec. 2004, i.e. three years, the calibration of the recharge model will be established over this period at an hourly time-step using a non-distributed precipitation while simulations will be performed using distributed precipitations. The parameterization of KRM_1, inputs, calibration and simulations are discussed in the following sections and compared with results provided by the RS3.0 model.

6.3.3.1.1. Hydrological recharge models

6.3.3.1.1.1 RS3.0: a semi-distributed model to assess recharge processes

The RS3.0[1] software is developed by e-dric.ch (cf. manual: e-dric [2012]). It is an improvement of the **Routing System II** program initially designed by Dubois and Boillat [2000] at the Laboratory of Hydraulic Constructions (LHC) at the Swiss Federal Institute of Technology (EPFL) in Lausanne. Initially, this model has been established to simulate free surface runoff generated by precipitations (rainfall + snowmelt) at land-surface. It includes an “effective precipitation” module as well as a flow-routing module in stream and river networks. Although this model has been especially developed for runoff in alpine stream catchments, RS3.0 may be applied to karst hydrology by assuming that the runoff infiltrates and flows through the conduit network.

In addition to a database which stores the meteorological time series (mainly rainfalls, snow height, temperatures and solar radiations), RS3.0 includes a series of **sub-models** which simulate the recharge through each compartment: atmosphere, ground surface, soil / sub-soil and aquifer (Figure 6—15): the snow pack sub-model, the glacier sub-model, the interception sub-model, the SWMM runoff sub-model and the GR3 infiltration sub-model.

[1] In practice, as the commercial use of RS3.0 is chargeable, it be replaced by RS MINERVE. This software is developed by CREALP and is available for free (http://www.crealp.ch/en/accueil/ressources/logiciels/rs-minerve.html). Besides the global configuration which allows for more flexibility, few differences between these two software do exist; they mainly concern the computation of PET and the calibration processes. Indeed, RS MINERVE includes an auto-calibration engine using up to three different algorithms (by ex. SCE-UA, UAMC and CLHR, see Foehn et al. 2015) while the calibration in RS3.0 is made by hand. Other model parameters and application fields are somehow comparable to RS3.0. Both software packages are derived from the same initial package (Routing System II, Hernandez et al. 2007).

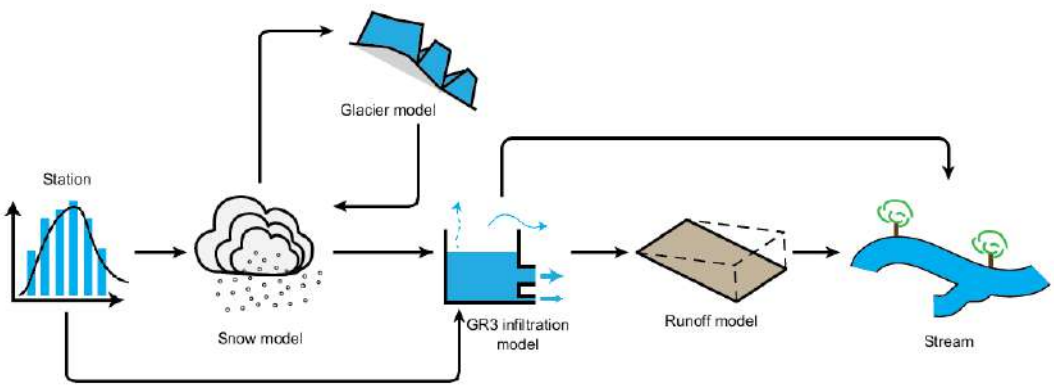


Figure 6—15. Routing principles of the RS semi-distributed software: details of a sub-catchment (i.e. for a given elevation range, here 200 m). Measured or inferred meteorological parameters (P, PET) are transferred to the GR3' reservoir which provides a part of surface runoff (SWMM module) and a part of infiltration

Catchment areas are usually subdivided in elevation bands (for example 200 m in the Alpine domain) providing distinct sub-catchments. For each generated sub-catchment, a **virtual meteorological station** is assigned. This provides the raw precipitation and the raw temperature corresponding to the respective elevation band. Virtual data are obtained by kriging measurements from existing meteorological stations in a chosen radius of the sub-catchment (Shepard's method, see Shepard [1968]).

The evolution of the precipitation rate with the elevation is still a non-fully resolved question as presented by Schäppi [2013]. For a singular event in the Alps, the author recorded diverging gradients with the elevation, positive ones, as well as negative ones (from -2.98 mm to +4.45 mm/100). However, at the scale of the year, it is usually admitted that the precipitation rates in the Swiss Alps evolves with the elevation from 0 to 200 mm per 100 m of elevation (Schwarb et al. [2001]). By default, a mean gradient of 100 mm/year per 100 m of elevation is considered for Switzerland.

The **snowpack sub-model** (and possibly a glacier sub-model) simulates the evolution of the snow height (resp. of the ice) and provides the equivalent precipitation (**P_{eq}**). The snowpack makes it possible to change the station input from liquid precipitations to solid ones depending on the temperature (degree-day). For temperatures lower than 0°C, precipitations are as assumed to be snow. When temperatures exceed 2°C, precipitations become liquid. Between these two values, the snowpack provides an equivalent precipitation of snow/liquid according to a linear distribution depending on the stock, the temperature (T) and the precipitation (P), as presented in Figure 6—16. Resulting P_{eq} produced by the snowpack sub-model can be used as input for the glacier or for the GR3 infiltration sub-model.

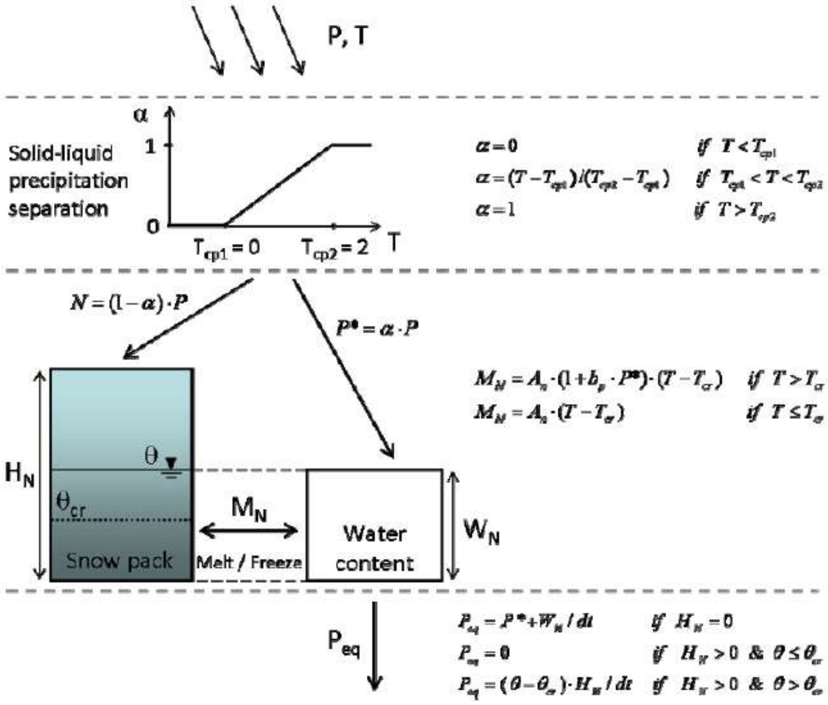


Figure 6—16. Details of the snowpack sub-model of RS3.0. This simulates the evolution of the snow (deposit and melt) as a function of the temperature (T) and precipitation (P) producing an equivalent precipitation (P_{eq}) used as input for the glacier or for the GR3 infiltration sub-model (fig. from e-dric [2012])

The **glacier sub-model** is mostly used for alpine flow-systems. It is composed of two packs: an **icepack** and a **snowpack** located at the top of the ice massif. The sub-model reproduces the snow height and the ice-volume dynamics of the glacier, depending on the precipitation, the temperature and in some cases the solar radiation. As the glacier is covered by snow, ice starts to melt only if the snow height is zero (i.e. all the snow stock is melted). Equivalent precipitation provided by the icepack and by the snowpack is transferred to two parallel reservoirs which return to the snowpack sub-model to supplement the equivalent precipitation.

The computed equivalent precipitation is driven to the **GR3 infiltration sub-model** (Figure 6—17). The sub-model makes it possible to assess the effective precipitation (and the effective infiltration) using the potential evapotranspiration (PET) and the water stored in the interflow reservoir. If the PET is not measured, values are computed by using the Turc Formula (Turc [1961]), using temperature measurements and discretized at daily time-step.

In the meantime, the **interception sub-model** computes vegetation and evaporation processes. Depending on the rainfall intensity and on the saturation level of the interception reservoir, a part of the water is intercepted and further evaporated whereas the remaining flows reach the ground where a part is expected to runoff while the rest infiltrates. The interception sub-model is integrated in the GR3 sub-model.

In detail, the GR3 infiltration sub-model is composed of a succession of two groundwater reservoirs for which outlets contribute to the model runoff: the **Interflow** reservoir (for "fast" flows) and the **Baseflow** reservoir (for "slow" flows) which evolve the same way. The Interflow reservoir supplies the Baseflow one by a transfer flow (cf. Equation 6—1) while a part of the water returns back to the atmosphere as evapotranspiration. Depending on the soil saturation, a part of the water is transferred to the **surface runoff sub-model** while the other part flows through the underlying Interflow reservoir and will be later released to the surface runoff or to the baseflow reservoirs.

When applied in karst, three types of flow components are distinguished: the surface runoff is assimilated to conduit flows, the interflow reservoir is assimilated to epikarst flows and the baseflow reservoir is considered as the low permeability volume of the aquifer (fissured flows).

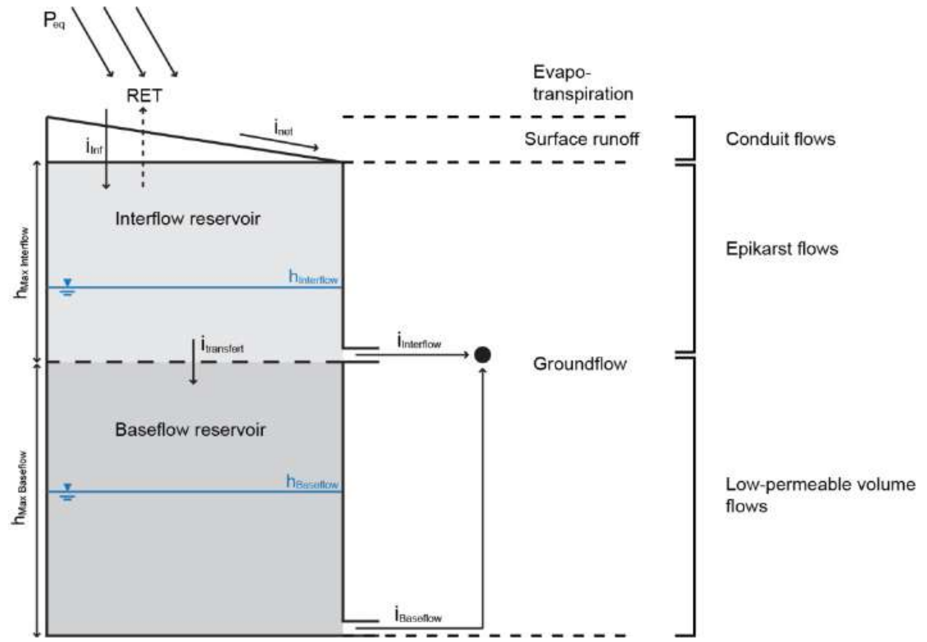


Figure 6—17. Details of the GR3 infiltration sub-model (e-dric [2012]); the GR3 is composed of two cascading reservoirs with distinct transfer functions depending on the water level.

Transfer equations of the GR3 sub-model are detailed hereafter.

$$i = k\ .\ (\frac{h}{h_{max}})^{aK}$$

→ Common expression of the flow generated by the reservoirs

$$if\ h_{Interflow} \leq h_{Max\ Interflow}$$

$$i_{Inf} = P_{eq} \cdot \left(I - (h_{Interflow}\ /\ h_{Max\ Interflow})^2\right)$$

$$if\ h_{Interflow} \geq h_{Max\ Interflow}$$

$$i_{Inf} = 0$$

→ Infiltration flow from the surface to the Interflow reservoir

$$i_{net} = P_{eq} - i_{Inf}$$

→ Surface runoff (as assume to be fast conduits flow in karst)

$$if\ T > T_{crPET}$$

$$RET = min\left(PET\sqrt{\frac{h_{Interflow}}{h_{Max\ Interflow}}} \cdot \frac{h_{Interflow}}{dt} - i_{Interflow} - i_{transfert}\right)$$

→ RET from the Interflow reservoir is computed based on PET and the critical temperature for PET

$$i_{transfer} = k_{transfer} \cdot \left(\frac{h_{inter}}{h_{\mathrm{Max\ Interflow}}}\right) . \left(1 - \frac{h_{base}}{h_{\mathrm{Max\ Baseflow}}}\right)$$

→ Transfer flow from the Interflow to the Baseflow reservoir

$$\mathrm{i_{Interflow}} = \mathrm{k_{Interflow}} \cdot \left(\frac{\mathrm{h_{Interflow}}}{\mathrm{h_{Max\ Interflow}}}\right)^{\mathrm{ak_{Interflow}}}$$

→ Interflow (assimilated as the flow from the soil/epikarst to the conduit network)

$$\mathrm{i_{Baseflow}} = \mathrm{k_{Baseflow}} \cdot \left(\frac{\mathrm{h_{Baseflow}}}{\mathrm{h_{Max\ Baseflow}}}\right)^{\mathrm{ak_{Baseflow}}}$$

→ Baseflow (assimilated as flow from the low permeability or from the phreatic fissured volumes to the conduit network)

Equation 6—1. Transfer equations of the GR3 reservoir (RS3.0)

The real evapotranspiration (RET) is computed using PET and the available water in the interflow reservoir. The **effective infiltration** (i_{eff}), i.e. the groundwater recharge, is obtained by subtracting RET and surface runoff (i_{net}) from the equivalent precipitations (P_{eq}).

$$i_{eff} = P_{eq} - i_{net} - RET$$

Equation 6—2. Computation of effective infiltration (i_{eff})

Pragmatically, the tool is based on object-oriented programming. Hydrological and hydraulic modeling is made according to a semi-distributed conceptual scheme. The basic principle of RS3.0 consists in associating each object to a certain hydraulic function being represented by icons. Icons can be manually connected according to the user-defined topology. In addition, hydraulic control elements such as gates, spillways, diversions, junctions, turbines and pumps can be plugged as well in the routing scheme.

A dedicated module is proposed for assisting calibration of the model parameters. This user-friendly module makes it possible to evaluate the fit of the parameters via two main indicators: **the Nash criteria** (Nash and Sutcliffe [1970]) and the **volume conservation coefficient** VCC (see Appendix 10.11). RS3.0 does not entail an auto-calibration module. Design and application of the RS3.0 simulation model are further described in Appendix 10.12.

The simulated recharge is considered as relevant once the simulated discharge of the flow-systems fits with the measured discharge on site (after having summed permanent and temporary outlets for each system) with respect of the volume conservation coefficient (VCC) and of the profile of the curve (peaks, flanks, etc.). Once the best fit has been found, the recharge time-series may be exported and further transferred to a pipe-flow model (SWMM).

Simulations using RS3.0 have been successfully applied in alpine flow-systems (Weber et al. [2011]; Weber et al. [2012]) or for flow-systems in elevated Jura (Finger [2012] and ISSKA [2013c]). Computed recharge for these flow-systems were judged consistent, making the demonstration that such a model is particularly appropriate for assessing recharge of karst aquifers in these contexts. However, a major deficiency of RS3.0 is related to the discretization of the evapotranspiration processes. Indeed, sub-models related to interception and soil infiltration processes may be seen as too simplified to correctly assess effective infiltration in contexts where these processes notably control or even dominate the aquifer recharge. Therefore, an alternative model **KRM_1** has been designed with the objective to focus on the interception and soil infiltration processes. Parameters, reservoir equations and calibration procedures of the **KRM_1** model are inspired from RS3.0 but they are significantly modified according to observations and existing models developed by the following authors: Sauter [1992] and Jeannin and Grasso [1995a].

6.3.3.1.1.2 KRM_1: a model for karst groundwater recharge assessment

KRM_1 was developed as an alternative to RS3.0 in order to further refine interception and soil infiltration processes in the discretization of the evapotranspiration, especially for lowland and vegetated karst environments where the recharge is significantly driven by these processes.

KRM_1 is a semi-distributed model. It has been developed within EXCEL® and Python as a succession of embedded reservoirs that reflect properties of ground covers and of the karst aquifer. The architecture of the model is presented in Figure 6—18. Reservoirs are described hereafter and their respective dynamics are expressed by the Equation 6—3.

KRM_1 has been designed for working at hourly time step. Besides physical parameters related to the size of the catchment area, the land-use distribution and the reservoir parameters, the model requires two further inputs: the equivalent precipitation ($\mathbf{P_{eq}}$) and **PET**. In its actual form, KRM_1 has not been fully developed to compute equivalent precipitations starting from raw precipitations (rainfalls + snow). Equivalent precipitations should still be computed apart by using RS3.0 which includes specific modules for assessing precipitation due to snowpack or glacier-melt. PET may be measured on site or estimated using temperature and/or other measurements (see §. 2.3.1.1).

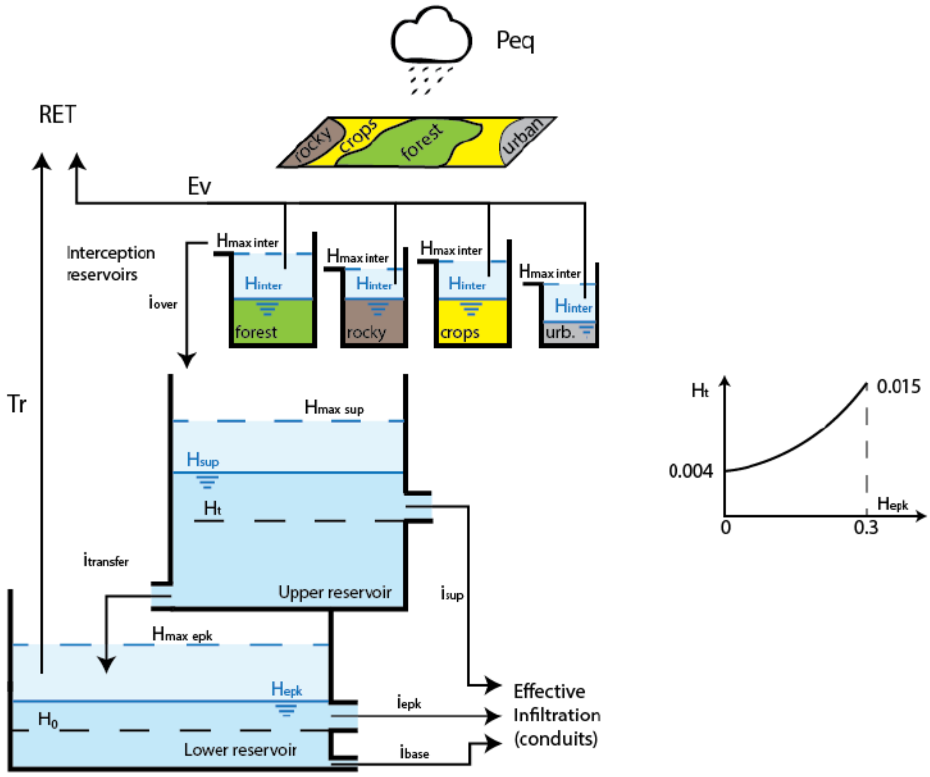


Figure 6—18. Reservoirs organization in KRM_1; the model entails three cascading reservoirs: the Interception reservoir and the Upper and Lower reservoirs reflecting the tandem soil / epikarst. P_{eq} is computed with RS3.0. Resulting time series are the effective infiltration (i.e. the water penetrating the conduits).

Transfer equations of **KRM_1** are detailed hereafter.

$$P_{eq} = RET + i_{sup} + i_{epk} + i_{base} + \Delta V$$

$$RET = T_R + E_V$$

if $H_{inter} > H_{\max\ inter}$,

$$i_{over} = k_{over}.S * (\frac{H_{inter}}{H_{\max\ inter}})^{a_{inter}}$$

→ Interception overflow to upper reservoir

$$i_{transfer} = k_{transfert}.S * (\frac{H_{sup}}{H_{\max\ sup}})^{a_{transfer}}$$

→ Upper reservoir to Lower reservoir

if $H_{sup} > H_t$,

$$i_{sup} = k_{sup}.S * (\frac{H_{epk}}{H_{\max sup}})^{a_{sup}}$$

→ Upper reservoir to karst conduits

$$i_{epk} = k_{epk}.S * (\frac{H_{epk}}{H_{\max\ epk}})^{a_{epk}}$$

→ Lower reservoir overflow to karst conduits

$i_{base} = k_{base}.S * (\frac{H_{epk}}{H_{\max\ epk}})^{a_{base}}$	*→ Lower reservoir seepage to karst conduits*

*Equation 6—3. Reservoirs and transfer equations of **KRM_1**; **i** is the computed flow [m^3/s], **k** is the hydraulic conductivity [m/s], **S** refers to the different areas (rocks, crops, urban, forest, etc.) of the whole catchment [m^2], **H** is the equivalent storage of the considered reservoir [m], and **a** is an empiric coefficient that refers to the shape of the outlet [-]*

6.3.3.1.1.2.1 Interception reservoirs

Equivalent precipitations (**P_{eq}**) are transferred to the **Interception reservoirs**. Four interception reservoirs have been designed: forest, cultivated lands, no-covered soils (i.e. rocky areas) and urbanized areas. These reflect the most usual areas found under temperate climate. The size of the interception reservoirs depends on the respective distribution of these areas over the catchment area. Non-covered soils and urban interception reservoirs show a fixed storage capacity pro surface unit over the year (**$H_{max\ inter}$**). Forest and crops reservoirs show a fluctuating storage capacity over the year in order to reproduce the seasonal growing / falling stages of the vegetation and of the harvests. For these two last reservoirs, a specific curve mimicking the seasonal evolution of the storage capacity has been addressed, based or inferred from indications found in the literature (see §. 2.3.1.2.1). Regarding interception reservoirs for forests areas, the **storage capacity** is based on values proposed by Gerrits et al. [2010] for the canopy (Figure 6—19, right). Regarding cultivated lands, the storage capacity over the year is fixed by the curve for cereal fields (Figure 6—19, left). For urban and denudated areas (for instance quarries, charrenfields, etc.), a maximal capacity of 1 mm is considered for these two reservoirs.

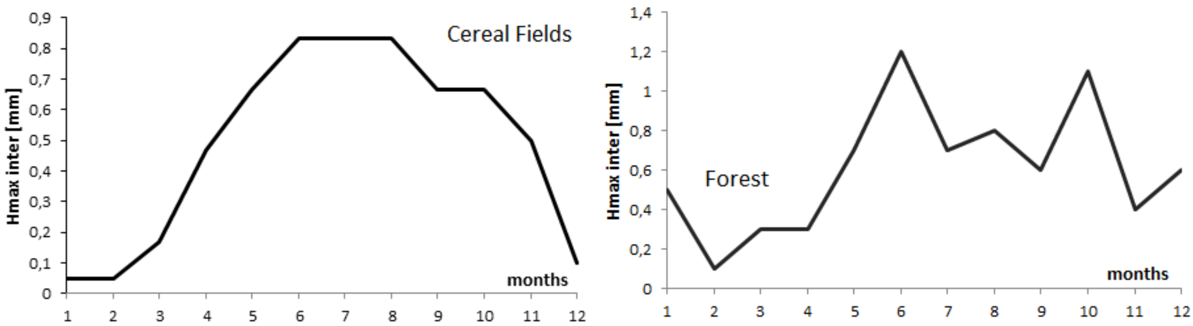


Figure 6—19. Evolution of the seasonal storage capacity for the cultivated lands reservoir (left) and the forest canopy reservoir (right, Gerrits et al. [2010])

Regarding the Upper and the Lower underground reservoirs (reflecting soils and epikarst), **H_0** is fixed at 140 mm - as demonstrated by Jeannin and Grasso [1995a].

When the storage capacity of the interception reservoir is exceeded, the overflow (**i_{over}**) activates and the water infiltrates through the soil and reaches the Upper reservoir (soil and sub-soil). As the retention capacity of the Interception reservoir evolves through the hydrological year for the forest and the crops interception reservoirs, the activation of i_{over} does not strictly depend on P_{eq}.

6.3.3.1.1.2.2 Upper and Lower reservoirs

The **Upper and the Lower reservoirs** act as the tandem soil/epikarst without being explicitly separated. These expand over the whole catchment of the modeled karst system. The Upper reservoir has two outlets:

- One at the bottom end ($\mathbf{i_{transfer}}$) reproducing the underlying transfer flows to the Lower reservoir;
- One overflow ($\mathbf{i_{sup}}$) reproducing the concentrated percolation and discharging to the conduits domain.

The Lower reservoir has two outlets:

- One at the bottom end ($\mathbf{i_{base}}$) reflecting the delayed percolation through the low permeability volumes of soils / epikarst toward the conduits domain;
- One intermediate ($\mathbf{i_{epk}}$) corresponding to the circulation through the epikarst conduits toward the conduits domain.

$\mathbf{H_{max\ sup}}$ and $\mathbf{H_{max\ epk}}$ are fixed as the simulation starts. $\mathbf{H_0}$ reflects the available water for transpiration ($\mathbf{T_R}$). H_0 is fixed as the simulation starts. $\mathbf{H_t}$ reflects the water storage in the sub-soils. The storage capacity of this reservoir is conditioned by the relative humidity of the underlying reservoir ($\mathbf{H_{epk}}$, see graphic in Figure 6—18). This relation $\mathbf{H_t}$ vs $\mathbf{f(H_{epk})}$ makes it possible to reduce the storage capacity of the tandem soil/epikarst when soil dries up and contracts. In such a case, small events of recharge may reach the conduits domain. Dry soils may even become hydrophobic for a while and thanks to cracks, infiltrated water flow fast toward the conduits. This is frequently observed during summer or even drought periods.

6.3.3.1.1.2.3 The exchanger module

The **exchanger** module simulates **storage processes in the epiphreatic zone**. Water exchanges from the conduits to the surrounding storage features (the low permeability volumes of aquifer: cracks, fissures, smaller conduits, etc.), and conversely, water exchanges from low permeability volumes to the conduits. Exchanges are driven by hydraulic head differences (Figure 6—20). Effective infiltrations ($\mathbf{i_{sup}}$ + $\mathbf{i_{epk}}$ + $\mathbf{i_{base}}$) are inputs into the exchanger.

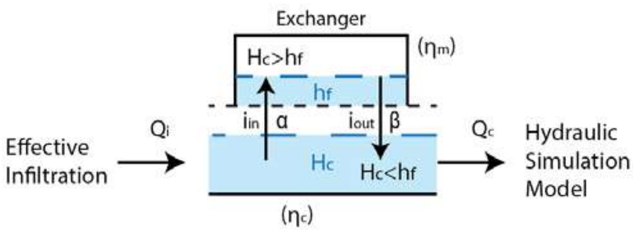


Figure 6—20. Operating principle of the exchanger module; depending on a pseudo hydraulic head which is computed proportionally to the input flow-rates, it is assumed that a part of the effective infiltrations is stored in low permeability volumes surrounding the conduits.

In the conduits domain, a fictive hydraulic head ($\mathbf{H_c}$) is simulated. It is proportional to the discharge rate ($\mathbf{Q_i}$) and inversely proportional to the size of the catchment area. It does not reflect the expected fluctuations of the hydraulic-head in the aquifer. In the surrounding storage zone, the hydraulic head ($\mathbf{h_f}$) is computed by difference between $\mathbf{i_{in}}$ and $\mathbf{i_{out}}$ and the supposed effective porosities of the two domains. $\boldsymbol{\eta_m}$ refers to the porosity of the low permeable volumes while $\boldsymbol{\eta_c}$ refers to the porosity of the conduits domain (Equation 6—4).

$$H_{c(t)} = \frac{Q_{i(t)}}{S * \eta_c}$$

$$h_{f(t)} = h_{f(t-1)} + \frac{\left(i_{in(t-1)} - i_{out(t-1)}\right)}{S * \eta_m}$$

if $H_{c(t)} > h_{f(t)}$,

$$i_{in(t)} = \alpha * S * \eta_c * \left(H_{c(t)} - h_{f(t)}\right)$$

$$i_{out(t)} = 0$$

if $h_{f(t)} > H_{c(t)}$,

$$i_{in(t)} = 0$$

$$i_{out(t)} = \beta * S * \eta_m * \left(h_{f(t)} - H_{c(t)}\right)$$

→ *Exchanger conduits/surrounding storage*

Equation 6—4. Main equations of the exchanger module in ***KRM_1****; S refers to the surface of the recharge area, η_c is the effective porosity of the conduit domain in the phreatic zone (~0.001), η_m is the effective porosity of the surrounding storage zone (~0.001), α and β are empiric coefficients which control exchange rates between the conduits and the surrounding storage (see Figure 6—21).*

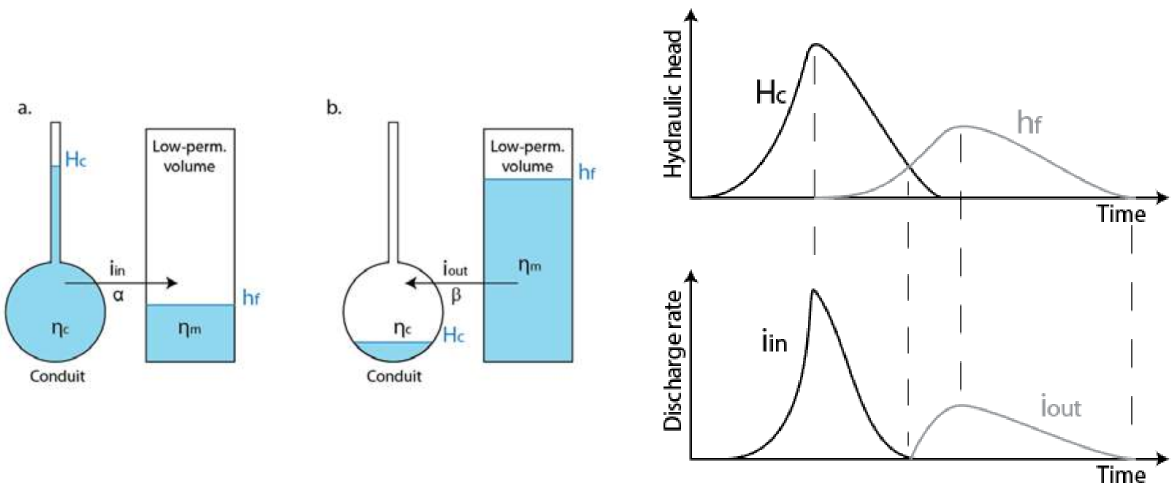


Figure 6—21. Principles of the exchanger functioning for a theoretical flood event; i_{in} refers to the part of water which is stored in the low permeability volumes while i_{out} refers to the water released by the low permeability volumes toward the conduits.

Simulated flows out of the exchanger are expected to transit only through the conduits. They can then be used as input for the **hydraulic pipe-flow model** (see the hydraulic simulation model, §. 6.3.4.1.1).

6.3.3.1.1.2.4 Real evapotranspiration (RET)

RET is successively provided by the **Interception** (**evaporation = E_V**) and by the Lower reservoir (**transpiration = T_R**). RET is computed on the PET and on the available amount of **residual water** in these reservoirs (**H_{epk}**). Due to the high storage capacity and to the restricted discharge rates of **i_{base}**, the Lower reservoir provides a more prolonged storage than the Interception reservoir and further supports RET over prolonged periods without recharge.

Thus at any time step:

if $H_{epk} < (PET - E_V)$,

$$T_R = H_{epk}$$

$$\text{and} \quad RET = E_V + H_{epk}$$

if $(PET - E_V) > 0$,

$$T_R = PET - E_V = \theta . H_{epk}, \quad \theta \in]0;1[$$

$$\text{and} \quad RET = PET$$

if $PET - E_V = 0$

$$T_R = 0$$

$$\text{and} \quad RET = E_V$$

Equation 6—5. Computation of transpiration from soils and epikarst (T_R) depends on PET, E_V (from the interception reservoirs) and on the water availability in the soils and epikarst reservoir (H_{epk}). The coefficient θ refers to the efficiency of extracting water from the soil/epikarst

As the storage capacity of the Interception reservoir $\mathbf{H_t}$ evolves with the seasons, variations of **RET are also partially controlled by seasons** and not exclusively by climatic parameters (as already explained by Primault [1962]). Furthermore, an empiric coefficient is implemented to the Lower reservoir (θ). This reflects that RET may be less easy to withdraw from the tandem soil/epikarst than from the interception reservoir.

6.3.3.1.1.2.5 Calibration and validation

All the parameters of the here above equations (k, H, H_{max}, a) should be adjusted. Various indicators may be used to control the calibration of the model parameters and to validate the model consistency: (i) efficiency criteria based on the comparison with the observed values, (ii) indicative values of real evapotranspiration rates, storage capacity, etc.

Efficiency criteria for the calibration and the validation of models are presented in Appendix 10.11. In the following sections, models will be mainly evaluated using the **VCC** (Volume Conservation Coefficient) and the **KGE** (Kling Gupta Efficiency) coefficients.

Estimated **real evapotranspiration rates** may be compared with values from the literature in order to discuss the calibration and the validation of the model. Several rates may be compared:

- The annual rate of the evapotranspiration compared to the total precipitation. Depending on the location, the elevation and the land-uses of the system catchment, the ratio ETP/P varies;
- The hourly maximal evapotranspiration rates. Values may be found in the literature to control the evapotranspiration rates depending on climatic conditions.

The **storage** may be used as criteria of calibration / validation. In karst aquifers, the annual storage is of a few percent of the recharge (see § 2.3.2).

6.3.3.1.1.2.6 Spatial distribution

As the input parameters (P_{eq} and PET) can be **distributed over surfaces** using RS3.0, KRM_1 (using files of distributed P_{eq} from RS3.0) may be seen as a **semi-distributed model**. Therefore an automatic workflow was developed in order to operate calculations over dozens or hundreds of input .xls files. In the frame of the project, dedicated python scripts have been written in order to process multiple .xls files referring to flow-dynamics over discretized surfaces. The workflow is presented hereafter (Figure 6—22).

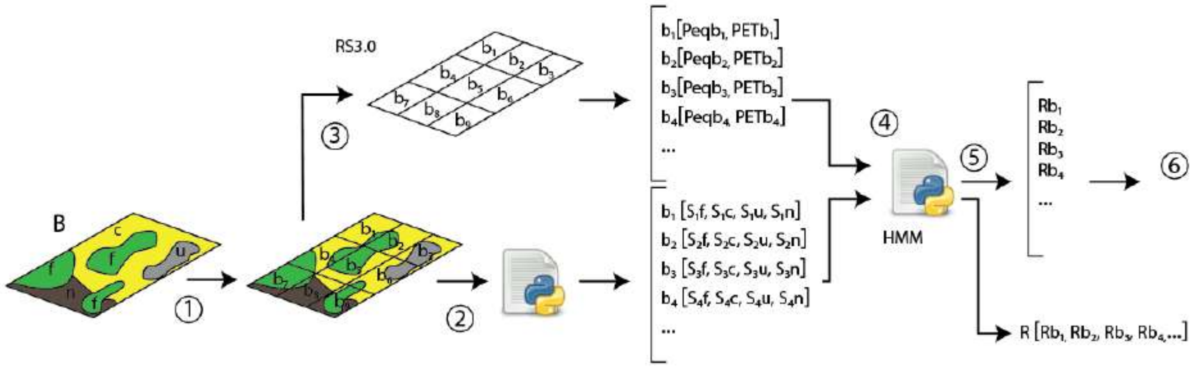


Figure 6—22. Workflow of recharge assessment over distributed surfaces; 1) subdivision of the B catchment into sub-catchments b_1, b_2, b_3, etc.; 2) calculation of the soils properties over each sub-catchment, 3) computation of distributed P_{eq} and PET over each sub-catchment; 4) application of KRM_1 over each sub-catchment, starting from the respective soil occupation and input series P_{eq} and PET; 5) computation of the global recharge R over the catchment B and the distributed recharge over the sub-catchments Rb_1, Rb_2, Rb_3, etc.; 6) further flow modelling (for instance hydraulic pipe-flow model).

6.3.3.2. Model inputs

6.3.3.2.1. Catchment areas and land-use

Catchment areas of BC and BV are characterized by the presence of **thick developed soils** (up to three meters) and the **lack of apparent infiltration features** such as active swallow-holes. Carbonate outcrops are scarce. These are mainly covered by **forests** (64% of the territory), **cultivated lands** (33%) and **urban or denudated areas** (about 3%). Forests are constituted by mixed deciduous and coniferous trees, mainly beeches (36%), silver firs (25%), spruce (18%) and ashes (~5%). Cultivated lands consist in various crop rotations that are harvested all along the year: maize, corn, alfalfa, beet, sunflower and colza. Downstream from Creugenat, pastures dominate. Urban areas cover a minor proportion of these two catchment areas, and denudated zones (i.e. rocky zones without cover, lakes, etc.) are anecdotic.

Catchment areas of BC and BV system are subdivided into sub-catchments of nearly 500*500 m each (Figure 6—23). Some of these sub-catchments may also entail an upstream allogenic contribution (see §. 6.1, Fig. 8b): BC is subdivided into **237 sub-catchments** (incl. 15 allogenic sub-catchments) and BV is subdivided into **76 sub-catchments** (incl. 5 allogenic sub-catchments). The surface of each sub-catchment is discretized in 4 classes: forests, cultivated lands, urban zones and uncovered zones (i.e. denudated). The Table 6—4 gives the resume for BC and BV catchment areas.

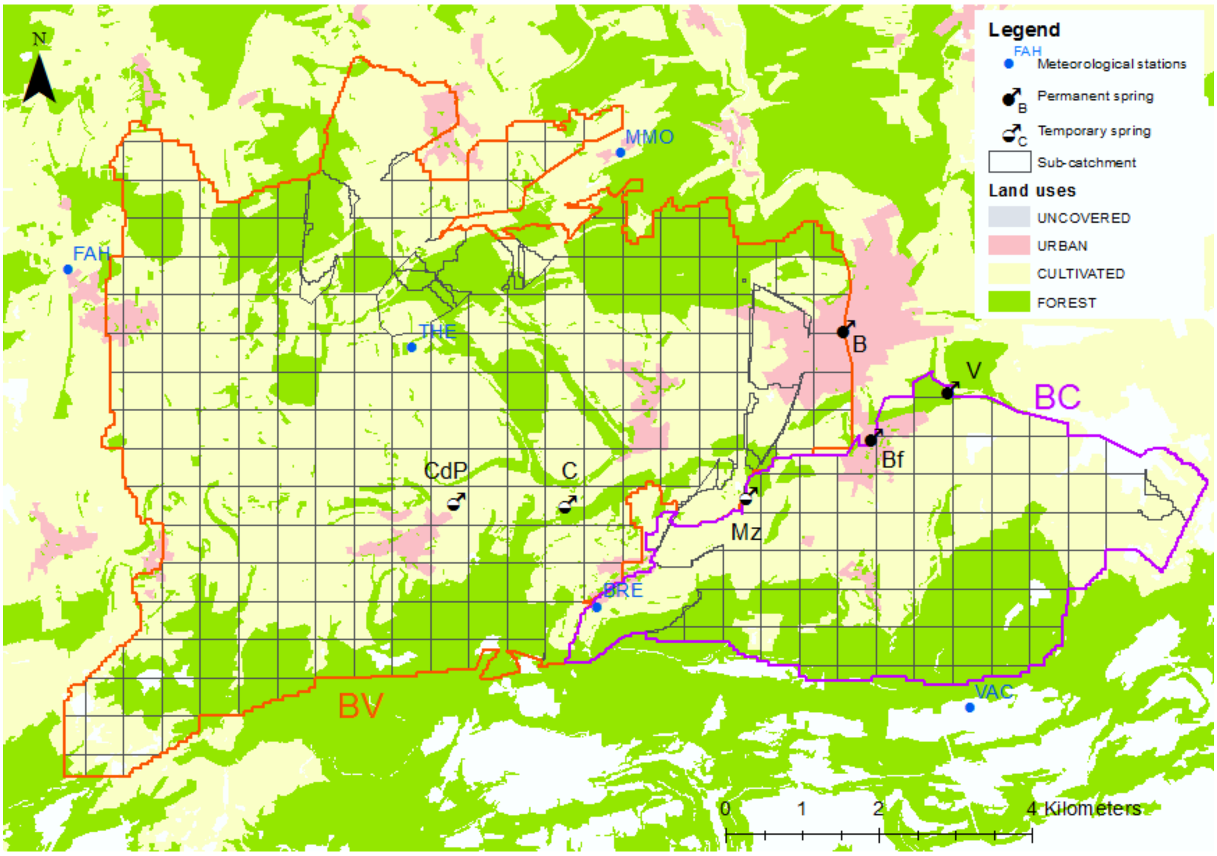


Figure 6—23. Land uses over the BC and BV catchment areas and location of the main meteorological stations FAH, MMO, THE, VAC and BRE. MTO is located 4 km eastward from VAC, out of the map.

Catchment	Forest areas [km^2]	Crops areas [km^2]	Urban areas [km^2]	Undefined areas [km^2]	Total [km^2]
BC	18.8	34.6	2.8	0.7	**56.9**
BV	7	10.5	0.6	0.7	**18.9**

Table 6—4. Respective surface and land-uses of the BC and BV catchment areas

6.3.3.2.2. Equivalent precipitation P_{eq} (rainfall data and meteorological stations)

Equivalent precipitations (P_{eq}) are obtained by the interpolation of records from the nearby meteorological stations. Meteorological stations are selected based on: (i) the location of the station, (ii) the availability of the data over the period, and (iii) the records time-step. 2003 is an extremely dry year for the decades compared to the years 2002 and 2004 for which hydrological regimes reveal more representatives for the decades.

Six meteorological stations do exist in a close perimeter of the catchment areas (i.e. within 20 km): Fahy (FAH), Montenol (MTO), Mormont (MMO), Vacherie-Mouillard (VAC), Theodoncourt (THE) and Bressaucourt (BRE). Locations and characteristics of the stations are respectively displayed in Figure 6—23 and in Table 6—3. FAH is the unique official station from the Swiss meteorological office; the time series entails hourly measurements of high accuracy. Additional parameters are also available at FAH: temperature (hourly average), evapotranspiration (daily sum), and snow (daily residual thickness at 5:40 am). The five other meteorological stations are part of the JU cantonal observation network and they only report daily data.

Analyze of the meteorological stations is discussed in Appendix 10.13. This shows that FAH, THE and BRE are the most representative stations regarding precipitation to be considered in the recharge simulations. Furthermore, disparities of precipitation for these three stations have been analyzed for the period 2002-2004.

These show that misfits between stations are usually about 2 to 5% but they may reach up to 30% for short events! Such disparities should be kept in mind for the results of the recharge simulations.

The interpolation method for computing distributed precipitation rates is the Shepard method (Shepard [1968]). Precipitations rates are computed depending on inverse distance weighting.

A non-distributed equivalent precipitation time-series (ND P_{eq}) is computed over the whole catchment using the three stations in these respective proportions: THE (45%), BRE (33%), FAH (22%) at hourly time step. ND P_{eq} will be considered as the mean representative precipitation rate to initiate the calibration.

ND P_{eq} reaches **3'440 mm over the 3-years period** (2002-2004). Over this period, the respective P_{eq} rates for the meteorological stations FAH, BRE and THE are 3112 mm, 3546 mm and 3386 mm, i.e. more than 400 mm of difference between the lowest and the highest cumulative. Such a difference - i.e. 15% - may be considered as the natural distribution of the rainfall, but it may also reveal local deficiencies in the measurements (wind disturbances, local relief effects, etc.).

A distributed equivalent precipitation time-series (D P_{eq}) is computed over the 237 + 76 sub-catchments for the 3-years period (2002-2004). In average D Peq reaches **3380 mm**.

6.3.3.2.3. Evapotranspiration

Potential evapotranspiration (PET) is computed at FAH at hourly time-step (MeteoSuisse). The station is located at 596 m a.s.l. As the catchment area equally ranges from 400 to 800 m a.s.l, measured values are assumed to be representative of the whole catchment area. PET values at FAH will be then considered for the whole catchment. The average PET at FAH for the period 2000-2012 is about **550 mm/year** (Table 6—5). For the 3-years period 2002-2004, **cumulated PET is about 1765 mm**. Values show moderate variations from a year to another (usually less than 50 mm). 2003 and 2011 were dry years, showing extreme records of PET.

Year\months	1	2	3	4	5	6	7	8	9	10	11	12	Sum
2000	3.1	6.8	25.7	53.9	70.4	127.9	81.7	88.2	44.1	16.0	11.3	6.0	**535.0**
2001	2.6	5.5	14.8	26.6	82.5	107.9	110.7	87.7	20.7	25.1	8.2	6.1	**498.6**
2002	4.4	4.8	37.8	64.3	71.7	111.5	82.2	54.9	30.1	18.1	5.9	2.3	**487.9**
2003	2.1	11.0	56.8	79.3	62.5	125.2	146.4	177.6	70.5	20.7	10.7	5.3	**768.1**
2004	2.2	8.8	34.6	48.2	96.1	87.7	102.5	57.9	44.8	17.6	4.5	3.8	**508.7**
2005	3.6	5.6	30.2	49.1	82.4	117.9	94.0	73.7	32.7	27.9	9.8	3.4	**530.2**
2006	4.3	3.2	20.2	54.3	51.9	132.2	157.2	48.5	36.4	20.7	16.1	9.0	**554.0**
2007	2.0	8.1	26.5	122.1	64.7	62.8	87.7	61.7	43.0	23.9	8.3	7.3	**518.0**
2008	4.7	12.8	23.7	36.5	86.5	76.1	96.7	72.9	37.8	20.5	8.0	3.5	**479.8**
2009	4.5	5.6	27.5	61.9	85.3	90.3	97.5	110.0	47.6	26.1	11.4	3.9	**571.5**
2010	1.6	6.0	32.3	83.0	43.9	83.4	131.0	68.5	49.9	22.8	7.2	3.5	**532.7**
2011	2.9	5.9	41.0	100.4	125.3	83.0	85.3	88.4	59.2	26.7	9.8	3.2	**631.1**
2012	2.2	8.1	57.3	34.3	83.8	71.9	96.1	88.7	40.7	20.5	8.5		**511.9**
Average	**3.1**	**7.1**	**33.0**	**62.6**	**77.5**	**98.3**	**105.3**	**83.0**	**42.9**	**22.1**	**9.2**	**4.8**	**548.3**

Table 6—5. Monthly averages of evapotranspiration rates (in mm) computed at FAH over the period 2000-2012 (data MeteoSuisse).

6.3.3.3. Calibration procedure

In order to save computation time, KRM_1 is first calibrated with the non-distributed equivalent precipitation (**ND P_{eq}**) as input. Model parameters are progressively adjusted according to a predetermined sequence:

i. Adjustment of the Discharge Balance Coefficient **VCC** (see Appendix 10.11) over the calibration period. Interception reservoirs parameters (**$H_{max\ inter}$, K_{over}, a_{inter}**) and soils reservoirs capacities (**H_t, H_0**) are adjusted at that stage. The calibration is considered as accurate if the hydrological balance is equilibrated and if RET is the order of 40% of the equivalent precipitation;

ii. Adjustment of exchange modalities between the conduits and the surrounding storage features (adjustment of effective porosity **η** and **α** in the exchanger module).

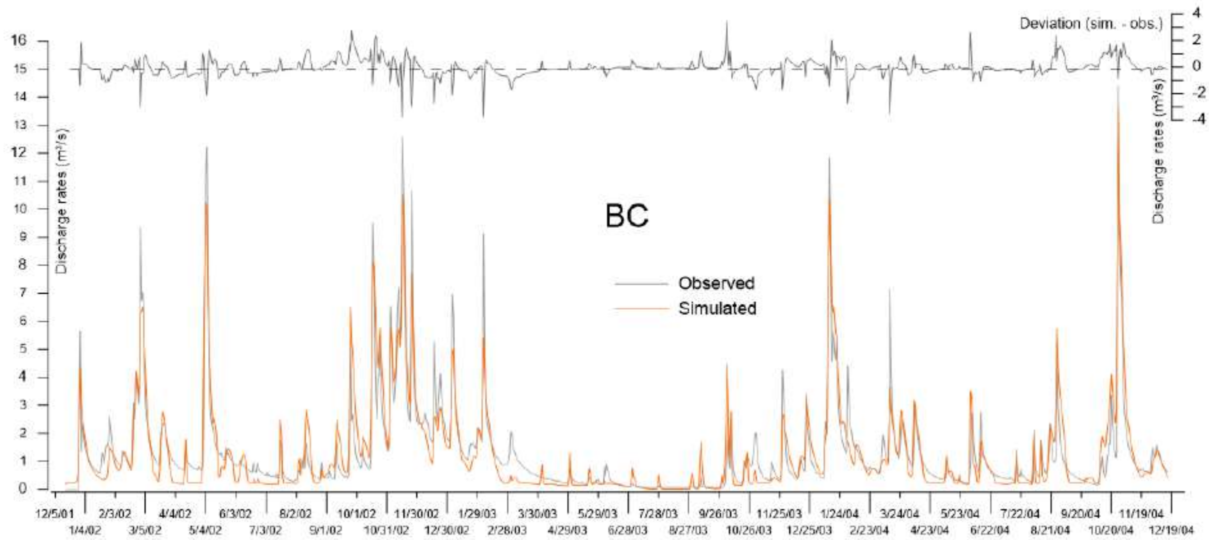
The procedure for the calibration is semi-automatic. A dedicated Python has been developed to test the sensibility of parameters and to calibrate the model. Optimized parameters for the calibration using the non-distributed equivalent precipitation (**ND P_{eq}**) are given in the Table 6—6. The following figures show the calibration results for the BC and the BV karst systems. RET (and ratio with P_{eq}) and values of VCC, VAR, NASH and KGE are provided to assess the accuracy of the calibration.

Parameters	**Hmax_sup [m]**	**ksup [-]**	**ktransfer [-]**	**asup [-]**	**atransfer [-]**	**coef_expHt [-]**	**ETR_Karst [-]**	**Hmax_epk [m]**
Values	0.7	0.3	1	1.8	2.1	0.005	0.90	13

Parameters	**kepk [-]**	**aepk [-]**	**kbase [-]**	**abase [-]**	**alpha [-]**	**beta [-]**	**η_c [-]**	**η_m [-]**
Values	2.5	1.5	0.002	1.05	0.8	0.2	0.001	0.01

Table 6—6. Optimized parameters for KRM_1 when applied to BC and BV flow-systems

Calibration results for BC and BV are displayed on the following figures.



SURF (km²)	**RET (mm)(%Peq)**	**VCC**	**NASH**	**KGE**
56.9	1316 (38)	0.96	0.86	0.92

Seasonal storage exchanger (%I_{eff})	**Max RET rates (mm/hr)**	**Storage soil + Epikarst min (mm) / max (mm)**
4	0.36	0 / 225

Figure 6—24. Calibration of KRM_1 for BC using ND P_{eq}. The deviation with the observed value is represented by the upper black curve (= simulation results – observed values at daily time-step)

Results of the calibration are globally satisfactory. KGE is close to 1. We can observe that **recharge is slightly underestimated** compared to the discharged volume (4% is missing). The general shape of the floods is consistent with the observations: the rising of floods are well simulated but recessions are sometimes steeper in the calibration than in reality – especially in summer. Regarding peak flows, all the largest peaks (>8 m^3/s) are underestimated compared to observed values (~15%), medium peaks (2 to 8 m^3/s) are a bit overestimated in late summer but underestimated in winter. The best match is in late autumn (November to December). Regarding small floods (up to 2 m^3/s) the best match is found in late autumn and winter, while they appear a bit overestimated in summer. Base flows are well simulated from November to April (winter) while in summer they are globally underestimated. Simulated discharges even fail to zero for the drought's event of 2003 although the Beuchire spring did not turn dry. Regarding the particular event of September 2002, the observed divergence may be related to deviations in the precipitation (see Appendix 10.13).

Regarding the BV flow-system, a first calibration based on the dimensions of 18.9 km^2 for the catchment area provided a VCC of 0.75, meaning that at least 25% of efficient infiltration is missing. As precipitation is fixed and the ratio PET/P_{eq} is set around 40%, the dimensions of the catchment area should be enlarged to 23 km^2 in order to improve VCC. This means that at least 1/5 of the catchment was possibly not identified when applying KARSYS… Regarding the 3D hydrogeological model, it appears difficult to extend the boundaries of the catchment area very much as the limits of the system are well constrained by geology. At the most the catchment area can be **extended southward over 3.3 km^2** by considering **additional allogenic contribution** (see Figure 6—25).

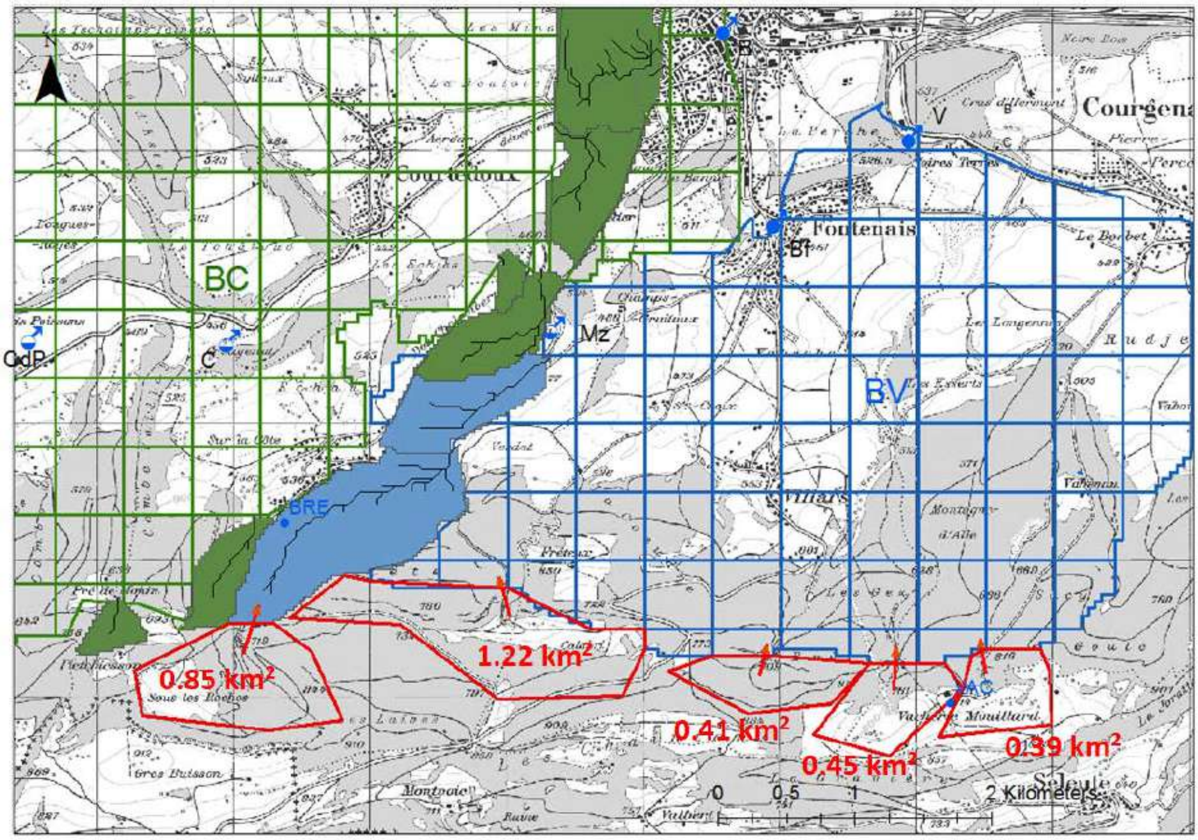
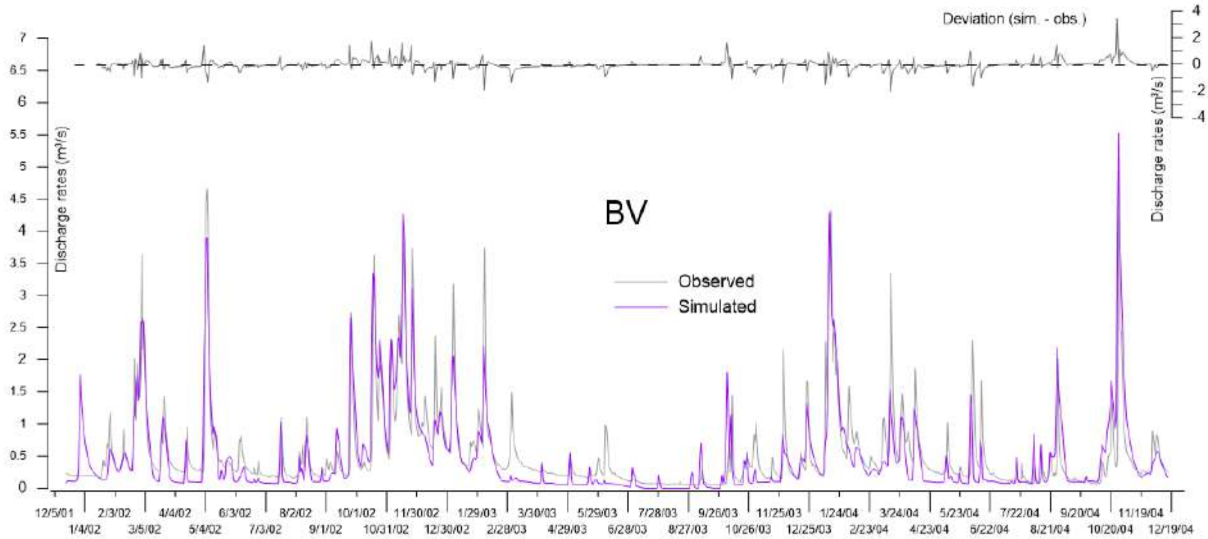


Figure 6—25. Five additional allogenic sub-catchments contribute to recharge the BV flow-system. The sum of the sub-catchments represents an additional contributing surface area of 3.3 km^2.

This enlargement is still consistent with the geological 3D model by taking into account the ephemeral streams that develop in the upstream parts of the BV catchment. These streams are supposed to contribute to the aquifer recharge by losses in the streambed. Therefore **five additional sub-catchments** (mainly covered by forests and pastures) have been integrated as allogenic inputs to the flow-system for the calibration. The overall catchment area of the **BV karst flow-system is thus expected to reach <u>22.2 km²</u>**. Corresponding calibration results are displayed in Figure 6—26.



SURF (km2)	RET (mm)(%Peq)	VCC	NASH	KGE
22.2	1337 (39)	0.92	0.68	0.84

Seasonal storage exchanger (%Ieff)	Max RET rates (mm/hr)	Storage soil + Epikarst min (mm) / max (mm)
4	0.36	0 / 225

Figure 6—26. Calibration of the recharge model for BV using ND P_{eq} (catchment enlarged to 22.2 km^2). The deviation with the observed value is represented by the upper black curve (= simulation results – observed values at daily time-step).

Although the catchment has been enlarged to 22.2 km^2, the volume of groundwater recharge still remains slightly underestimated compared to the observed discharged volume (8% is missing). Although this deficiency is visible on the curve, the general shape of the floods is consistent with the observed ones. As for BC, the shape of the base flows is well simulated from November to April (winter) while in summer base flows are globally underestimated. Simulated discharges even fail to zero for the drought's event of 2003 although the Bonnefontaine and Voyeboeuf springs were still flowing. The observed divergence for the flood events of June 2003 is probably related to deviations in the precipitation (see Appendix 10.13).

In addition to the efficiency criteria and to the visual appreciation of the curves, the accuracy of the calibration for BC and BV may also be validated through specific values:

- The computed RET is of **0.03 mm/hr** on average. Maximum values (up to **0.36 mm/hr**) are recorded in July. These are consistent with maximum rates recorded in the literature for temperate climate (see Kędziora and Olejnik [2002], §. 2.3.1.1).
- The computed storage in the low permeability volumes of the aquifer is low compared to recharge. Simulations show that nearly **4% of the recharge** is stored in the low permeability volumes via the exchanger. This value is in the order of magnitude of those indicated in §. 2.3.2 for the seasonal storage in karst aquifer.
- The **storage in the tandem soil + epikarst is about 130 mm** on average and maximum values reach 225 mm. These are consistent with values already assessed by Grasso [1999] or Perrin [2003] (cf. §. 2.3.2).

Most deviations in the calibration are related to weaknesses of the model but other reasons may also explain some of the deviations:

- Problems of measurements (meteorological data measurements, overestimation of the groundwater discharge measurements, etc.). Uncertainty on precipitation might explain a part of the deviations because, as related above (§. 6.3.3.2.2), the average deviation of the recorded values at the three stations diverges for more than 10% over the period of time… Uncertainties related to the discharge measurements at the respective springs would mean in that case that discharge rates were systematically overestimated. Even though springs regime in karst are often not well measured, experience shows that errors and uncertainties more frequently lead to an underestimation of the regime than to an overestimation.
- The possible recharge by condensation; this may provide additional water in the aquifer without precipitation occur (as presented in §. 2.3.1.3). In the conditions of BC and BV, where the average thickness of the vadose zone ranges between 50 and 200 m, and where ventilation is supposed to be limited due to the soil cover, recharge by condensation may represent 0.5 to 1 L/s/km2 at the most, i.e. max. 2.5% of the annual recharge. This reason does not appear sufficient to explain the recharge underestimation.
- The recharge contribution from the underlying Sequanian aquifer which is not considered here.
- The supposed exchange of water between BC and BV (diffluence) as identified by Schweizer [1970].

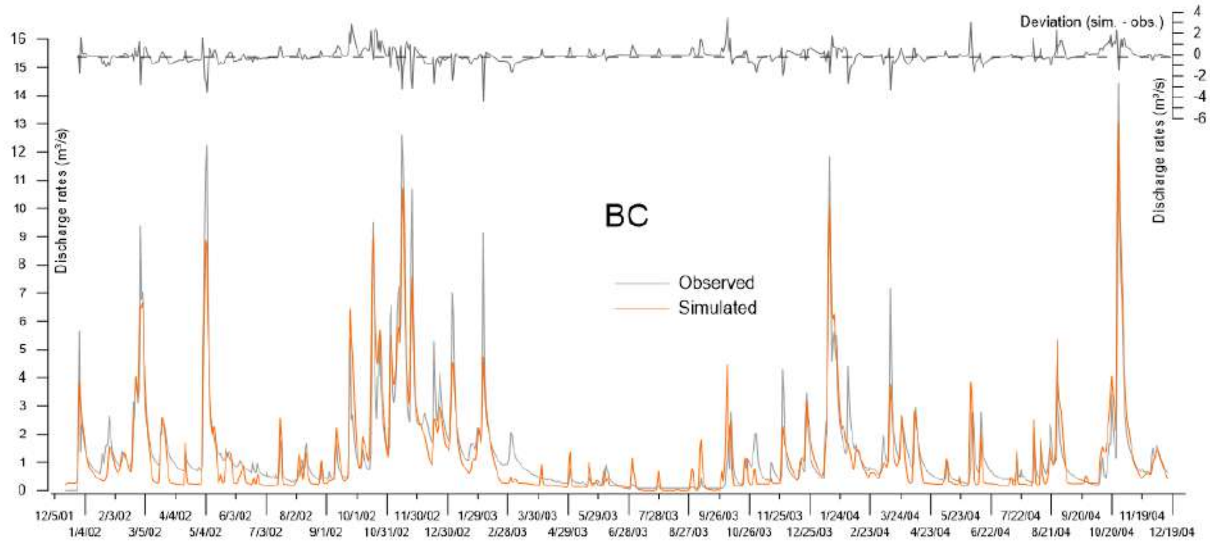
The relevance of the calibration using KRM_1 may be compared with the calibration results obtained with RS3.0 over the period 2002-2004 (see Model in Appendix 10.12). Even if VCC is better for RS3.0, computed RET does not exceed 20% of P_{eq} which is too low. Simulations results provided by KRM_1 show a lower VCC but RET is about 40% of P_{eq}, which is more realistic in this environment(Jeannin and Grasso [1995a]). Furthermore, compared to RS3.0, simulated floods in KRM_1 are not as divergent from the observations. For both models, best matches with the observed floods are in late autumn (November to December). Simulations with RS3.0 show that flood peaks are systematically underestimated in winter (January to February) while in summer (August to November) flood peaks are significantly overestimated by about a factor 2. KRM_1 provides better fits in winter than RS3.0 and flood events are globally much better reproduced. Seasonal misfits in simulation results with KRM_1 are not as systematic and pronounced as results provided by RS3.0.

6.3.3.4. Simulations

Simulations are operated over the two different periods: (i) Dec. 2001 to Dec. 2004 and (ii) August 2007.

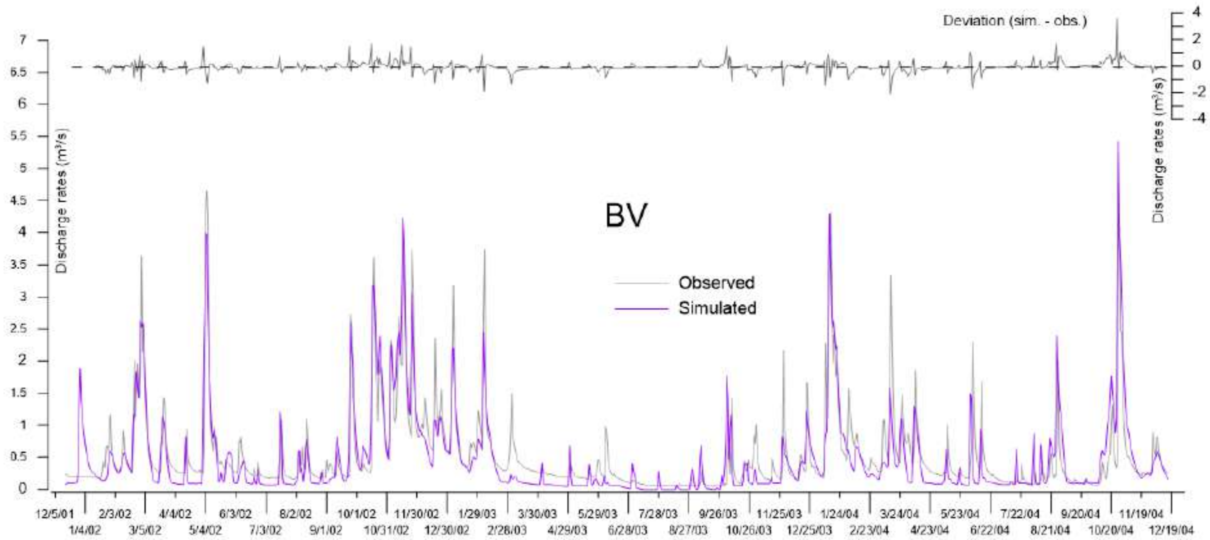
6.3.3.4.1. Period 1: Dec. 2001 – Dec. 2004

Simulations are performed over the 3-years with the **distributed equivalent precipitation (P_{eq})**. Results are presented Figure 6—27 for the BC karst flow-system and Figure 6—28 for BV after the 5 additional sub-catchments have been added.



SURF (km^2)	VCC	RET (mm)(%Peq)	NASH	KGE
57	0.9	1399 (41)	0.85	0.87

Figure 6—27. Simulated recharge for BC using the distributed P_{eq}. The deviation is given by the upper black curve (= simulation results – observed values at daily time-step).



SURF (m^2)	VCC	RET (mm)(%Peq)	NASH	KGE
22.2	0.89	1396 (40)	0.67	0.83

Figure 6—28. Simulated recharge for BV using the distributed P_{eq}. The deviation is given by the upper black curve (=simulation results – observed values at daily time-step).

Simulated time-series for BC and BV flow-systems using the **distributed P_{eq}** do not really bring better results than the calibration with **ND P_{eq}**. Regarding BC, we observe that VCC, NASH and KGE criteria decrease compared to Figure 6—26. Peak floods are systematically underestimated in winter but summer peak floods are close or a bit overestimated compared to measurements. The base-flow does not change compared to the calibration. Regarding BV, efficiency criteria are a bit better, but visually the reliability of the simulated curve is close to those obtained during the calibration. Winter peak floods are reasonably reproduced (Nov. 2002 and Jan. 2004) but summer peak floods are still underestimated (for instance in 2003). As for BC, the base-flow does not change compared to the calibration.

6.3.3.4.2. Period 2: August 2007

The event of **August 8th**, 2007 was the most significant **flood event for the last 20 years**. It generated extensive damages in Switzerland, for a total amount of 380 billion Francs (see OFEV [2010]). This event is also the biggest event recorded at the BC karst system since the beginning of the measurements (early 2001). The peak discharge rates for the Creugenat overflow reached more than 18 m^3/s and CdP was active during the whole day of **August 9th** (see Figure 6—7). The estimated discharge rate for CdP ranged between 2 and 4 m^3/s. It was reported that the discharge rate of the water emerging from Mz was in the order of several hundreds of liters per second.

Precipitation rates recorded at the meteorological stations showed that intense rainfalls occur between the 6th and the 9th of August. FAH recorded **71 mm of rainfall for August 8th**, THEO recorded 65 mm and BRE 56 mm. As indicated by the FOEN, this event corresponds to a **return period of 20 to 100 years** in the north-western Switzerland.

Groundwater recharge was simulated over the period from 01 to 13th of August with KRM_1 at hourly time-step. As the Beuchire spring was not monitored over this period, computed recharge for BC could not be validated. It could only be validated for BV.

Unlike simulations (i) which are performed over a relative "long" period of several years, the simulation (ii) only covers a couple of days and it may require a better discretization of the precipitation with the time. Then, two sets of simulation are performed for being compared. The first set is based on the **distributed equivalent precipitation (D P_{eq})** over the 13 days using the 3 stations FAH, THEO and BRE. Computed **D P_{eq}** is of **158 mm** and RET is about **30 mm** (i.e. less than 19% of P_{eq}). The second set is based on **hourly measurements** obtained at FAH which have been distributed over BC and BV catchments. **FAH P_{eq}** is about **167 mm** over the 13 days and RET is of **28.5 mm** (same as **D P_{eq}**). Results of the simulations are displayed in Figure 6—29.

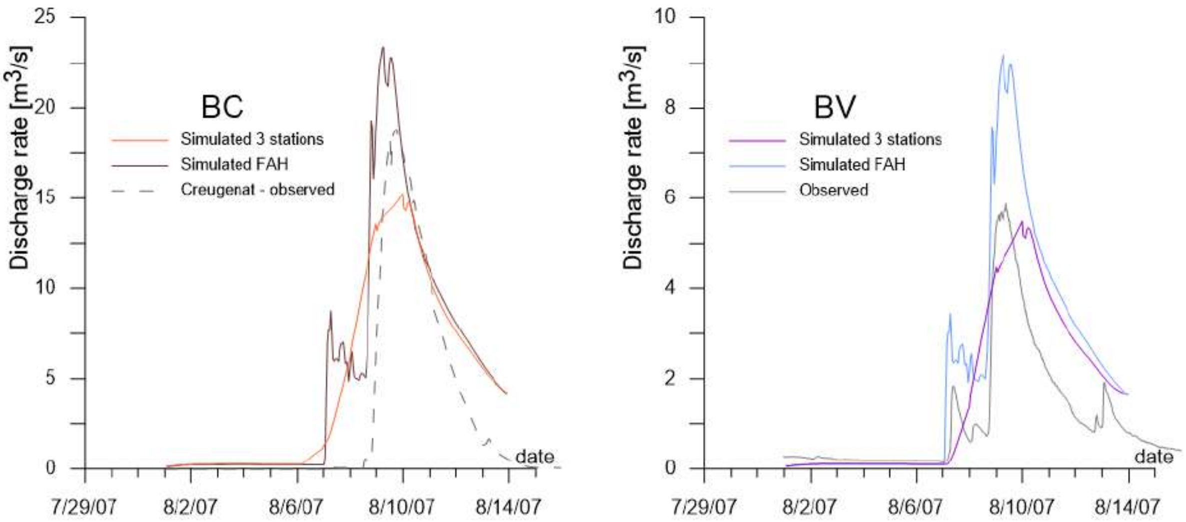


Figure 6—29. Simulated recharge for BC and BV for the flood event in August 2007. Over this period, measurements for comparison are only available for BV. As measurements for the Beuchire spring and for Creux-des-Près are missing, the simulated recharge for BC can only be compared to the measured discharge rate at Creugenat.

Results of the two simulation sets show strong differences. Globally, computed recharge with **D P_{eq}** seems to be slightly underestimated compared to measurements. For BV, the computed peak of recharge is of 5.5 m^3/s instead of 6 m^3/s, as it has been measured, and the peak is delayed for a half day. For BC, the peak of the computed recharge is of ~15 m^3/s. This seems also underestimated as we can expect that cumulated discharge rates for Beuchire, Creugenat and Creux-des-Près all together probably reached 3 + 19 +2 = **~24 m^3/s** during the peak of the event.

Computed recharge with **FAH P_{eq}** shows a better fit. Regarding BV, the simulation reproduces the small flood which occurs the 7th of August, which was not the case with D P_{eq}. The rise of the floods – i.e. the flank of the curve - is much closer to the observed rise. However, it seems that the computed recharge is a bit overestimated for BV compared to measurements (9 m^3/s instead of **6 m^3/s**) while for BC, the computed peak is of 24 m^3/s which seems to be not overestimated compared to our expectations for the flood peak (about ~24 m^3/s). As the computed recharge using **FAH P_{eq}** provides better results, the recharge files will be used as input of the hydraulic model.

These results could be also compared with those obtained by applying RS3.0 (see Appendix 10.12). Whatever the calibration, RS3.0 significantly overestimates the groundwater recharge for the flood peak (more than 50 m^3/s for BC, and about 18 m^3/s for BV). These results are consistent with the previous calibration made over the period 2002-2004 which shows that summer floods are systematically overestimated.

6.3.3.5. Discussion / conclusion on the recharge simulation models

Assessing groundwater recharge in lowland karst aquifers as in the Swiss tabular Jura cannot be addressed by using the RS3.0 model as it is commonly applied for alpine karst aquifers. In such low-elevated environments, the significance of vegetation and soils in the recharge processes become dominant as they control most of the RET which may reach up to 40% of the equivalent precipitation. This requires the development of a dedicated model. KRM_1 is a distributed reservoirs model which makes it possible to explicitly consider and to spatially discretize **interception processes** over the catchment area and **seasonal changes** in the superficial reservoirs: vegetation, soils and epikarst. Vegetative stages and the related humidity in the soils are considered. Compared to RS3.0, distributed interception reservoirs depending on land-uses and their seasonal variability are the key point in KRM_1 to address the recharge.

In addition to a strict recharge model which only computes **effective infiltration**, KRM_1 makes it possible to assess **storage dynamics** in the phreatic zone. Thanks to the "Exchanger" module, water from the conduits may penetrate in the low permeability volume of the phreatic zone depending on the rise of a pseudo hydraulic gradient. Conversely, water may be released from the low permeability volume to the conduits when hydraulic heads revert. This may be considered as a bias in the computation of the groundwater recharge as storage in the phreatic zone is more controlled by **hydraulic** (head differences between conduits and low permeability volumes) than by the precipitation / evapotranspiration. Ideally, storage should be computed in the flows model (i.e. in the hydraulic model) but most hydraulic models do not allow the computation of water exchanges through the walls of the pipes.

The calibration of KRM_1 over a 3-years period with the non-distributed **ND P_{eq}** gives reasonable results according to efficiency criteria (VCC, NASH and KGE). Besides these criteria, the relevance of the calibration may also be evaluated through the dynamics of interception, soil and epikarst reservoirs, especially regarding **RET** and **storage**. In detail, it appears that the average simulated recharge rates for BC and BV flow-systems are slightly lower than observed (7% in average). Different reasons may be suggested to explain the deficit of the simulated recharge for BC and BV: (i) dimensions of catchment areas for both systems may still probably be underestimated by about a few percent, (ii) Equivalent precipitation P_{eq} may have been probably underestimated, (iii) discharge rates measurements may be overestimated (especially the flows out of the Creugenat due to the configuration of the gauging station), (iv) the recharge by condensation is not considered here – as related by Dublyansky and Dublyansky [1998], it may reach several liters per second per square kilometer of catchment area, (v) the contribution from underlying aquifer (for instance here the Sequanian aquifer). Altogether, these reasons may represent the observed deficit in the simulated recharge.

Regarding the intensity of floods peaks, simulations with KRM_1 still show seasonal misfits: summer floods are often a bit overestimated while winter floods are often underestimated. However these misfits are not as systematic and pronounced as those obtained by using RS3.0. These deviations in KRM_1 reflect a weakness of the interception reservoirs module. Storage capacities of the forest (trees, forest floors) and of the crop reservoirs are climate and site-specific. Capacities have been parameterized thank to values collected in the literature but ideally they must be adapted to the real land-uses (type of trees, trees density, type of crops, etc.). Knowing that land-uses change over the time (forest felling, crop rotation, etc.), a perfect parameterization of these reservoirs is difficult.

Simulations performed over the 3-years period with **distributed Peq** do not provide a real better fit than the calibration using **ND P_{eq}**. However, the simulation of the groundwater recharge for the flood event in August 2007 provides better results when using only the **hourly measurements from FAH** instead of the measurements of the three stations together.

Simulated time series using distributed P_{eq}, scenarios (i) and (ii) will be used in the following section **as inputs for calibrating the hydraulic model**.

6.3.4. **Hydraulic simulations**

6.3.4.1. Introduction

Recharge models presented in section 6.3.3 provide good results for times variations of flow through the karst aquifers. In this section, **a pipe-flow model** is designed for BC and BV in order to assess heads in order to reproduce the dynamic of the different permanent and overflow springs which are responsible for the floods that threat the city of Porrentruy (Ajoie, JU, Switzerland). This requires the **consideration of hydraulic principles** in constrained and free-surface flow conduits. Therefore a pipe-flow model has been built for BC and BV systems using the Storm Water Management Model SWMM® 5.0 (Rossman [2004]). Objectives of the model are: (i) to validate the **geometry and the organization** of the supposed conduit network, (ii) to assess the **evolution of the hydraulic gradient** in the conduit-network, (iii) to assess respective **discharge rates** of permanent and overflow springs and (iv) to characterize potential **water exchanges** between BV and BC flow-systems. The model is designed with the previously generated conduit network which has been **adapted for high-flow conditions** on the basis of observed hydraulic relationships between the different outlets. The model is calibrated over the period 2002-2004 and compared to existing measurements (heads and discharge rates). This calibration process helps to confirm the position of thresholds, narrowing and of by-pass conduits which have been identified thanks to hydraulic relationships and gives an indication on the equivalent diameter of the conduits. Finally, hydraulic simulations are performed over 2007 in order to reproduce the flood event of August. Design, calibration and simulation will be discussed.

6.3.4.1.1. Hydraulic flow models

The EPA Storm Water Management Model (**SWMM**) is a dynamic **rainfall-runoff simulation** model used for single event or long-term (continuous) simulation of runoff, drainage and sewers water quantity and quality. It was basically developed for urban areas (Rossman [2004]). The runoff component of SWMM operates on a collection of sub-catchments that receive precipitation and it computes resulting runoff and pollutant loads. The routing module of SWMM transfers the runoff through a **network of pipes**, channels, storage/treatment devices, pumps, and regulators. SWMM tracks the quantity and quality of runoff generated within each sub-catchment, and the flow rate, flow depth, and quality of water for each pipe (or channel) over the simulated period. SWMM efficiently solves the 1D Saint-Venant equation based on conservation of mass and momentum (MacDonald et al. [1995]). SWMM respects the **hydraulic principles** of Darcy-Weisbach formula (Equation 2—4). Friction losses in conduits are expressed by the Manning equation (Equation 2—2).

Due to the respects of these hydraulic processes in karst conduit networks, the use of such hydraulic simulation models reveals appropriate in karst (as demonstrated by Lauritzen et al. [1985] or later by Jeannin [2001]). More recently, various contributions to karst hydraulic have been made using comparable software: Campbell and Sullivan [2002]; Peterson and Wicks [2006], Gill et al. [2013]. Such models make it possible to reproduce **hydraulic gradients** and **flows** within the karst conduits (considered as a branched-circuit of closed pipes and storage units). These models are really well designed to simulate the propagation of a recharge event through a karst massif (buffered storage, conduits narrowing, activation of overflow springs, etc.). It can also be applied for extreme recharge events (hours to days) providing hydraulic heads and discharge rates at many locations of the aquifer. Coupling the model results with the 3D model of the aquifer enables the identification and the positioning of perched outlets, as well as areas of potential flooding.

Many references do exist regarding the automatic **calibration** of SWMM models (Mancipe Muñoz et al. [2012] Kleidorfer [2009];). Most of them require a commercial license excepting a free calibrator module (SWMM 5 EA, Pathirana [2012]) which makes it possible to adjust a set of parameters in a defined oscillations range. Unfortunately, this engine is rather limited; it cannot be applied to calibrate complex models. Furthermore, most of the calibration engines admit that the structure and the organization of the conduit network are fixed parameters and they search for the best fit in adapting the length, the diameter and the roughness of the conduits. This is a limitation, as in the manual calibration, the organization of the conduits (elevation, by-pass, thresholds) may be judiciously adjusted along the calibration process.

6.3.4.2. Design of the hydraulic simulation model

The conduits organization of the **pipe-network model** is built within a GIS program (ArcGIS 10.3©). A dedicated Add-on "InpPINS" (Pina et al. [2011]) makes it possible to transfer GIS data to a SWMM project keeping all attributes about **geometries**, **junctions** and **conduits** (ID, elevation, diameter, topology, etc.). Automatic and semi-automatic processes of catchment delineation and conduits design (Malard et al. [2015a]) have been adapted in order to facilitate the transfer from GIS program data to SWMM projects. Labels and topological relations have been scripted in GIS in order to insure relationships between sub-catchments, conduits and junctions.

Regarding **junctions**; Pit-base Nodes, Vadose Nodes and Vadose-phreatic Nodes (see Malard et al. [2015a]) are plotted at the elevation of the aquifer basement. Phreatic nodes are placed 5 m below the top of the low-flow phreatic zone as the exact elevations of the phreatic conduits are not known.

Conduits diameters are roughly estimated according to the existing surveys (maps of the Creugenat and the Creux-des-Prés caves). In the vadose zone, the size of the conduits does not really impact the hydrological functioning of the system while it becomes a crucial parameter in the phreatic and epiphreatic zones where it conditions the evolution of the hydraulic heads during flood events.

As groundwater recharge has been already computed using KRM_1, implementation of sub-catchments within SWMM for computing runoff is not required. Thus, recharge files are implemented as inputs at the nodes of the conduit network (i.e. the "Pit-base Nodes").

Before calibrating parameters in SWMM, some hydraulic characteristics of BC and BV conduits-system which have been proposed for low-flow conditions (Malard et al. [2015a]) are adapted according to changes observed for high-flow conditions. These are detailed in the next sections.

6.3.4.2.1. Hydraulic characteristics of BC conduits-system

According to previous observations for high-flow conditions (§. 6.3.2.2), additional hydraulic features have been implemented in BC conduits-system.

A **threshold** has been positioned at an elevation of **438 m a.s.l.** to disconnect the Creugenat low-flow water level from the Beuchire stream (see Figure 6—5). As the hydraulic gradient raises in the aquifer this threshold becomes flooded once the Beuchire discharge rate reaches 0.7 m^3/s.

A **perched by-pass conduit** between the Creugenat and the Beuchire springs has been implemented to the low-flow conduit system to explain the observed plateau at **443 m a.s.l** (Figure 6—3) and the water table oscillations in the POR3 borehole.

Beuchire spring (B): The spring never becomes dry and even for extreme high-flow conditions the spring cannot discharge more than 3.3 m^3/s. This plateau has never been exceeded in the measurements. The Creugenat starts overflowing once the discharge rate at the Beuchire spring exceeds 2 m^3/s. This makes it possible to adjust the conduits diameter in the downstream part of the model. Minor springs (Chaumont, Boucherie and Pont-des-Graviers) are not distinguished in the model; these are merged as a unique outlet.

Champs-Montant pit (PdCM): observations show that water level only starts to rise once the Creugenat already overflows (see § 6.3.2.2.1.2). Under high-flow conditions, the water in the pit may rise very close to the ground level (~432 m a.s.l) but it never overflows... This station and its measurements are not further considered in the model calibration.

POR3 borehole (POR3): the water table oscillates in the borehole between 431 and 444 m a.s.l, max 445 m a.s.l. (Figure 6—4). As the borehole is located few dozens of meters downstream of Creugenat, measurements allow (i) to identify a threshold at 438 m a.s.l. and (ii) to infer the equivalent diameter of the conduits connecting these two points.

Creugenat overflow (C): In the downstream part of Creugenat, the conduit diameter decreases and the collapsed artificial wall represents an insurmountable barrier for the divers. Only the upstream parts have been explored and mapped. The survey gives indications of the conduits diameter. The entrance doline of Creugenat is 15 meters high and its diameter enlarges significantly from the bottom to the top of the conduit. Close to the surface, the diameter is 30 m.

Creux des Prés (CdP): the groundwater level in the cave oscillates between ~443 m (elevation of the final sump) and 465 m a.s.l (elevation of the entrance). A threshold at 443 m a.s.l should exist in order to explain the head difference with Creugenat (Δh = 8 m for less than 800 m). CdP becomes emissive when the discharge rate flowing out Creugenat exceeds 16 m^3/s (see Figure 6—8). As indicated in the previous paragraphs, the estimated discharge rate during the flood observed in August 2007 was about 2-4 m^3/s. For the same event, the maximum discharge rate at Creugenat was around 18 m^3/s. This indication is valuable to assess the maximum hydraulic gradient as well as the conduits diameter.

6.3.4.2.2. Hydraulic features of BV conduits-system

The following indications about the high-flow characteristics of the BV conduits-system were considered in the design of the SWMM hydraulic model. V and Bf springs are permanent.

Voyeboeuf spring (V): the discharge rate of the spring ranges from 0.02 to 2.5 m^3/s. High discharge values do not form any “plateau” (no overflow spring).

Bonnefontaine spring (Bf): the discharge rate of the spring for low-flow conditions is comparable to V spring (0.02 m^3/s). However, for high-flows, Bf spring may discharge up to 3 m^3/s.

Mavaloz (Mz): the cave is supposed to activate once or twice a year. The maximum discharge rate of Mz cave is assumed to be 0.5 m^3/s. These indications make it to fix the relative conduits diameter between V and Bf springs and the cave.

By-pass conduit 450 m: this threshold is supposed to connect BC and BV systems. The position and elevation of the conduit is inferred from the Figure 6—13. The equivalent diameter of the conduit is not known. Various scenarios will be tested.

6.3.4.3. Hydraulic settings and model calibration

Conduits are considered as circular and their diameter in the phreatic zone (order of magnitude) is inferred and extrapolated from existing cave surveys (Creugenat, Creux-des-Prés). The diameter of a conduit is constant between two nodes, but at the scale of the global network it is assumed that **conduits progressively enlarge downstream**. As the vadose conduits do not flood, their diameter is not considered as a limiting factor. They all have the same diameter (2 m for BC and 1 m for BV). The diameter of the phreatic conduits ranges between **0.5 m** and **3 m** (e.g. Creugenat). The **Manning's roughness** coefficient (n) for conduits is fixed at **0.05** for all conduits (Jeannin [2001]).

The complete SWMM model is presented in Figure 6—30. In the meantime, a simplified SWMM model accounting only a few conduits has been designed for comparison as well as for testing various scenarios as the computation time is faster. The design and the calibration of this simplified model are presented in Appendix 10.14.

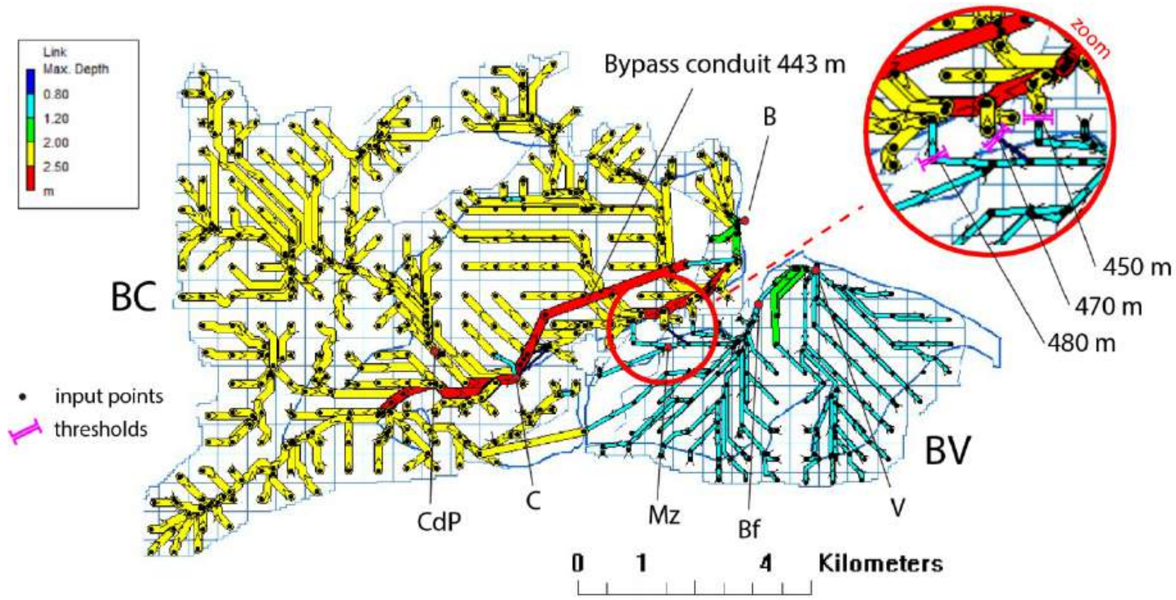


Figure 6—30. The BC/BV complete SWMM model; colors refer to the diameter of the conduits (Link Max. depth). The model entails the three additional thresholds between the two systems at 450, 470 and 480 m a.s.l., and the long and large by-pass conduit at 443 m in the downstream part of the BC karst system (3 m of diameter).

BC conduit network entails **237 input points** (= entrance conduits) while **BV** entails **76 input points**. For each input point, a specific recharge file at hourly time-step is computed by the recharge model (KRM_1) and attached to the SWMM model as a .txt file.

The **calibration** period ranges **from Dec. 2001 to Dec. 2004**. As the computation time is long, the model is calibrated over shorter selected periods (a few weeks to a few months depending on the type of events). Calibrations are manually performed until simulated outputs reach a sufficient degree of consistency. The quality of the calibration is thus validated by three means: (i) the comparison of the simulated outlets discharge rate with the observed ones (Figure 6—31, daily mean values), (ii) the comparison of the simulated hydraulic heads in the systems with the observed ones (POR3, daily mean values) or the estimated ones (Mz) (Figure 6—32) and (iii) the hydraulic relationship between the Beuchire discharge rate and the hydraulic head in Creugenat (Figure 6—33) by comparison with the Figure 6—3. Results of the calibration obtained with the simplified hydraulic model presented in Appendix 10.14 are plotted for comparison.

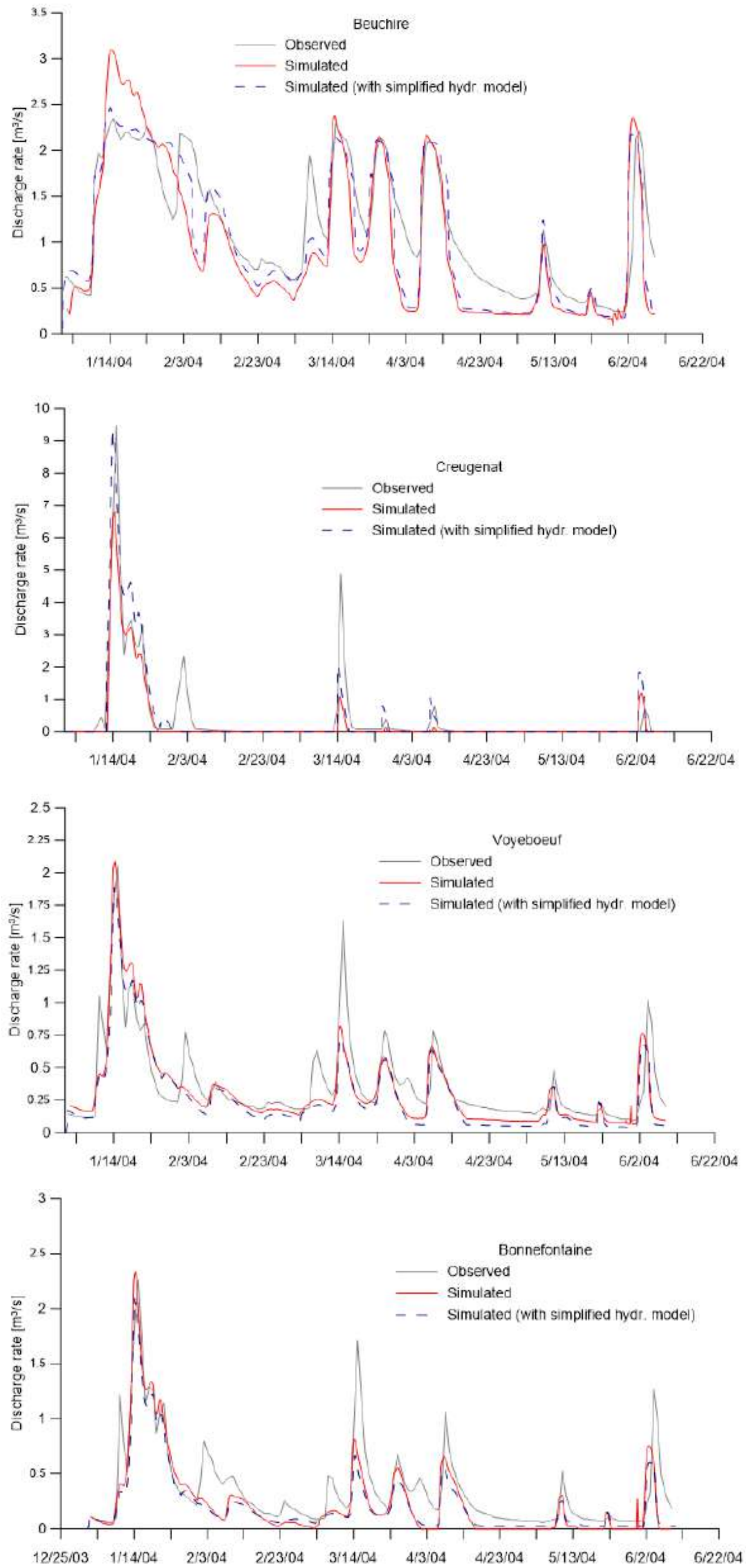


Figure 6—31. Calibration results of the simulated regimes for the four outlets (B, C, V and Bf) over a selected period (Jan. to Jun. 2004) are compared with the measurements (daily mean values) and the results of the calibration performed with the simplified hydraulic model (see Appendix 10.14)

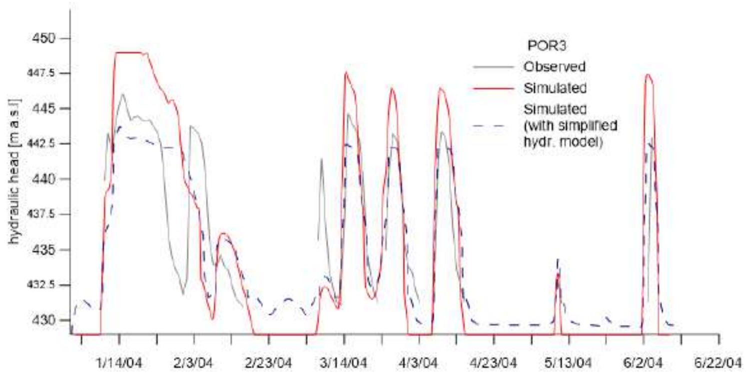
Over the considered period, simulated regimes for the **Beuchire spring** are globally consistent with the measurements. However, some differences may be observed:

- The rising of the floods are well reproduced while simulated recessions of the floods are sharper than measured and low-flow simulated regimes are underestimated compared to measurements. This observation is valid for the current and the simplified model. This results from the recharge model and not from hydraulic processes.
- The discharge rate of the flood peak in late January is overestimated of about 1 m3/s compared to the measurements which display a smoothed plateau around 2.2 m3/s. This plateau results from hydraulic head-losses which have been better fixed in the simplified model as shown by the dashed curve. Hydraulic processes in the downstream part of the flow-system are easier to calibrate with the simplified model as there are less input conduits between the Creugenat and the Beuchire spring. This observation may be repeated for the other floods of March and April 2004.
- Regarding minor floods of May 2004, it should be observed that simulated flood-peaks with the current model are of lower intensity compared to measurements and to the simulation results with the simplified hydraulic model.

Simulated regimes for **the Creugenat overflow spring** over the selected period are consistent in frequency with the observations (i.e. the activation of the overflow is well reproduced) with the exception of the flood event in late January which was not reproduced with the recharge model. However intensities of the flood-peaks are underestimated compared to the measured ones and compared to simulations obtained with the simplified hydraulic model. This proves that the underestimation results from hydraulic processes which are not well fixed in the detailed model; a part of the flows is then routed toward the Beuchire spring instead of overflowing at the Creugenat. Results of the simplified hydraulic model show that these processes are much better addressed with the simplified geometry of the conduit network. It also shows that inputs conduits in the downstream part of the flow-system (i.e. between Beuchire and Creugenat) are probably less contributive as it is supposed in the detailed model.

Simulated regimes for **Voyeboeuf and Bonnefontaine springs** show comparable results. With the exception of the flood event of late January for which the rising, the intensity of the peak and the recession are well reproduced, it could be observed that flood events of March and April are underestimated compared to measurements and recessions are sharper than observed. This results from a weakness in the recharge model. Simulated regimes for the flood events of May and June are still underestimated but it also results from an underestimation of the recharge and not from hydraulic processes. Compared to Beuchire and to Creugenat, Simulated regimes do not show significant deviation between the detailed and the simplified hydraulic models.

All over this 6 months period, the amount of water flowing via the by-pass conduits at 450 and 470 m a.s.l is negligible.



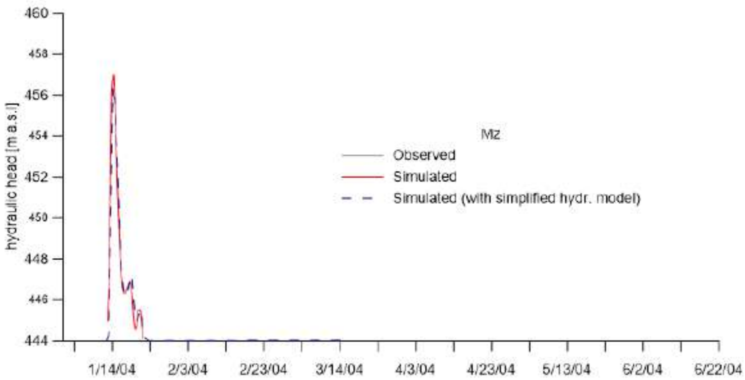


Figure 6—32. Calibration results of the hydraulic heads variations for the borehole POR3 and the Mavaloz cave (Mz) over a selected period (Jan. to Jun. 2004) are compared with the measurements (only for POR3, daily mean values) and the results of the calibration performed with the simplified hydraulic model (see Appendix 10.14)

Simulated **Hydraulic head variations in POR3** are consistent in frequency with the observations. Rising and recession parts of the curve are similar to the observed trends. Regarding the intensity, it should be observed here that the model overestimates hydraulic heads in the downstream part of the flow-system. Indeed, while measurements show maximal heads of about 443-444 m, simulated ones exceed 447.6 m a.s.l (i.e. the elevation of the ground) and the borehole becomes emissive (a few liters per second) although it is not the case in reality… Results provided by the simplified hydraulic model show a better fit. Maximal hydraulic heads are about 443 m and the borehole never overflows. This deviation results from the calibration of the hydraulic processes between Creugenat and POR3 (i.e. the length and the equivalent diameter of the narrow conduit) which is more difficult as several inputs conduits connect in the downstream part of the flow-system. Deviations prove here that the current model is not as accurate as the simplified one to reproduce variations of the hydraulic heads in this part of the flow system.

Regarding Mz, simulations results are the same whatever the models. These show that the water table in the cave rises up to 457 m for the flood event of late January but the cave does not overflow. This is consistent with general observations (Mz cave activates one or two times per year as mentioned by the aforementioned authors).

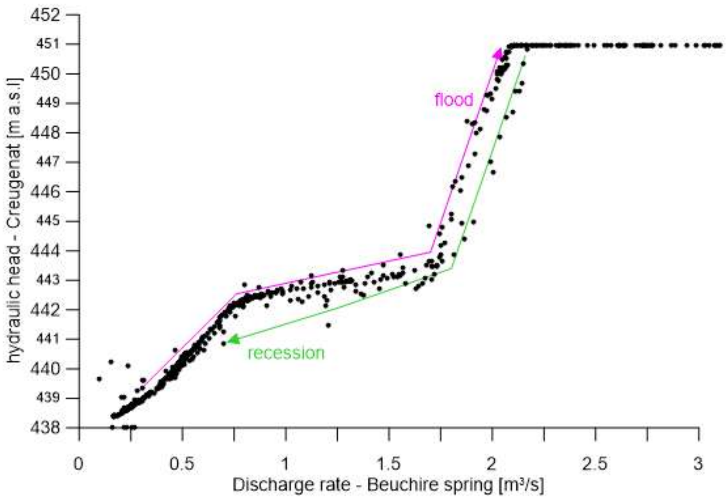


Figure 6—33. Hydraulic model calibration; comparison of the Beuchire discharge rates with the simulated hydraulic heads in the Creugenat (see Figure 6—3 for comparison)

The simulated hydraulic relationship in Figure 6—33 between the Beuchire discharge rates and the hydraulic heads in the Creugenat presents slight deviations compared to the observed relationship (Figure 6—3). Compared to the observations, here the hydraulic head in the Creugenat starts rising once the discharge rate at the Beuchire spring exceeds 100 L/s, and the threshold at 443 m a.s.l is reached for 0.8 m^3/s (instead of 1.3 m^3/s). Finally the Creugenat starts overflowing once the discharge rates at the Beuchire spring reaches 2.1 m^3/s which is consistent with the observations (2.2 m^3/s). This shows that the model reacts faster than observations on site. Indeed, for a given discharge rate at the Beuchire spring, the simulated hydraulic head in the conduit network is larger than observed on the measurements. The relationship has been better reproduced in the simplified hydraulic model. As there is less conduits in the simplified model, the hydraulic relationship between Creugenat and Beuchire is easier to calibrate. In the current model, the additional input conduits in the downstream part of the flow-system make the hydraulic relationship more difficult to calibrate.

Globally, the calibration of the hydraulic model for the BC and BV flow-systems is consistent with the observations with the exception of the downstream part of the BC flow-system where simulated hydraulic heads are difficult to calibrate. As a consequence, simulated discharge rates at Beuchire are overestimated and simulated discharge rates at Creugenat are underestimated. These deviations have been better addressed in the simplified hydraulic model (see Appendix 10.14). Indeed, as there is less conduits in the simplified model, hydraulic relationships are easier to calibrate in comparison with the detailed model which is more complex. Then, it should be concluded the detailed model does not bring better results in regard to the complexity of the conduits organization. Furthermore, the cross-comparison of the calibration results between the simplified and the complex hydraulic model tends to indicate that there are no significant input conduits in the downstream part of the flow-system. Most of the groundwater flowing out the Beuchire spring is supposed to pass via the Creugenat.

6.3.4.4. Simulation of the flood event of August 2007

Hydraulic simulations have been performed over the period of August 2007 at hourly time-step in order to reproduce the flood event of August 9th. The computed recharge using hourly measurements at FAHY are used as inputs of the simulations (see 6.3.3.4.2). Results are compared with the existing measurements and the simulations results obtained with the simplified hydraulic mode (see Appendix 10.14).

6.3.4.4.1. Simulation results for BC flow-system

The Figure 6—34 displays the computed flow regime for the Beuchire permanent spring and for the Creugenat overflow spring over the period from 04 to 14th of August (at hourly time step). Simulated overflow of CdP and simulated fluctuations of the water table in POR 3 are respectively presented in Figure 6—35 and Figure 6—36.

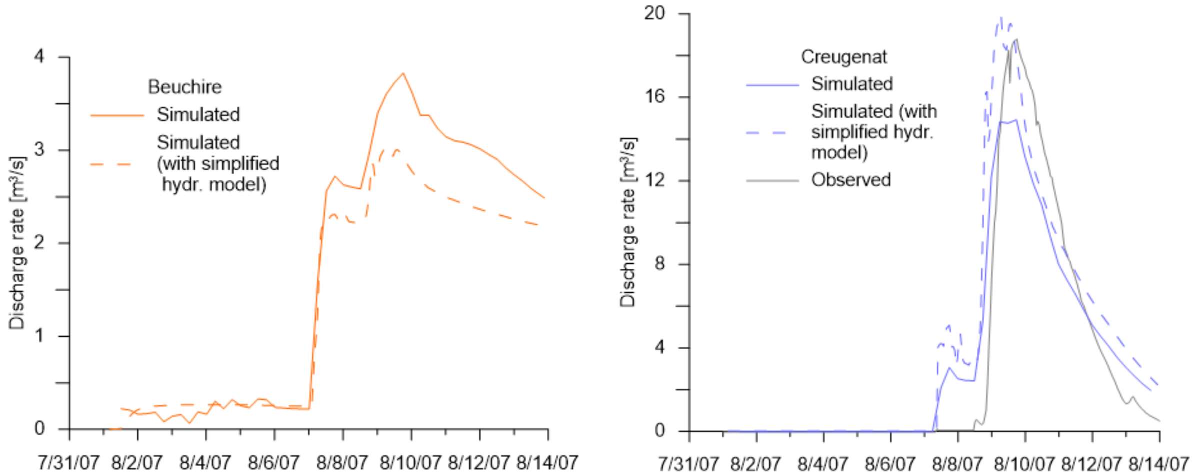


Figure 6—34. Simulated regime of the Beuchire permanent spring (left) and of the Creugenat overflow spring (right) for the flood-event of August 2007 [no measurements do exist at the Beuchire spring for comparison]; simulation results obtained with the simplified hydraulic model (see Appendix 10.14) are plotted for comparison.

Simulations results for the **Beuchire** spring, i.e. the shape of the curve and the maximal computed discharge rates (the simulated flood-peak reaches ~4 m^3/s), seem to be consistent with the expected dynamic of the spring during the flood event. Results obtained with the simplified hydraulic model gives a max discharge rate for the spring of about 3 m^3/s. As no measurements do exist for comparison, it reveals difficult to discuss the reliability of the simulations. Regarding the **Creugenat**, the simulated peak is consistent in the shape with the rising and the recession parts of the measurements. However, the peak of the flood seems underestimated; it is about 15 m^3/s while the recorded max discharge rate was of 18.5 m^3/s. The simulated flood-peak shows a small plateau which probably refers to the overflow of the Creux-des-Près. This plateau is not observed in the measurements. In comparison, the simulation performed with the simplified model gives better results as the max discharge rate reaches 20 m^3/s and no plateau forms at the top of the peak.

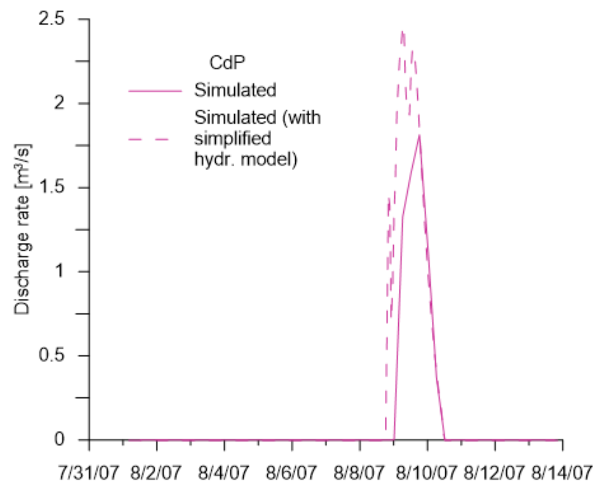


Figure 6—35. Simulated regime of the Creux-des-Prés (CdP) overflow spring for the flood-event of August 2007 [no existing measurements]; simulation results obtained with the simplified hydraulic model (see Appendix 10.14) are plotted for comparison.

The simulated overflow of **CdP** with the current hydraulic model reaches 1.8 m^3/s the 9th of August. This is consistent with the estimation made on the field (see Figure 6—7). The simulation performed with the simplified hydraulic model provides a max discharge of 2.4 m^3/s, which is also in the range of the observations.

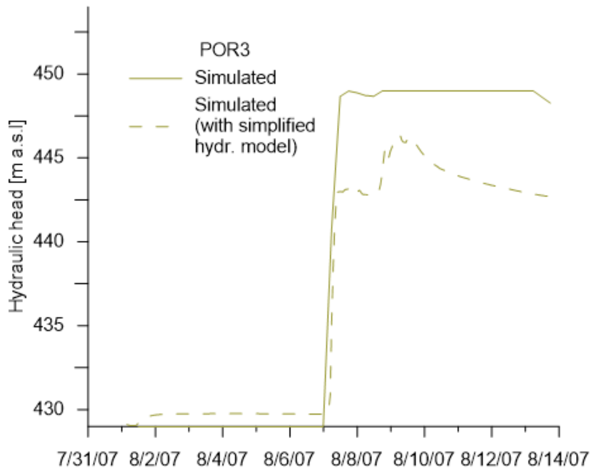


Figure 6—36. Simulated variations of the water table in POR3 for the flood-event of August 2007 [no existing measurements]; simulation results obtained with the simplified hydraulic model (see Appendix 10.14) are plotted for comparison.

Regarding **POR3**, simulations indicate that hydraulic heads rapidly reach the ground surface and the borehole is continuously emissive from 8th to 14th of August (a few liters per second). In the reality, even if no measurements do exist, no overflow was observed… The simulations results obtained with the simplified hydraulic model give a max hydraulic head of 446 m a.s.l. These results seem more reliable compared to measurements made over the period 2001-2004 or in 2012.

6.3.4.4.2. Simulation results for BV flow-system

The Figure 6—37 displays the computed flow regime for the Voyeboeuf and the Bonnefontaine permanent springs over the period from 04 to 14th of August (at hourly time step). The Figure 6—38 displays the computed overflow of Mz cave.

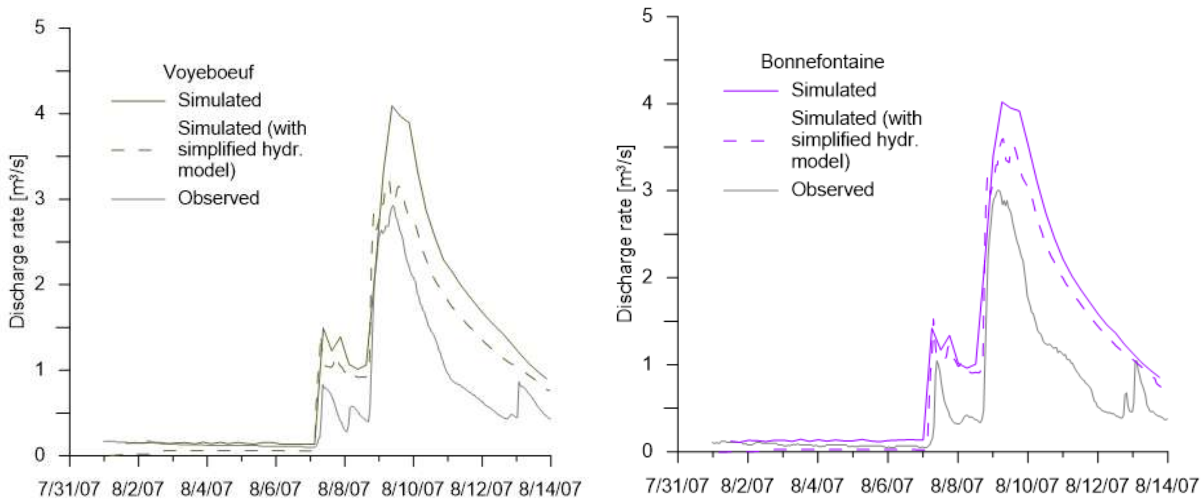


Figure 6—37. Computed regime of the Voyeboeuf and of the Bonnefontaine permanent springs for the flood-event of August 2007 [measured values for comparison]; simulation results obtained with the simplified hydraulic model (see Appendix 10.14) are plotted for comparison.

Simulations results for **V** and **Bf** springs show a consistent shape with the measurements, especially the rising part (the recession of the discharge rates is slower than observed). Regarding the intensity of the flood-peak, simulated peaks are larger than observed (4 m^3/s instead of 3 m^3/s). The simulation performed with the simplified hydraulic model gives comparable results regarding the shape of the curve but flood-peak are closer to the measurements (3.1 m^3/s for V, and 3.5 m^3/s for Bf).

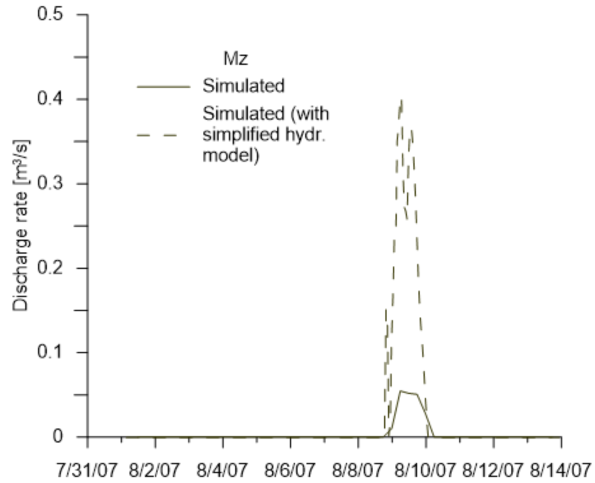


Figure 6—38. Simulated overflow rates of the Mz cave during the flood event of August 2007 [no existing measurements for comparison]; simulation results obtained with the simplified hydraulic model (see Appendix 10.14) are plotted for comparison.

During this event, **Mz cave** overflowed, what is reproduced by the model. The simulated peak discharge rate in the model reached 50 L/s. This rate is probably underestimated compared to the supposed one, which was probably in the order of several hundred of liters per second. The configuration of the entrance of the cave (partially blocked by boulders and other materials, see Figure 6—7) makes high discharge rates impossible but other minor outlets in the vicinity of Mz (for instance in the stream bed) may have been activated during this event… The simulation performed with the simplified hydraulic model provides a flood-peak of 400 L/s which seems to be a more reliable regime for this outlet.

Simulation results for this event show that a part of BV groundwater flows through the Banné anticline to feed BC. Over the 9th of August, cumulated discharge rates of the **by-pass conduits**, especially those present at **470 m** and **480 m a.s.l.**, reach ~700 L/s (for comparison, the simplified hydraulic model in Appendix gives a groundwater diffluence of about 1 m^3/s at the peak of the flood). This result demonstrates that for high-flow events, groundwater may be transferred from BV to BC, a priori by flowing through the by-pass conduits. This result should be confirmed as the presence of these by-pass conduits is supposed but still not verified. We may be sure that a part of the recharge falling on BV is transferred to BC, otherwise simulated discharge rates at Bf, V and Mz would be significantly higher than recorded ones. However, this groundwater may also be (partially or totally) transferred via minor springs emerging in the streambed of Mavaloz for which flows are routed downstream to the gauging station of Creugenat (see Figure 6—12). These results conform to the dye tracing investigations which have been performed by Schweizer [1970] but additional investigations should be undertaken in order to confirm the presence of these by-pass conduits.

6.3.4.5. Discussion / conclusion on hydraulic simulation models

In this section we designed a distributed hydraulic model for the BC and the BV flow-systems which is based on the KARSYS model and on the generated conduit network. As the conduits model was initially generated for low-flow conditions, the first step is to **adapt the conduits geometries** and properties for high-flow conditions thanks to observations and hydraulic relationships which have been measured on the field. In parallel, the model has been calibrated step-by-step and compared to measurements for checking geometries and properties of the conduits.

Thanks to these procedures, the **3D organization** and the **conduit properties** of the BC and BV conduit network have been précised (connectivity, diameter, narrowing, etc.). Their values are globally consistent with the known and surveyed sections (respectively in Creugenat and CdP caves).

The main results of the calibration and of the simulations with the distributed hydraulic model are:

- Globally, the simulated discharge rates of all the permanent outlets and the activation of the overflow springs are fairly good reproduced when compared to existing measurements. This means that the inferred organization of the conduit network and the properties of the conduits are consistent with the physical world. However, the model fails in reproducing the observed hydraulic head in the downstream part of the BC flow-system. This is evidenced by the simulated fluctuations at POR3 which are overestimated by the model.
- Two **thresholds** disrupting the hydraulic connectivity between the Creugenat and the Beuchire spring have been identified and positioned at 438 and 443 m a.s.l. A third threshold has been identified at 444 m downstream CdP. Simulation confirms that an upper **by-pass conduit** develops at about 443 m a.s.l. for more than 2 km and with a mean diameter of about 3 m.
- **Diffluences** between BC and BV have been reproduced within the model. Results show that groundwater may be transferred from BV to BC for high-flow events via the supposed by-pass conduits at 450, 470 and 480 m a.s.l. Simulations of the flood-event of August 2007 indicate that transferred water may reach 700 L/s. This result supports the observations made by Schweizer [1970] when he performed the dye-tracing test. However, as discussed above, the reliability of this test is not fully guaranteed. The existence of these conduits is still hypothetic and new investigations should be operated in the field in order to validate their existence.
- As the model is based on the distributed conduit network obtained in §. 6.1, it gives an indication of the supposed hydraulic head and discharge rate below each **discretized** autogenic sub-catchments (here the discretization is 500 m by 500 m).

In parallel, a more **simplified hydraulic model** accounting ~25 conduits instead of more than 300 in the here-detailed model has been designed (see Appendix 10.14). This model has been calibrated and simulations were run over the same period. This simplified model exclusively focuses on the **main hydraulic obstacles** which have been identified (i.e. local thresholds, local narrowing and by-pass conduits). In comparison with the complex model detailed here, the simplified model globally provides better results:

- Hydraulic head fluctuations in the downstream part of the BC flow-system are better simulated (cf. POR3). This result tends to indicate that no major tributary conduits connect with the main phreatic conduit which link Beuchire to Creugenat.
- Simulated discharge rates of the main outlets for the flood-event of August 2007 are better reproduced with this simplified model.

The main outputs of the section are:

- This section provides **procedures for designing and calibrating** hydraulic simulation models based on the KARSYS approach. KARSYS and the conduits generator provide a consistent conduit network for low-fow conditions which should be adapted for high-flows.
- Simulation results and comparison between the simplified and the complex models show that **most of the hydraulics is controlled by a few obstacles**: tresholds, narrowing, by-pass conduits, etc.
- Thus, a **simplified model** with a restricted number of conduits and focusing on these few hydraulic obstacles provides **satisfactory and even better results** as parameterization and calibration processes are simplified. This agrees with observation made by Jeannin [2001] for the Hölloch karst flow-system.
- Indirectly, calibrations and simulations made with the hydraulic models **validate the groundwater recharge** which has been previously computed over the calibration period (2001-2004) and the flood-event of August 2007.
- As the hydraulic model is able to reproduce the overflow of caves that rarely activate (i.e. the CdP), the accuracy of the forecasts may be guaranted at least for events with a **return period** of about **10 years**.
- As the hydraulic model may be fully distributed over the catchment area, it can simulate hydraulic-heads and discharge rates **at any place of the aquifer**. This mainly depends on the discretization of the infiltration model in input of the conduits generator (§. 6.1). This reveals **efficient for applied issues** such as flood-hazards, underground construction, hydropower potential, etc. (applications in progress).

Finally, the Figure 6—39 displays the inferred organization of the "main" conduit network for BC and BV as a shematic profile. As demonstrated above and with the simplified model in Appendix 10.14, these are the minimal features / properties of the conduit network which should explicitly be taken into consideration for designing a hydraulic model of the six outlets (B, C, CdP, Bf, V, Mz).

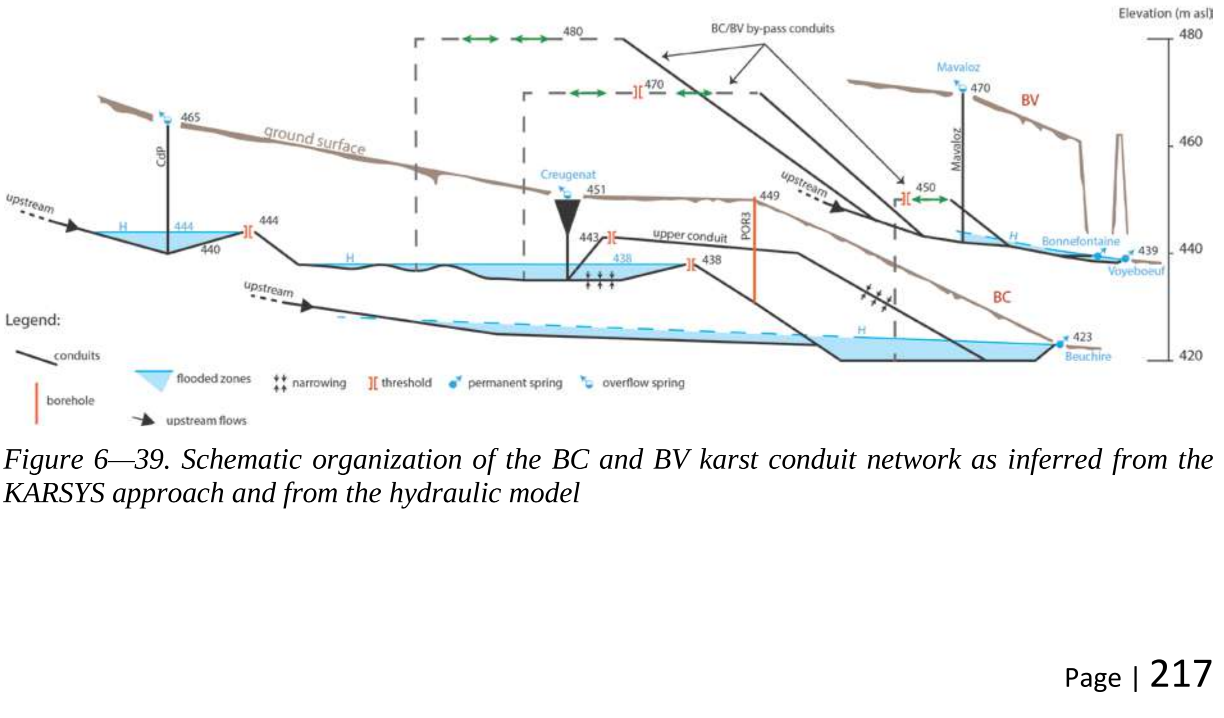


Figure 6—39. Schematic organization of the BC and BV karst conduit network as inferred from the KARSYS approach and from the hydraulic model

This figure shows that the organization of the conduit network is **complex**. The profile crossing the BC flow-system evidence that flooded zones at Creugenat and CdP are perched phreatic zones which overflow in cascade toward the Beuchire spring or flowing through the upper by-passing conduit. Three supposed by-pass conduits link BC and BV at 450, 470 and 480 m a.s.l. These have been suggested through (i) the KARSYS model, (ii) the calibration of the hydraulic models (the complex and the simplified one) and (iii) the dye-tracer tests made by Schweizer [1970].

In order to **improve the accuracy** of the hydraulic model, it would be interesting to acquire and consider the following data which would be really usefull to precise the hydraulic model, especially in the upstream part of the flow-systems:

- Hydraulic heads variations at Mz. With these data we could better estimate the transferred flows between BV and BC
- Hydraulic heads variations at CdP. This could give a better estimate on the evolution of the hydraulic gradient in the upstream part of the BC flow-system.

6.3.5. Discussion / conclusion on flow simulations in karst

Extensions related to hydrological and hydraulic simulations have been developed to the original KARSYS approach. It provides temporal results on the karst flow-system (recharge, storage, hydraulic heads, discharge, etc.) which base on spatial parameters obtained through the application of KARSYS. Indeed, spatial properties of the flow-systems may be deduced and quantified from the explicit 3D conceptual model:

- **The location and distribution of the resp. supposed vadose and saturated zones of the aquifer where the conduits develop:** this provides concrete elements on the supposed organization of the conduit network and their characteristics (orientation of the conduits, connectivity, length, etc.);
- **The extensions of the underground drainage area and the respective catchments over the ground surface:** (i) discretization of the recharge areas depending on the elevation, the soils thickness or the land-uses and (i) the type of the recharge processes (autogenic, allogenic, mixed or undefined);

This spatial information is a prerequisite for the design, the parameterization and the calibration of **hydrological (recharge)** and **hydraulic (flow)** models. The application of KARSYS to the Beuchire-Creugenat (BC) and the Bonnefontaine-Voyeboeuf (BV) karst systems, combined with a recharge simulation model and a hydraulic pipe-flow model made it possible to assess:

(i) **The hydrological regime of the flow-system(s)**, i.e. the discretized recharge over the catchments, by taking into account land-uses and storage processes in the different zones of the aquifers (soils / epikarst and low permeable volumes of the phreatic zone);

(ii) **The hydraulics of all permanent and overflow springs** by simulating the karst hydraulics. Properties of the karst conduit network are adapted to high-flow conditions and tested by calibration. This procedure provides the high-flow characteristics of the conduit network (thresholds, by-pass conduits, equivalent diameter of the conduits, etc.) which are further considered in the flow simulations.

In order to simulate groundwater flows (fluxes and heads) the following **steps** were necessary: (0) the establishment of the KARSYS 3D conceptual model, (1) the generation of the supposed karst conduits and of the catchment areas, (2) the computation of a distributed groundwater recharge, (3) the adaptation of the hydrological and hydraulic characteristics of the flow-system(s) for high-flow conditions (catchment and conduit network properties) and (4) the design / computation of a hydraulic flow model (even a simplified one accounting for the main conduits). The workflow of KARSYS + hydrological and hydraulic extensions is presented Figure 6—40.

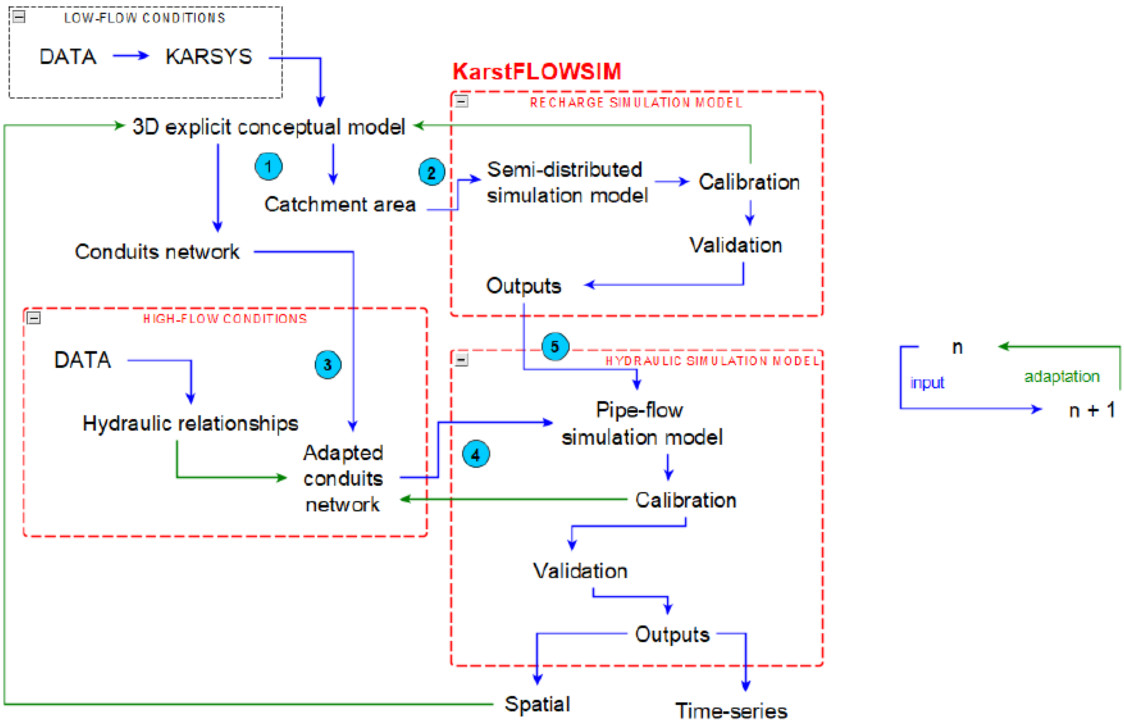


Figure 6—40. Workflow of KARSYS extensions to assess the hydraulic functioning of karst flow-systems on the basis of a KARSYS model. ***1)*** *The 3D KARSYS model (output §. 5.2.1.4 for low-flow conditions) is further analyzed for the generation of the conduit network (low-flow conditions) and the delineation of the catchment area (§. 6.1).* ***2)*** *The catchment area and the discretized sub-catchments are implemented in the recharge simulation model (here KRM_1, §. 6.3.3.1.1.2).* ***3)*** *the generated geometry of the conduit network is tested for high-flow conditions and adapted if necessary.* ***4)*** *The adapted geometry of the conduit network is used for the pipe-flow simulation model which considers the previously computed recharge* ***5)*** *as input (§. 6.3.4).*

Outputs of the pipe-flow simulation model (**spatial** and **time-series**) may be used for different issues (e.g. for flood-hazards assessment). This is an iterative approach; each model, calibration and result providing concrete indications on the way to adapt the conceptual model.

In comparison with recent publications dedicated to flow modelling in karst aquifers, hydrological and hydraulic extensions to KARSYS provides an integrated approach from conceptual models (KARSYS) to numerical models. The Table 6—7 compares recent models published by a set of selected authors working on conduits and flow modeling in karst aquifers with the contribution provided by KARSYS + hydrological and hydraulic extensions.

Models or authors	Catchment	Conduits	Recharge	Hydraulic	Transport
Gill *et al.* [2013]	No method for delineating the catchment area	Conduits are deterministically inferred	Distributed runoff-routing model,	Distributed Pipe model (Infowork CS),	No
Hartmann *et al.* [2012]	Catchment properties inferred from functional approaches	No generator	Various distributed recharge models	No consideration of hydraulic processes	No
SKS: Borghi [2013]	No method for delineating the catchment area	Stochastic approach considering vadose/phreatic zones + fractures + speleogenetic phases	Distributed runoff-routing model,	Head fields simulation	Simulation of conservative tracers flow
Chen and Goldscheider [2014]	No method for delineating the catchment area	Conduits are deterministically inferred	Reservoir model, spatially distributed	Distributed SWMM model: discharge and hydraulic-heads simulation	No
KARSYS + extensions	Catchment boundaries (incl. autogenic + allogenic areas) inferred from KARSYS	Automatic generator considering catchment, vadose/phreatic zones + inception horizons	Two distributed recharge models: elevation-dominated and surface-processes dominated	Distributed SWMM model, discharge and hydraulic-heads simulation	No

Table 6—7. Contribution of KARSYS + hydrological and hydraulic extensions to recharge and flow modelling in karst aquifers compared to other recent models.

The application of KARSYS + hydrological and hydraulic extensions provide similar results as the models developed by Gill *et al.* [2013], Borghi [2013] and Chen and Goldscheider [2014]. In addition, KARSYS also provides a 3D conceptual model of the aquifer and rules for the delineation of the catchment area. Different models of the conduit network may be generated and resulting conduits may be combined with recharge-simulation models to assess the hydraulics of the flow-system.

6.3.5.1. Contribution of distributed hydrological models

Basically, the original KARSYS approach provides spatial characteristics of the flow-system for low-flow conditions which are used as inputs for designing recharge simulation models. Minimal characteristics for such a model are: the geometry of the catchment area (including a distinction between autogenic and allogenic areas), the relief and the respective land-uses (glaciers, vegetation, crops, etc.).

In the previous sections, groundwater recharge (i.e. effective infiltration) is assessed by using hydrological models (RS3.0 or KRM_1) which are distributed over the catchment area of the flow-system. Applications showed that the selection of the most appropriate recharge simulation model depends on the expecting dominating recharge processes (Figure 6—41). For a system “**A**” (**elevation-dominated recharge**), the recharge may be computed using RS3.0 as it mainly depends on the elevation contrasted recharge processes (rainfall, snow-melt, glacier melting, etc.). For a system “**B**” (**surface-processes-dominated recharge**), the recharge may be computed using KRM_1. In both cases, equivalent precipitations ($\mathbf{P_{eq}}$) are computed with RS3.0.

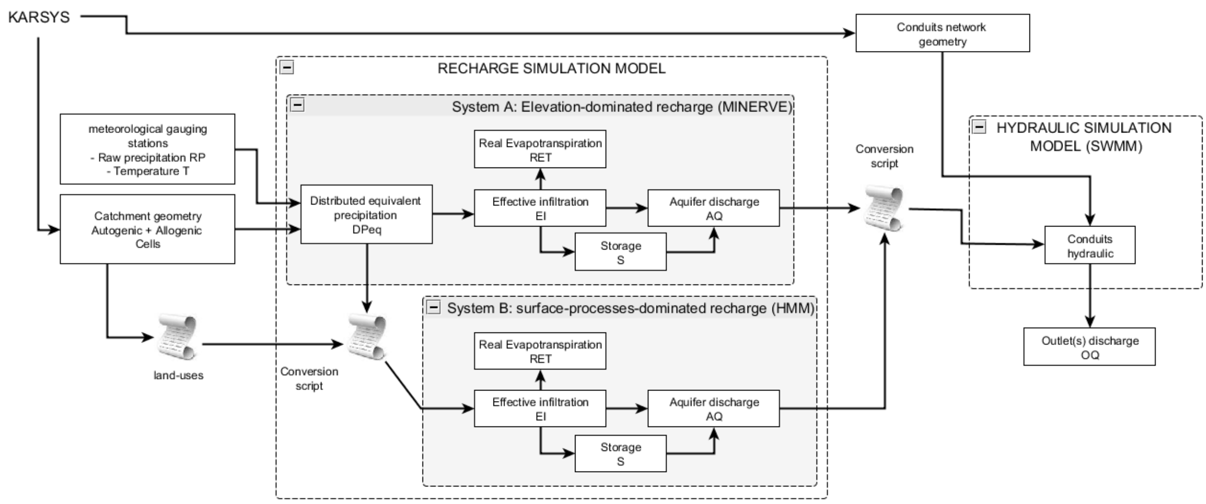


*Figure 6—41. Recommended workflow for assessing groundwater recharge depending on the dominating recharge process ("**A**" = elevation-dominated recharge, "**B**" = surface-processes-dominated recharge). Distributed recharge may be further introduced as input for hydraulic models (such as SWMM©).*

Effects of vegetation, soils, sub-soils, epikarst and unsaturated zones in the flow processes appear to be negligible in **elevation-dominated system** as the recharge contrast in the catchment area is high which induces an overriding control of the snow (melting processes are mainly controlled by the elevation) and of the rainfall (higher gradient with the elevation) on the recharge compared to **lower elevated karst environments**. These effects become dominant for low-elevated aquifers as demonstrated for the BC and BV karst flow-systems of the tabular Jura or for other systems of the folded Jura (cf. ISSKA [2013] or Weber et al. [2012]). For these types of systems, recharge processes are more sensitive to vegetation cycles and soil / sub-soils processes. This means however that the spatial variations of recharge are lower than in systems with high relief.

In a first appreciation, the application of the recharge models depends on the geographic context (which is mainly dominated by the elevation as it controls the soil development and the presence of vegetation) and of the hydro-climatic regime. At that stage of the demonstration, the Table 6—8 and the Figure 6—42 indicate the appropriate geographic and hydro-climatic contexts in Switzerland for which RS3.0 and KRM_1 may be applied with reliability. Five zones are distinguished for the applicability of these distributed recharge models.

Expected type of karst system	Recommended recharge simulation model	Geographic contexts	Hydro-climatic dominant regimes
Elevation-dominated recharge	RS3.0	Moderate (1000-1500 m) to higher elevation Ex. Alps	Glacial, glacio-nival, nivo-glacial, alpine nival, southern nivo-pluvial, southern pluvio-nival, nival of transition
Surface-processes-dominated recharge	KRM_1	Low to moderate elevation (300-1000 m) Ex. Tabular Jura, Folded Jura and lower part of the Prealps	jurassian nivo-pluvial, jurassian pluvio-nival, pluvial of transition, southern nivo-pluvial, southern pluvio-nival

Table 6—8. Appropriate contexts for the application of recharge simulation models in karst environments (at least in Switzerland)

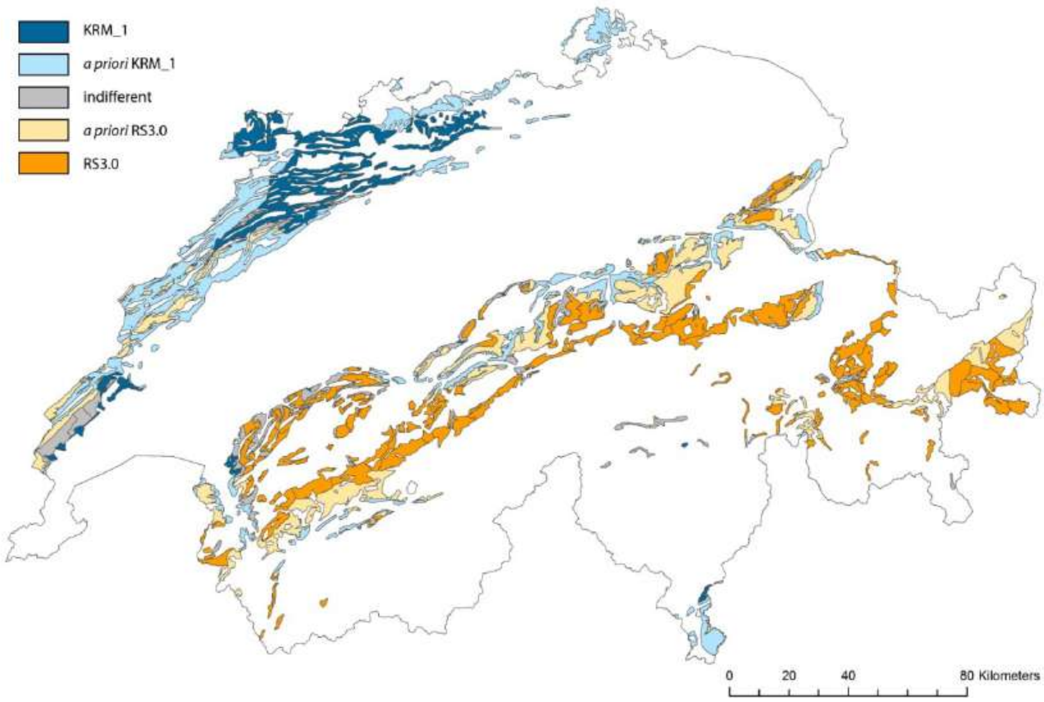


Figure 6—42. Recommended recharge simulation models for karst aquifers in Switzerland. For grey zones, there is no recommended model, RS3.0 or KRM_1 may be a priori used providing the same interval of confidence; on the blue zones, KRM_1 could be applied with a high degree of confidence (dark blue) or a moderate degree of reliability (light blue); on the orange zones, RS3.0 should be applied with a high degree of confidence (dark orange) or a moderate degree of reliability (light orange).

Furthermore, applications of these hydrological models prove that systems with spring's hydrograph dominated by the shape of the recharge may be well reproduced by a strict hydrological model. On the opposite, systems for which spring's hydrograph is significantly modified by hydraulic processes in the aquifer may not be well reproduced as hydraulic parameters are not considered at all.

For instance, the application of RS3.0 in elevation-dominated systems with a unique outlet shows that the regime of the flow-system may be well reproduced without considering conduits geometry, or hydraulic processes. Applications to Flims (Weber et al. [2011]) or to the Areuse spring (ISSKA [2014c]) demonstrate that the hydrograph of a karst flow-system with a few springs may still be adequately simulated by only using hydrological models (here RS3.0) and by adding a few discharge / level relationships (**implicit consideration of the hydraulic processes**).

On the opposite, if several outlets do exist for a same flow-system or if several phases of karstification occurred in the aquifer (for instance the BC and BV karst flow-systems), flow become more controlled by hydraulic processes (for instance the Brunnmühle-Wasserhooliloch karst flow-system, cf. Jeannin et al. [2015a]) and spring's hydrographs cannot be properly assessed without **explicitely considering hydraulic processes**. These observations show that a distinction between **recharge-dominated flow-systems** and **conduits-dominated flow-systems** could be done as already observed by Covington et al. [2009].

Then, depending on the context and if the user is only interested to produce a time-series (i.e a spring's hydrograph) the most appropriate recharge simulation model may be selected and depending on the type of the flow system (recharge- or conduits-dominated), hydraulic processes may be considered via the establishment of a SWMM model or not considered at all (Figure 6—43).

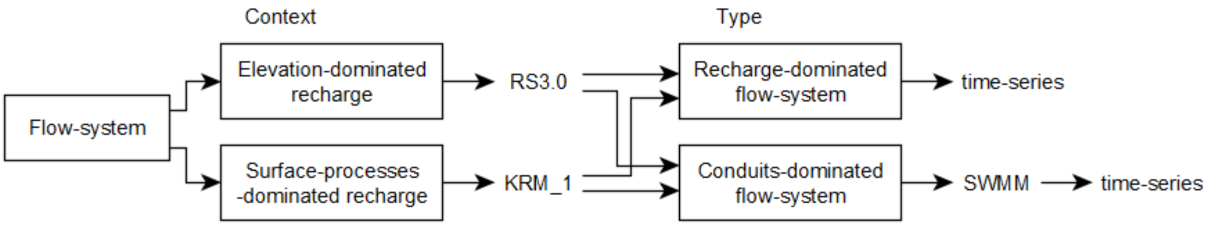


Figure 6—43. Hydroclimatic contexts and type of the flow-system guide the selection of the appropriate recharge simulation model and the consideration of hydraulic processes via an additional model (here SWMM) or not in order to simulate the spring's hydrograph

In terms of reliability - and considering the limitations of the RS3.0 program - prospective hydrological simulations in the framework of global changes seem thus to be more accurate for alpine systems than for low elevated ones (Weber et al. [2012]). Conversely, KRM_1 should be restricted to relative flat areas covered by forests, fields or urban areas.

6.3.5.2. Contribution of hydraulic simulation model (SWMM)

As shown in the previous section (Figure 6—43), depending on the type of the flow-sytem and on the issues, hydraulic simulation models may be seen as an indispensable or an optional extension to the recharge simulation models.

The main difficulty when building hydraulic models is related to the complexity of designing and calibrating the properties of the conduit network (connectivity, lengths, equivalent diameter, etc.) as information on the conduits are always incomplete. In this view, applying KARSYS is a relevant prerequisite for designing a pipe flow model because pipe networks have to be constrained within the proposed 3D KARSYS model (§. 5.2.1.3). Such hydraulic models may intervene at various steps of the KARSYS approach as it is an aid to thinking about the organization of the conduit network. Ideally, the hydraulic model is gradually established along the application as it helps to design the KARSYS 3D conceptual model.

Before strictly moving to the hydraulic model, conduit network must thus be adapted depending on data and on **hydraulic relationships** which are observed for high-flow conditions. Additional connections (by-pass conduits) or obstacles (thresholds, narrowing) may exist, especially in the epiphreatic zone and they usually play a significant role for high-flow conditions. These features are mostly relics from **paleo phases of karstification** but some of them may also develop under flow conditions prevailing today. Perched temporary outflows are the best evidences of existing conduits in the epiphreatic zone. Such characteristics of the flow-systems deriving from observations or measurements in the field for high-flow conditions (geomorphology, speleological surveys, tracer tests, etc.) must be included in the 3D KARSYS model as explicit feature(s).

Hydraulic relationships linking the different outlets (hydraulic heads vs. discharge rates, hydraulic heads vs. hydraulic heads or discharge rates vs. discharge rates, etc.) provide much information. These relationships are analyzed and compared with the aim of understanding hydraulic processes and to infer geometries of the conduit network under such conditions. During the process of adapting conduits, it is useful to distinguish three types of functioning (Figure 6—44): a.) the **simple functioning**, b) the **by-pass functioning** and c) the **threshold functioning**. Each of them induces specific hydraulic relationships between the outlets and the hydraulic heads in the conduit network. Nevertheless, these three types of functioning may clearly be combined in the same flow-system resulting in complex flow dynamics (see for instance the Brunnmühle-Wasserhooliloch karst system, Jeannin et al. [2015a]).

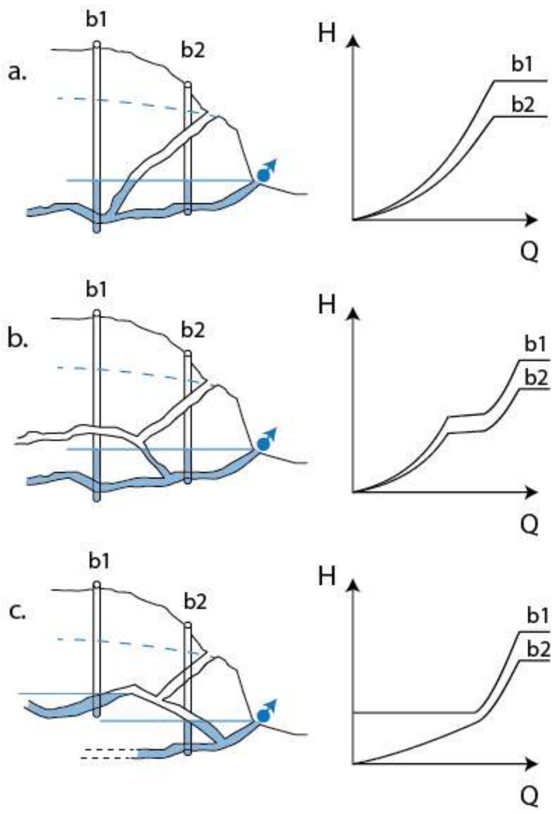


*Figure 6—44. Hydraulic functioning for high-flow conditions for three types of situations: **a.** Simple functioning, **b.** By-pass functioning, **c.** Threshold functioning. The network type may thus be inferred from the relationship between hydraulic head (H) and discharge rate (Q). Such relations provide indications on the conduit organization and on the existence of several conduit levels.*

The establishment of a **speleogenetic model** (see Filipponi et al. [2012]) using spatial observations (geomorphology, cave surveys, etc.) or more in-depth investigations (boreholes or geophysics) makes it possible to point out levels of previous phases of karstification. This speleogenetic model may be combined with a 3D model of the **inception horizons** (Lowe and Gunn [1997]) in order to predict where the main conduits may develop in the epiphreatic zone.

Once the conduit network model has been adapted, conduit characteristics and time series of effective infiltration rates are transferred into a **pipe-flow model** (SWMM). Thanks to a few head measurements (borehole, caves, estavelles, etc.) the consistency of the calibration may be checked at various locations of the karst conduit network. In case of mismatch, conduits must be modified accordingly and compared to the 3D KARSYS model. Outputs of the hydraulic simulation model are of two types: **spatial** (mainly the spatial distribution of hydraulic heads) and **temporal** (mainly time-series reflecting the outlet discharge-rates or the time-variation of observed hydraulic heads at a given place).

Applications in the frame of this thesis reveal that most of the hydraulic processes in karst aquifer results from a few obstacles, mainly of three types (narrowing, thresholds and bypasses). Thus, the modeled conduit-network may be significantly simplified in focusing on these few obstacles. As demonstrated for the BC and the BV flow system, the simplified model provides even better results compared to the complex one. However, simplified model does not provide a high spatial discretization as the complex one.

6.3.5.3. Limitations

At that stage, a few limitations may be enounced regarding the application of hydrological and hydraulic extensions to KARSYS:

1) Recharge simulation models are calibrated on the springs discharge curves. However, discharge curves result from the combination of recharge + storage + hydraulic processes which may be more or less pronounced depending on the flow-system and/or on the period. This means that we probably

overestimate the effects of the recharge processes on the regime of the flow-sytem. In this section, we summed the respective discharge rates of the different outlets for a same flow-system in order to ignore hydraulic processes (only at that stage). Then it should be kept in mind that the calibration of the groundwater recharge processes based on the springs discharge curves overestimates the effect of the recharge processes.

2) As it is difficult to ignore effects of storage processes on the springs discharge curves, we implemented the exchanger module in order to take into account storage processes in the conduits and in the low-permeability volume of the aquifer in an empiric way. This procedure could be considered as a bias to a strict recharge model. In theory, storage in the conduits and in the low permeability volumes of the aquifer should be computed via the hydraulic model as exchanges between conduits and low permeability volumes are controlled by the fluctuations of the hydraulic heads in the aquifer. In practice, it is still a bit difficult to implement as hydraulic modelling program are mostly designed for close pipes with limited exchanges possibilities with the surrounding matrix. This is an avenue to explore for improving the procedure.
3) As SWMM has been developed for computing storm-water runoff in sewers or other drainage networks in urban areas, its application to karst hydraulics can be criticized… Indeed, SWMM models lead to an oversimplification of the natural and irregular karst conduit networks which are converted into a network of regular cylindrical pipes and storage devices… However, the above-presented examples and the other related case-studies developed at SISKA or found through the literature (Campbell and Sullivan [2002]; Peterson and Wicks [2006]; Jeannin et al. [2007]; Wu et al. [2008] Malard et al. [2015b]; etc.) demonstrated that – in spite of the simplification - such a software may be well suited for assessing springs hydrographs and/or the head fluctuations (e.g. for caves or boreholes). The number of quoted examples and the diversity of topics which has been addressed attest that SWMM or equivalent programs (Infowork®, Comsol®, AFT®, etc.) may reveal really efficient to assess the hydraulic properties of the conduits system (length, diameter) and to reproduce the effects of hydraulic obstacles (thresholds, cascading conduits, by-pass conduits, overflow outlets, etc.).

7. *Karst groundwater resources in Switzerland, evolution with climate changes and perspectives for water management*

This chapter addresses three sections related to karst groundwater resources in Switzerland.

The first section concerns the topic of **karst groundwater recharge in Switzerland**. In the frame of a FOEN project in 2013, a new approach has been developed for assessing the annual recharge of karst aquifers. Principles of the approach and results are described in the form of a published paper.

The second section is dedicated to the **evolution of the karst groundwater resources** with the climate changes for the coming decades. Conclusions of the Swisskarst project (ISSKA [2014c]) indicate that climate changes will slightly impact groundwater resources at the scale of the Swiss karst aquifers. With the exception of alpine flow-systems which will evolve from nivo-glacial conditions to nival or pluvio-nival conditions and low-elevated flow-systems which may experience more droughts in summer, effects of climate changes should remain moderate, at least by considering that groundwater resources - as well as surface water resources - will be exploited in a sustainable way. However, a larger effect is expected due to changes in land-use, water and energy demand. These changes are expected to affect the quality, the availability and the accessibility of groundwater resources.

The third section discusses **perspectives for the management of karst groundwater and environments** within the context of climate changes. More specifically, as karst aquifers represent the most significant groundwater reserves and resources in Switzerland, it is expected that exploitation of these aquifers will be reinforced to meet future requirements in agriculture, energy production, snow-culture, etc. In this case, recommendations of strategies and guidelines are essential to insure a sustainable management.

7.1. Annual resources in karst aquifers

This work has been realized in 2013 on behalf of the FOEN. A dedicated report has been established (ISSKA [2013d]) and the following paper has been published in Hydrological Processes (Malard et al. [2016]). This approach has been developed in order to give an estimate of the annual groundwater resources flowing through karst aquifers in Switzerland.

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A novel approach for estimating karst groundwater recharge in mountainous regions and its application in Switzerland

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Abstract:

A pragmatic and simple approach for estimating the groundwater recharge of karst aquifers in mountainous regions by extrapolation of the hydrological regimes of gauged and well-documented systems is presented. Specific discharge rates are derived using annual precipitation and spring measurements by taking into account catchment size and elevation, which are assumed to be the dominant factors. Reference sites with high data reliability are used for calibration and regional extrapolation. This is performed with normalized values employing spatial precipitation deviations and correlation with the elevation of the catchment areas. A tiered step procedure provides minimum and maximum normalized gradients for the relationship between recharge quantity and elevation for karst regions. The normalized recharge can therefore be obtained and extrapolated for any location using the spatial precipitation variability to provide an estimate of annual groundwater recharge.

The approach was applied to Switzerland (approximately 7500 km^2 of karst terrain situated between 200 and over 4000 m a.s.l.)
using annual precipitation data from meteorological stations for the years 2000 to 2011. Results show that the average recharge rates of different Swiss karst domains range from 20 to 46 L/km^{2}s, which corresponds to an infiltration ratio between 0.6 and 0.9 of total precipitation. Despite uncertainties inherent in the approach, these results provide a benchmark for renewable karst groundwater resources in Switzerland of about 8.4 km^3/year. The approach can be applied to any other mountainous karst region, that is, where a clear relationship between elevation, precipitation and recharge can be assumed.

KEY WORDS aquifer recharge; karst groundwater; precipitation; discharge; Switzerland

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INTRODUCTION

In Europe, karst aquifers represent nearly 35% of the land surface, and numerous European cities are dependent on these aquifers for water supply (Zwahlen, 2003). Infiltrated water is stored in the epikarst and in the vadose and the epiphreatic zones and is predominantly discharged back to the surface via karst springs, or it can directly infiltrate into adjacent or downstream aquifers, or other hydrologic systems. According to the geometry and the recharge of karst aquifers, groundwater reserves and resources may be distinguished using the definition provided by Castany (1962) where reserves are defined as the water volume stored in the aquifer, which can be released by gravity. This volume includes permanent reserves plus dynamic storage as introduced by Mangin (1970). Groundwater resources are considered to be the exploitable part of these reserves in terms of availability, withdrawal techniques and renewability. Figure 1 displays the different components for the definition of karst groundwater resources as used in the present study:

- Recharge is defined as the volume of water reaching the groundwater body (effective infiltration);
- Dynamic storage is considered to be the amount of water buffered in the epikarst and the epiphreatic zone of the karst aquifer over a given period (i.e. recharge event or seasonal recharge);
- Discharge refers to the volume of groundwater released from the aquifer, concentrated at springs or over diffuse exfiltration zones;
- Withdrawal represents the groundwater abstraction volume for water supply (through boreholes or spring tapping);
- Ecological services provided by karst discharge include the minimal amount of water required by the environment downstream of the discharge zone, including groundwater-dependent ecosystems

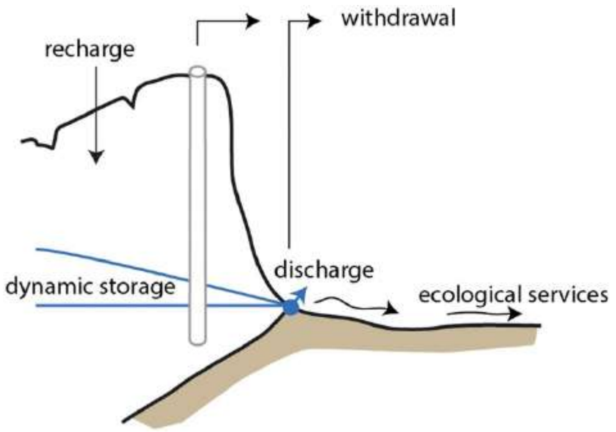

Figure 1. Components for the definition of groundwater resources in karst aquifers

As dynamic storage can be neglected for long-term and steady-state recharge assessment, the discharge from a natural system is considered to be equal to the recharge volume. Over the whole period of a hydrological cycle, it therefore corresponds to the renewable groundwater resources of given system.

The literature indicates that recharge in karst aquifers may exceed 50% of the precipitation volume (Burger, 1959; Kessler, 1965; Tripet, 1972; Soulios, 1984; LaMoreaux et al., 1984; Bakalowicz, 1995; Bonacci, 2001), which is significantly higher than in most other environments (except young volcanic rocks as highlighted by Charlier et al., 2011, among others). Under certain conditions, effective infiltration rates may reach up to 80% of raw precipitation (Wildberger, 1981). Classically, groundwater recharge may be deduced from the water balance, taking into account precipitation, evapotranspiration and runoff. However, it is difficult to directly assess karst recharge as local-scale experiments would have to be performed (Gregory et al., 2009; Meeks and Hunkeler, 2015). The concept of using elevation-dependent precipitation in conjunction with spring measurements for estimating karst recharge at catchment scale has been studied, that is, for given hydro-climatic conditions (Soulios, 1984; Bonacci, 2001; Fiorillo et al., 2015). At this scale, additional data on the geometry of the catchment area, the soil-cover (including thickness), the snow depth and temperature variations and others is always required. As illustrated by Fiorillo et al. (2015), discrete processes must be addressed over the whole catchment in order to determine the effective infiltration (real evapotranspiration, aquifer storage, eventual runoff, etc.). As a consequence, assessing recharge at the catchment scale needs the development and relevant calibration of a distributed model to quantify spatial and temporal variations of these processes (Weber et al., 2011; Bailly-Comte et al., 2012; Ladouche et al., 2014; Lauber et al., 2014).

However, it has not yet been possible to reliably extrapolate recharge estimates from the catchment scale to the regional scale. The present approach therefore uses well-characterized reference sites with good monitoring in order to calibrate a relationship between precipitation and karst spring discharge, taking into account site elevation, catchment size and local meteorological parameters. A first approximation of recharge can then be determined for any point of a karst region based on its elevation and the regional characteristics. This approach was developed within the framework of the Swisskarst project (part of the NRP61 National Research Program) and addresses mountainous regions with temperate climate conditions, such as Central Europe. Documented sites in Switzerland were considered in various contexts (Tabular Jura, Folded Jura, Prealps, Helvetic Alps and Austroalpine domain) and sites in neighbouring regions of France (Jura, Doubs, Bauges, Saône and Ain), Germany (Swabian Jura) and Italy (Dolomites). These systems represent different catchment sizes, elevations and recharge characteristics (allogenic and/or autogenic components) and are located in various hydro-climatic regimes.

APPROACH

In mountainous regions with temperate climatic conditions, the precipitation distribution is heavily dependent on elevation (Lavanchy et al., 1988) and regional factors, such as regional climatic characteristics, or more local aspects such as flank exposure, valley orientation and others. In most developed countries, the national meteorological agencies provide maps featuring the amount and distribution of annual precipitation; this is the basic information for performing recharge assessment. Assuming that recharge of such systems increases with precipitation rate and that the annual discharge of karst systems is close to the annual recharge (i.e. excluding changes in inter-annual storage), the concept of the proposed approach involves assessment of the specific relationship between annual discharge and precipitation for known and gauged karst systems and the use of precipitation distribution in order to assess karst recharge in areas without gauged systems. In summary, for the presented approach, the main assumptions made to justify the hypothesis of the precipitation-discharge equivalent are the following: (i) precipitation increases significantly with elevation in mountainous regions; (ii) allogenic components feeding karst aquifers are not significant on a regional scale with respect to the surface of the autogenic recharge zones; and (iii) inter-annual (dynamic) storage is considered to be negligible over the long term. These assumptions must be considered as significant generalizations compared with the actual recharge processes at work, which are more complex, but initially this is deemed appropriate given the scale of this study.

Put another way, the proportion of recharge with respect to discharge is assessed for individual systems and this serves as calibration for larger regions. Figure 2 illustrates the workflow of the approach, which is thereafter specified by its application in Switzerland. The procedure contains the following nine steps, with data processing generally performed in a geographic information system:

Step 1 Delineation of the entire karst-recharge area (at least limestone outcrops) within the considered region;

Step 2 Calculation of the mean annual precipitation grid over the entire territory;

Step 3 Delineation of the karst-recharge area into elevation classes (e.g. interval of 100 or 200 m), depending on the variation in elevation of the area and the distribution of meteorological stations and data availability for which the mean annual precipitation (mm) is computed;

Step 4 Establishment of the spatial precipitation deviation (mm) around the mean annual value of the corresponding elevation class (combination of the grids from steps 1 and 3) within the karst-recharge area and for each elevation class;

Step 5 Allocation of an average and a related spatial precipitation deviation value (± % of the expected average value for each elevation class and grid-cell);

Step 6 Selection of gauged (reference) karst flow systems (representative of the range of climatic and geographic contexts within the relevant region) and determination of their annual specific discharge rates based on existing studies or measurements (one average value for each system);

Step 7 Normalization of the specific discharge rates of the systems by considering a mean deviation factor for the regional grid over the respective catchment areas (step 5);

Step 8 Establishment of normalized minimum and maximum gradients for specific discharge rates (i.e. specific recharge rate) with elevation. These gradients may be adjusted by the user, according to the reliability of the data of the respective reference sites. Two gradients will be considered as the reference gradients (minimum and maximum scenarios) for extrapolation over the entirety of the karst areas;

Step 9 Computation of the specific discharge grids at the scale of the entirety of the karst areas using the

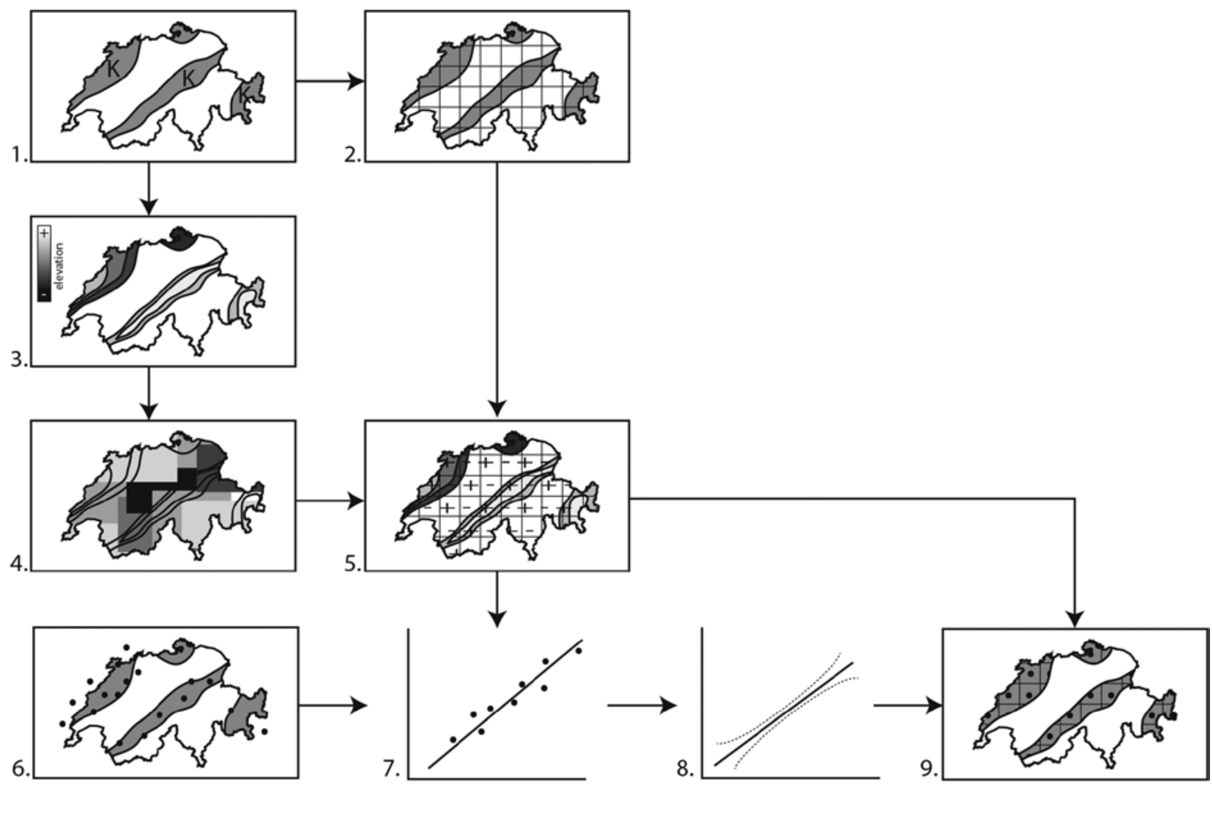

Figure 2. Workflow of the recharge assessment approach, which is divided into nine steps as described in detail in the text

normalized minimum and maximum gradients (step 8) and the spatial deviation grid (step 5).

APPLICATION IN SWITZERLAND

Distribution of karst-recharge zones

Karst terrains are distributed in Switzerland mainly along the Jura Mountains and the Alpine chain. Karst recharge zones cover 20% of the territory, that is, some 7500 km^2 (step 1 in Figure 2). At this scale, karst terrains refer to carbonate outcrops where recharge is assumed to be autogenic. These are located at elevations between 200 and over 4000 m, with 90% situated between 500 and 2500 m a.s.l. (Figure 3). Two elevation ranges predominate: 460 to 600 m a.s.l. (northern Tabular Jura) and 900 to 1300 m a.s.l. (Folded Jura and Prealps). Elevations between 1500 and 2300 m a.s.l. are still well represented, although the significance of karst decreases markedly above 2300 m a.s.l. with very few outcrops above 3000 m a.s.l.

Effective precipitation characteristics

The main characteristics of the precipitation distribution in Switzerland have been discussed by Sevruk (1997). In the framework of the present study, precipitation has been analysed using the official annual grids RhiresY from the years 2000 to 2011 (MeteoSwiss, 2013). These grids feature discretization of the annual raw precipitation at a resolution of 1 km^2 (step 2). The provided data is then transformed into variability values and a regional precipitation deviation grid established accordingly (steps 3 and 4). Figure 4 displays the spatial variability of the annual precipitation for each cell with respect to the calculated average value (2000–2011) per 200 m elevation interval integrated over the whole territory (step 5). For each individual class (e.g. 400–600, 600–800, …, 2800–3000 m, etc.), some areas may exhibit an annual precipitation deficit of up to 50% compared with the average value (red shading in Figure 4), whereas other areas exhibit an annual precipitation excess of up to 50% (blue shading in Figure 4). The spatial variability of the annual precipitation for a given elevation class may therefore exceed 100%. It is vital to consider such regional disparities in order to assess groundwater recharge.

In addition to this spatial variability, inter-annual variability for the same location must also be considered. For the period 2000–2011, the average annual precipitation over the entire Swiss territory was 1350 mm for a hydrological year, with variability ranging from 25% (1018 mm in 2003) to +30% (1710 mm in 2002). The year-on-year variation in annual precipitation could therefore reach 60%. Moreover, two years with the same average precipitation could exhibit very different spatial distributions. In an extreme case, a relatively dry year could nonetheless result in a precipitation excess in some karst regions, providing even more recharge than a wetter year, with the reverse also true. In reality, the recharge processes are heavily dependent on the seasonal variations and distribution of the raw precipitation (winter snows, summer storms, etc.) which are not addressed here. Another assumption is that the computed variability of the precipitation is the same as for effective recharge.

Selection of reference sites

To apply the approach, 35 sites were selected as reference sites within Switzerland together with a further 7 sites located in neighbouring countries although within the same (peri-)alpine domains

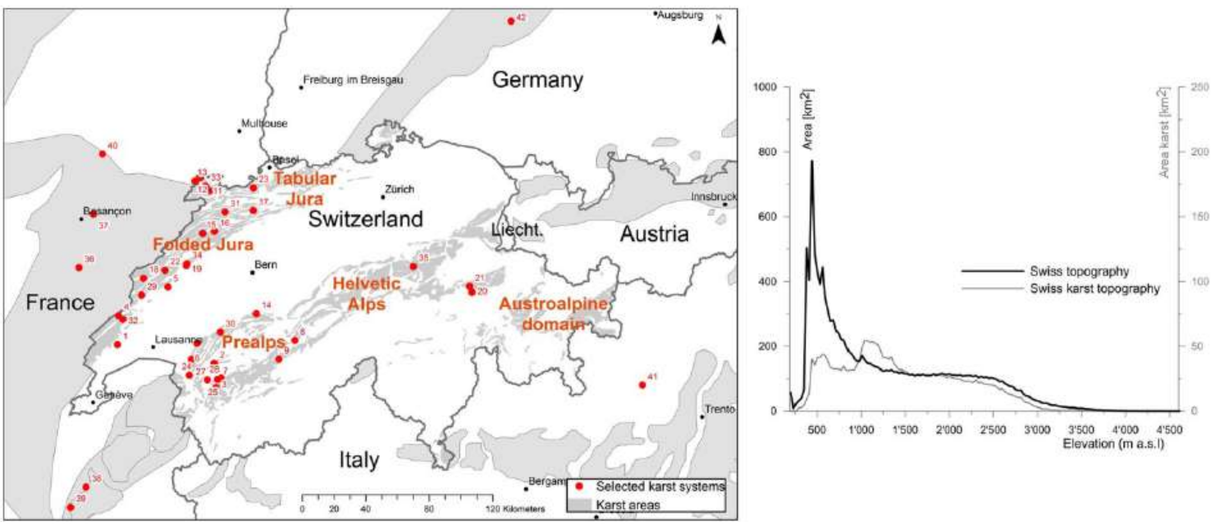

Figure 3. Karst terrain outcrop in Central Europe with principle domains in Switzerland (left) and elevation distribution compared with the whole Swiss territory (right)

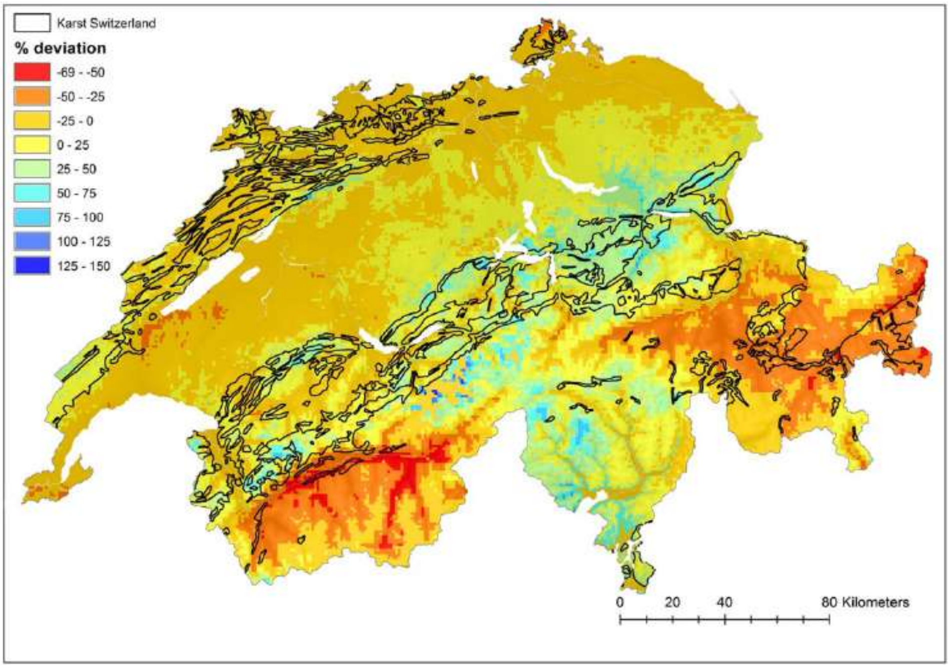

Figure 4. Spatial variability (in %) of precipitation in Switzerland with elevation distribution taken into account. Calculations based on precipitation data of the years 2000–2011 (MeteoSwiss, 2013); contours represent karst terrains

relatively close to the Swiss border (step 6, Table I). These sites are deemed to cover the complete range of climatic and geographic contexts of the region (temperate pluvial to glacial regime, at elevations ranging from 500 to 2500 m a.s.l.). Selection criteria for the sites were data availability in relation to system catchment and spring discharge (i.e. reasonable delineation of the catchment boundaries and regular monitoring of the springs). However, there was great disparity in data availability and precision between the sites. As a result, a reliability indicator was assigned to each site. For the present study, the main limitations in relation to data were (i) catchment delineation, which is not always thoroughly and accurately validated, (ii) fluctuation of catchment boundaries depending on flow conditions, which is not always taken into account, and (iii) the discharge rate of the related springs, which is often underestimated. High reliability (+++) was attributed to systems where both catchment and discharge information were available in a consistent and accurate manner. These systems were used as prime sites for the evaluation of annual recharge. Moderate reliability (++) was assigned to systems where only one of the two criteria was fulfilled, while for systems of low reliability (+) constraints had to be assumed for both catchment characterization and discharge measurement. As the number of well-documented sites is quite limited and as data from sites of low reliability may still provide insightful information, the latter ones are nonetheless taken into account rather than being discarded.

In general, reduced data reliability tends to under-estimate rather than over-estimate specific discharge rates. Indeed, gauged sites of low-to-moderate reliability exhibit a presumed under-estimated regime compared with what would be expected considering the size and elevation of the catchment area. Such under-estimation is quite frequently a result of the monitoring of the discharge regime of karst springs and is due to a variety of reasons: (i) low-flow regimes of the spring are often not well-measured and are frequently underestimated (flow by-passing gauging weirs); (ii) overflow springs are usually not measured; and (iii) catchment delineation is often performed for high water stages and is therefore over-estimated. Although preliminary screening provided a relatively high number of 42 promising sites across the concerned region (with either catchment or discharge characteristics, or both, described), only half of these were confirmed appropriate, that is, more rigorous data analysis indicated high reliability. Within the limits of availability, data included in the period 2000–2011 have been preferably chosen for the assessment of the specific discharge rates in order to match precipitation data; otherwise, older data have been considered by default.

Computation of specific discharge rates

For each site, the value of the specific discharge rate Q_{spec} is calculated (step 6), which is defined as the annual mean discharge of the system divided by the size of its

Table I. Characteristics of the 42 alpine and peri-alpine groundwater flow systems selected as references sites for karst recharge assessment in Central Europe, classified as high (+++), moderate (++) and low (+) data reliability (see text for detailed explanation of the rating)

No		Elevation (m a.s.l.) Maximum	Minimum	Mean	Specific discharge rate Q_{spec} (L/km^2s)	Reliability	Reference
1	Aubonne, CH	1676	764	1337	32	+++	Luetscher and Perrin, 2005
2	Bornels, CH	2421	1195	1893	16	++	GEOLEP, 1987
3	Lue-Mou, CH	2789	1702	2320	9	+	ABA-GEOL, 1997
4	Orbe, CH	1550	768	1199	37	+++	FOEN, 2013a
5	Raisse-Dia, CH	1463	429	1060	34	+++	Kiraly, 1973
6	Granchamps (Confin du Renard/Repremier), CH	2044	515	1427	45	++	Maréchal et al., 1997
7	Roc-à-Ours, CH	2488	1202	1832	23	++	MARIC, 2001
8	Wyssbachhoehle, CH	2749	2154	2510	6	+	SISKA, 2012
9	Geltenbach, CH	3609	1554	2704	2	+	Gerber, 1991
10	Voyeboeuf-Bonnefontaine, CH	879	439	583	19	+++	Grétillat, 1998
11	Beuchire-Creugenat, CH	912	418	574	21	+++	Grétillat, 1998
12	Milandrine, CH	600	510	550	17	+++	Perrin et al., 2003
13	La Batte-Lavoir, CH	608	459	564	5	+	—
14	Blattenheid, CH	1823	1029	1456	7	+	Wanner, 2002
15	Dou-Torrent-Raissette, CH	1291	715	1085	43	++	Wicht, 1995
16	Bez, CH	1572	710	1211	18	+	Kellerhals and Haefeli AG, 1996
17	Gore Virat, CH	1302	1028	1184	6	+	Kellerhals and Haefeli AG, 1984
18	Areuse, CH	1330	793	1115	36	+++	FOEN, 2013b
19	Serrière, CH	1450	472	1060	28	+++	Mathey, 1978
20	Lag Tiert-Tunnel, CH	3025	1250	2184	51	+++	SISKA, 2007
21	Tarschlims, CH	2884	1647	2321	50	+++	SISKA, 2011
22	Noiraigue, CH	1300	750	1101	29	+++	Pronk, 2008
23	Lutzelquelle, CH	691	392	565	15	+++	Auckenthaler, 2004
24	Lizettes, CH	2128	444	1530	10	+	Blanc, 1991
25	Coussy, CH	2107	1400	1799	14	++	MARIC, 1997
26	Villard-Dessous-et-Villard-Bony, CH	2002	1408	1711	23	++	Canton Fribourg (pers. comm.)
27	Avants, CH	1752	1029	1429	30	++	Maréchal et al., 1997
28	Grand Moilles (Gros-pre), CH	1629	1313	1486	12	+	—
29	Covatannaz, CH	1581	779	1201	27	+++	Audétat et al., 2002
30	Auges (Fulateire), CH	1461	874	1188	16	+	—
31	Blanches-Fontaines, CH	1276	577	984	13	+	Piquerez, 2014
32	Nozon, CH	1187	944	1082	25	++	Perrin, 2002
33	Domont, CH	607	406	534	8	++	Kovács and Jeannin, 2003
34	Seyon, CH	980	533	780	19	+++	Mathey, 1978
35	Hölloch (Schlichenden Brünnen), CH	2320	638	1622	63	++	FOEN, 2013c
36	Lison, F	885	400	700	29	+++	Jauffret, 2005
37	Arcier, F	600	275	400	12	+++	Reilé, 2010
38	Bange-Eau-Morte, F	1699	640	1225	27	+++	Mathevet, 2002
39	Revard Doria, F	1550	1010	1300	47	+++	Hobléa et al., 2008
40	Champdamoy, F	380	224	280	11	+++	Nicod, 2010
41	Centonia, I	2935	1380	2250	32	+	Borsato, 2001 (and pers. comm.)
42	Blautopf, D	850	450	720	15	++	Schwarz et al., 2009; Lauber et al., 2013

catchment area (expressed as L/km^2s). This is plotted in Figure 5 for each system versus the mean elevation of the catchment.

There is a discernable pattern for the systems considered to be of high reliability according to Table I, indicating a relationship between recharge and mean

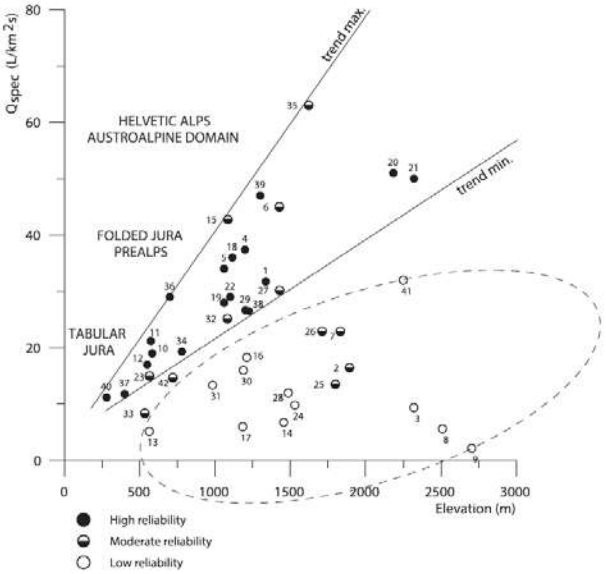

Figure 5. discharge rates Q_{spec} of the 42 selected karst systems as a function of their mean catchment elevation; datasets are distinguished according to their degree of reliability

catchment elevation. These data are distributed between divergent boundaries, with a minimum gradient ($\Delta Q_{spec} = +1.7$ L/km^{2}s for $\Delta z = 100$ m) and a maximum gradient ($\Delta Q_{spec} = +3.4$ L/km^{2}s for $\Delta z = 100$ m) respectively. It is assumed that the divergence of the curves mainly reflects the spatial variability of the precipitation and local factors (e.g. exposure and influence of glacier melting), in addition to monitoring uncertainties. Three domains can be distinguished within (Figure 5): the low-elevation Tabular Jura (450–800 m a.s.l.) where Q_{spec} ranges from approximately 10 to 20 L/km^{2}s, the elevated Folded Jura and Prealps (1000–1400 m a.s.l.) with Q_{spec} between 25 and 45 L/km^{2}s and the Helvetic Alps and Austroalpine domain (>1500 m a.s.l.) where Q_{spec} is over 45 L/km^{2}s. The highest specific discharge rates are observed in alpine karst flow systems with the highest precipitation rates (site 35) or sites that are partially fed by one or several glaciers (sites 20 and 21). In the latter case, rates may be overestimated because of a recharge surplus as a result of glacier-melting under changing climatic conditions (although a low specific discharge rate is observed for system no. 41, which is also partially fed by a glacier, although measure- ments seem less reliable). In contrast, the lowest values are observed for less-elevated karst systems of moderate extent and only moderate variation in elevation. This relationship is also valid for some of the systems with data of only moderate reliability (sites 6, 15, 23, 27, 32 and 35). The other moderate- reliability sites, together with all systems of low reliability, do not exhibit elevation-dependent specific discharge (data enclosed in the ellipse).

This dispersed distribution is assumed to be due to a significant under-estimation of annual discharge (or an over-estimation of the catchment area) compared with the sites with more accurate data.

In the following (step 7), the spatial variability of the specific discharge rates for the reference systems is corrected by applying the deviation grid over their respective catchment areas in order to derive a normalized gradient for Switzerland (from regionalized values to normalized ones). During this step, the values computed for the seven systems outside Switzerland (sites 36 to 42) are based on mean precipitation data found in the literature – and consistent with the measurement periods – that are normalized with the deviation grid computed for Switzerland. The result is displayed in Figure 6.

It appears that data of high reliability is aligned along a band, whereby the lower and upper boundaries can be considered as the minimum and maximum gradients of normalized specific discharge with elevation. At this stage, it should be noted that only 22 of the 42 previously selected systems (18 of high reliability, 4 of moderate reliability) conform to this trend; these include the most documented sites. The equations of the trend lines are $Q_{spec} = 0.0146z + 7$ for the minimum and $Q_{spec} = 0.0146z + 19$ for the maximum (Step 8), yielding a mean trend of $Q_{spec} = 0.0146z + 13$. Again, most of the sites with reduced data reliability exhibit normalized specific discharge rates that appear to be under-estimated compared with the expected values. Conversely, two systems of moderate reliability (6 and 15), with good monitoring in the medium term but with suspected under-sized catchment

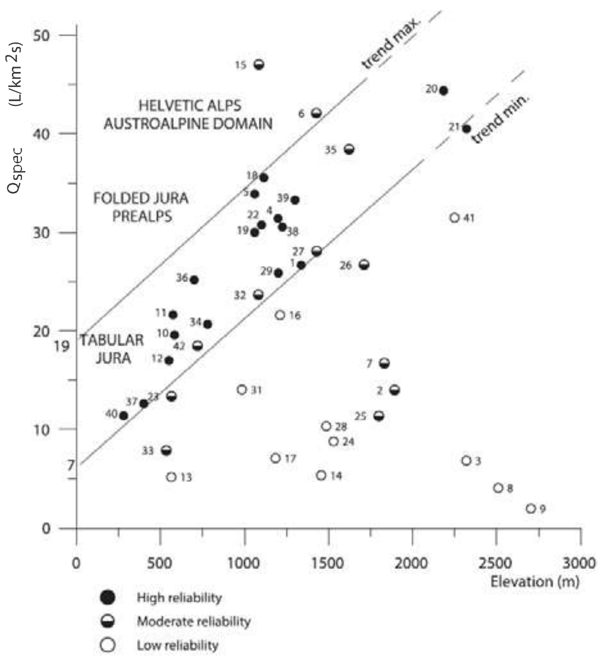

Figure 6. Specific discharge rates Q_{spec} of the selected systems as a function of elevation (from Figure 5), normalized using the previously established regional deviation grid related to precipitation distribution

delineation, appear to be over-estimated with respect to their hydrogeological context.

In order to attempt validation, Figure 7 displays the computed mean Q_{spec} values (using the mean scenario trend and following regionalization) versus the measured values for the 42 systems. The distribution of the values appears as follows: (i) all high reliability sites have a distribution close to the 1 : 1 ratio line 'measured Q_{spec} = mean computed Q_{spec}'. A slight deviation may be observed for both the lower values (<25 L/km^{2}s) and the higher values (>35 L/km^{2}s) that tend to deviate from the line, indicating that the trend may not be strictly linear over the whole elevation range; nonetheless, most of the reliable sites fall within the confidence interval (grey band), which represents the deviation between the minimum and maximum trends (±6 L/km^{2}s compared with mean trend); (ii) some data of moderate reliability are distributed close to the median line (e.g. sites 23, 42, 32 and 27) suggesting that they may be more reliable, whereas the remainder are distributed above and below the median line, indicating that their extent may be over-estimated (sites 6, 15 and 35) or under-estimated (sites 33, 7, 25, 2, 26 and 41); (iii) not surprisingly, low-reliability data are grouped above the trend line where computed Q_{spec} > measured Q_{spec}, suggesting that the measured discharge rates of the flow systems are under-estimated in relation to the size of the delineated catchment. The figure highlights the fact that even for high- reliability data, use of only the mean trend for measured versus computed Q_{spec} cannot encompass the diversity of the sites. As uncertainties are still pronounced, minimum and maximum normalized gradients will be used as reference trends rather than simply using the mean trend. These are extrapolated over the whole region in order to assess the specific discharge rates for all karst-recharge areas. Then, the resulting values are regionalized again by applying the deviation grid in the opposite direction (from normalized to regionalized, step 9). These values are assumed to reasonably represent the range of recharge values for karst systems in Switzerland.

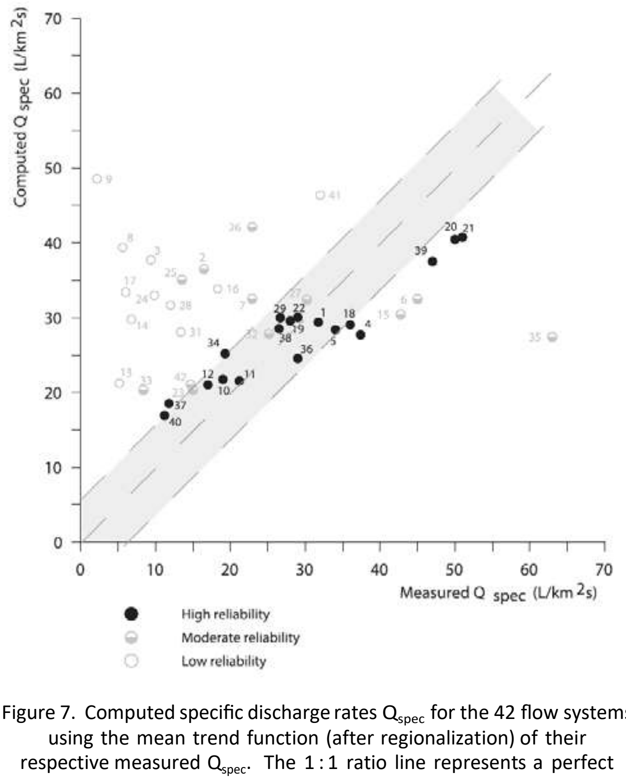

Figure 7. Computed specific discharge rates Q_{spec} for the 42 flow systems using the mean trend function (after regionalization) of their respective measured Q_{spec}. The 1 : 1 ratio line represents a perfect match between measured and computed values using the mean trend while the grey band represents the confidence interval between minimum and maximum trends

RESULTS AND DISCUSSION

Annual recharge of Swisskarst aquifers

Application of the minimum and maximum gradient scenarios and its extrapolation to Swiss karst-recharge areas yields the results shown in Figure 8 (step 9). For the minimum scenario, the specific recharge rates range from 6 to 92 L/km^{2}s depending on location and elevation with an average of Q_{spec} = 29 L/km^{2}s. According to this scenario, the northern Jura Mountains, Prealps and Austroalpine domain are characterized by low Q_{spec} values (<25 L/km^{2}s). Conversely, the southern Jura Mountains and Alpine domains are characterized by higher values (25–75 L/km^{2}s). The highest rates (>75 L/km^{2}s) are restricted to a few high-elevation massifs in central Switzerland. For the maximum scenario, the specific recharge rates range from 10 to 115 L/km^{2}s with an average of 42 L/km^{2}s. According to this scenario, the northern Jura domain (low elevation) and a few sectors of the Alps exhibit low Q_{spec} values (<25 L/km^{2}s). The elevated Folded Jura, Prealps and Austroalpine domain are characterized by higher rates exceeding 25 L/km^{2}s, and even >50 L/km^{2}s along the Helvetic Alpine chain. The highest rates (>80 L/km^{2}s) are obtained for most of the high-elevation massifs in the Helvetic Alps because of higher precipitation.

These results refer to single grid cell pixels and therefore include extreme values. Specific discharge rates for entire karst systems are more balanced. Furthermore, rates can be grouped for the different domains (average values of Q_{spec} from 20 to 46 L/km^{2}s) and for the whole karst terrain in Switzerland, as performed in Table II. The annual resources deduced in this way, that is, annual mean discharge Q_{mean} expressed in cubic meter per second, are a function of the karst outcrop area of each domain. The findings also highlight the differing relationship between annual discharge and annual

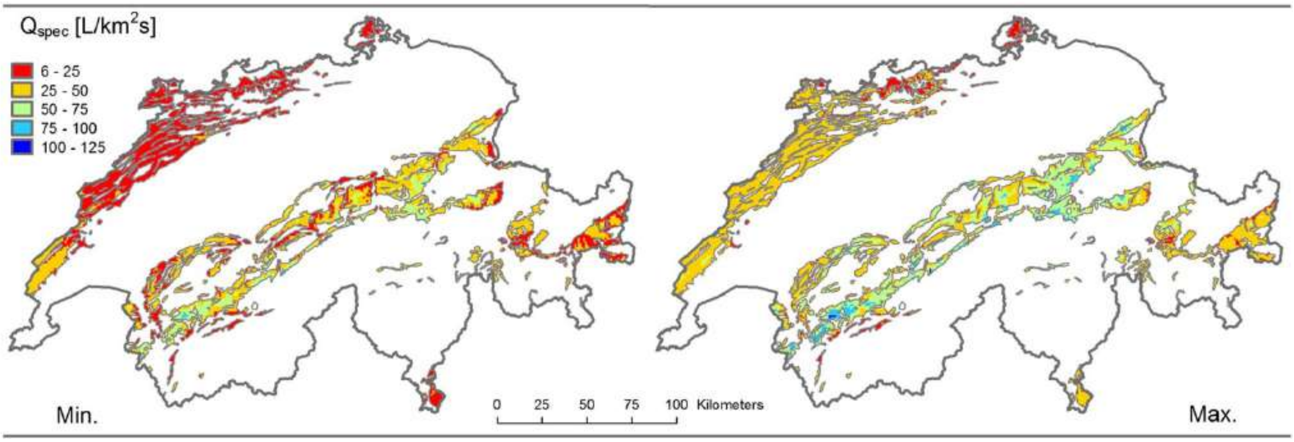

Figure 8. Annual specific recharge rates (Q in L/km^{2}s) for minimum and maximum scenarios determined for all karst terrains in Switzerland

precipitation, that is, the infiltration ratio, which ranges from an average of 0.6 in the Tabular Jura and Folded Jura to 0.8–0.9 in the Helvetic Alps and Austroalpine domain. This ratio derived from precipitation as input component is classically calculated from the water budget if evapotranspiration and runoff components are known. As these are often not available or difficult to assess, the present estimate provides a useful alternative approach. Water budget calculations nonetheless represent an appropriate means for validation of the presented results on a catchment scale. Computed values here are consistent with previous local studies that consider an effective infiltration of 0.4 of the precipitation in the Tabular Jura (Jeannin and Grasso, 1995), of 0.7 in the Folded Jura (Burger, 1959) and up to 0.8 in the Alps (Wildberger, 1981) as the evapotranspiration component decreases significantly with elevation and because the soils become thinner.

The difference between recharge volumes derived from the minimum and maximum gradients can extend to 40%, depending on the considered domain (especially for the Tabular Jura). This discrepancy could be seen as the uncertainty inherent in the approach and includes: (i) model approximation, (ii) data quality and (iii) inter-annual disparities in the recharge process. In fact, annual precipitation may fluctuate between 70% and +150% of the average value depending on the domain and by up to ±60% from one year to the next. Given these conditions, it is difficult to provide a better estimate of karst groundwater recharge at this scale. However, benchmark values provided by the proposed approach are nevertheless very useful for management of resources and for providing a means of preliminary assessment of the size of a catchment area for a given karst system in a given domain if the annual discharge regime of the spring is known, and vice-versa to deduce spring yield once a preliminary catchment delineation of the system has been performed.

Despite these uncertainties, the following results can be outlined in relation to the different elevation levels in Switzerland:

- Low-elevation karst systems (<700 m a.s.l.), mainly located in the northern Jura, represent 15% of the whole karst recharge area of Switzerland and less than 8% of the annual karst recharge;
- Mid-elevation karst systems, mainly located in the Folded Jura and in the Prealps domain (between 800 and 1500 m a.s.l.) represent 43% of the karst outcrops although only 32% of the annual recharge;
- Alpine-karst systems for which the mean elevation exceeds 1500 m a.s.l. represent 42% of the karst recharge areas in Switzerland although 60% of the annual recharge. Recharge of karst areas located above 2500 m (i.e. 8% of the karst territory) are obviously underestimated as many systems are partially fed by glacier-melt (which is an increasing phenomenon because of climate change) and do not strictly reflect the rainfall regime (e.g. Gremaud et al., 2009). It is expected that specific recharge rates in these regions will increase over coming decades because of progressive glacier melting.

All over Switzerland, groundwater recharge feeding karst aquifers is assessed as ranging between 6.9 and 9.9 km^3/year, depending on the scenario and trend, which were taken into account (Table II). The average of both scenarios therefore provides a benchmark recharge of 8.4 (±1.5) km^3/year, yielding a total discharge from Swiss karst springs of some 270 m^3/s, which corresponds to the average annual renewable karst groundwater resources of the country. Compared with other aquifer types (Sinreich et al., 2012), that is, unconsolidated and fissured aquifers respectively, karst spring recharge/discharge represents nearly 40% of the total renewable groundwater resources of Switzerland. This is relatively high, because karst

Table II. Synthesis of karst groundwater recharge assessment (renewable resources) for Switzerland

	Minimum scenario	Maximum scenario	Average
Tabular Jura			
Surface area: 600 km^2			
Annual precipitation: 35 L/km^{2}s			
Annual specific recharge rate Q_{spec} (L/km^{2}s)	14.5	26	20
Infiltration ratio (-)	0.4	0.7	0.6
Annual $\sum Q_{mean}$ (m^3/s)	9	16	13
Folded Jura			
Surface area: 2040 km^2			
Annual precipitation: 45 L/km^{2}s			
Annual specific recharge rate Q_{spec} (L/km^{2}s)	22	34	28
Infiltration ratio (-)	0.5	0.7	0.6
Annual $\sum Q_{mean}$ (m^3/s)	44	68	56
Prealps			
Surface area: 1090 km^2			
Annual precipitation: 54 L/km^{2}s			
Annual specific recharge rate Q_{spec} (L/km^{2}s)	31	45	38
Infiltration ratio (-)	0.6	0.8	0.7
Annual $\sum Q_{mean}$ (m^3/s)	34	49	36
Helvetic Alps			
Surface area: 2630 km^2			
Annual precipitation: 55 L/km^{2}s			
Annual specific recharge rate Q_{spec} (L/km^{2}s	39	53	46
Infiltration ratio (-)	0.7	1	0.8
Annual $\sum Q_{mean}$ (m^3/s)	102	139	121
Austroalpine domain			
Surface area: 1140 km^2			
Annual precipitation: 35 L/km^{2}s			
Annual specific recharge rate Q_{spec} (L/km^{2}s)	29	37	33
Infiltration ratio (-)	0.8	1	0.9
Annual $\sum Q_{mean}$ (m^3/s)	31	42	37
Switzerland			
Surface area: 7500 km^2			
Annual precipitation: 48 L/km^{2}s			
Annual specific recharge rate Q_{spec} (L/km^{2}s)	29	42	36
Infiltration ratio (-)	0.6	0.9	0.7
Annual $\sum Q_{mean}$ (m^3/s)	220	314	267
Swiss karst groundwater recharge (km^3/year)	6.9	9.9	8.4

terrains cover only about 20% of the territory but is a logical consequence of the relative high infiltration ratio.

This available volume of water, however, must be balanced against the ecological services required from karst discharge, as displayed in Figure 1. The sustainable yield, that is, renewable resources that could be used in a sustainable manner and that were assessed using a different approach (Sinreich et al., 2012), is estimated to be less than half of the total renewable resources. This discrepancy is particularly high, although is consistent with observations that for many karst areas springs may contribute the majority of the discharge of local streams, ensuring ecological services. Regarding the effectively used withdrawal volume from karst aquifers, the latter actually provide 18% of the Swiss drinking water supply (Spreafico and Weingartner, 2005), mainly from springs. This is still less than 10% of the sustainable resources and less than 5% of the total renewable resources, as determined in the present study, and highlights the considerable future potential for groundwater use from karst aquifers in Switzerland.

These values are provided according to the annual timescale. In detail, it should be mentioned that – because of rapid underground circulation in karst aquifers – system regimes are characterized by high seasonal or even daily variability. A large part of the estimated groundwater resources flows out of the aquifer over short periods of time and will therefore not benefit society. In other words, groundwater resources should be available in a timely manner, which matches water requirements in order to be actively considered for potential uses.

Strengths, constraints and challenges of the approach

Because of simplified assumptions and the limited availability of data, the presented results cannot be considered as accurate values but instead represent a benchmark, which could be further refined once more karst systems have been well documented in the respective region. In relation to the three basic assumptions of the approach, their validity may be debatable in some cases, and numerous examples might be used as counter-arguments. For instance, the assumed increase in precipitation with elevation may not hold for high-elevation plateaus, where precipitation rates are higher on the steep flanks than on the top. Furthermore, the fact that allogenic surfaces – although these can contribute significantly to system recharge (e.g. Dörfliger et al., 2009; Mayaud et al., 2014) – could be disregarded also represents a significant simplification at this stage. To take these surfaces consistently into account would require precise mapping over the entire region of the non-carbonate areas, which partially or completely feed karst aquifers.

Uncertainties are mainly related to the general assumptions of the approach, the disparity between minimum and maximum assessment scenarios and – for some areas – the underrepresentation of highly reliable reference sites. In the present case of Switzerland, given the extreme diversity of karst aquifers, a minimum of nearly 20 well-characterized karst systems with high data reliability is reasonable for application of the approach at the national scale. Additional sites with catchment areas located at 800–1000 and 1500–2000 m a.s.l. in particular would be of high priority for the presented assessment as these actually correspond to systems with the least documentation in Switzerland. Further documentation is in progress and will close this gap.

Reference sites density is also a function of the study scale. The extent of a considered region may range from some hundreds up to several thousands of square kilometres. In extremis, the approach – or rather the first part of the approach (steps 1–6) excluding the regionalization – could be applied to a single catchment, as per Fiorillo et al. (2015). The larger the region, the more sites are required, particularly if different domains with specific precipitation characteristics are involved. In practice, the presented application in Switzerland can be used to infer recharge and discharge information for any ungauged catchment within the considered domains (including neighbouring countries) using specific discharge rates from Table II.

Thorough characterization of reference sites is vital for application of the proposed approach. However, it must be noted that such a set of sites with high data reliability, both in terms of catchment delineation and spring behaviour, is not always available. In many cases, Swiss karst system characterization is based on application of the KARSYS approach (Jeannin et al., 2013), which entails collecting all necessary data of a reliable assessment and explicitly develops a model of the karst flow system and its associated catchment area (Malard et al., 2015). Switzerland therefore represents one of the few regions for conducting this approach on a national scale – although with limited precision. Nonetheless, karst allogenic recharge areas (non-karst terrains feeding karst aquifers) and covered karst (lying below glaciers or significantly covered by surficial deposits) are not explicitly distinguished at that scale. This constraint can be reduced over time by refining the description of recharge processes for each flow system. In the process, the higher the density of the available reliable stations, the more domains can be subdivided with increasing specification.

Although the approach is valid in a general way, a new calibration is needed for each region. From a monitoring perspective, this requires meteorological data and long-term spring discharge data. The benefit of the present approach is the derivation of specific discharge rates that can be compared with results from other applications. Similar uncertainties can be expected for these values, and a large number of sites with high data reliability would be required to reduce uncertainty. Again, uncertainty is generally related to this part of the approach, and the use of data of reduced reliability may produce misleading results.

Given the availability of reference sites, the applicability of the approach is restricted to mountainous karst regions where precipitation dominates recharge. In level regions where the variation in elevation is low, elevation may not be the most significant factor affecting recharge, which restricts application of the approach in its current form. The approach may also be less well-adapted to the following karst contexts:

- Regions with more arid climates and where the regime of the karst springs may be subjected to little transitory surface flooding (Lange, 1998), to dominant evaporation processes (Hartmann et al., 2014) or to condensation in the unsaturated zone (Dublyansky and Dublyansky, 1998).
- Regions where the regime of the karst springs may be partially subjected to a slow emptying of the reserves (inter-annual dynamic), for example, in deep karst aquifers due to long vertical transits, large storage volumes or upwelling from deeper flow paths (e.g. Moore et al., 2009).
- High-elevation regions (i.e. >2500 m a.s.l) where steep slopes, permafrost and extended permanent ice cover may form a significant obstacle preventing water infiltration. Precipitation may flow out of the catchment through surface runoff in the form of water and snow. Despite abundant precipitation, karst systems may then exhibit low specific recharge rates. Consequently, the linear relationship between precipitation and recharge may diminish for elevation exceeding 2500–3000 m.

It should also be mentioned that annual recharge in some high-elevated systems is a function not only of annual precipitation but also of glacier-melting. This does not affect recharge volume under stable climatic conditions but clearly provides additional water, independently of annual precipitation. The approach explicitly does not consider the potential recharge surplus corresponding to glacier melt, which may represent a significant input in the wake of alpine climate warming (for Switzerland up to 1 km^3/year; FOEN, 2012). Actual rates of glacier melting should be taken into appropriate account for these sites in order to refine the recharge assessment. Furthermore, future scenarios in relation to climatic conditions and precipitation, respectively, could be applied. For Switzerland, no significant changes are predicted for total annual precipitation (FOEN, 2012). However, complementary data processing in terms of seasonal variations would make it possible to assess – by means of the presented approach and given precipitation scenarios for the sites referenced to date – the potential effect of climate change on karst groundwater recharge.

CONCLUSIONS

A pragmatic approach for assessing karst groundwater recharge at large scale was developed for mountainous regions and applied to Switzerland. It indicates that annual recharge of karst aquifers is approximately 8.4 km^3, which corresponds to the renewable karst groundwater resource. This in turn represents nearly 40% of the total annual groundwater recharge in Switzerland, although karst outcrops cover only 20% of the country's territory and thereby underlines the importance of karst groundwater for both drinking water supply and ecological services.

The presented approach can be applied to mountainous karst systems provided that there are data about the spatial distribution of precipitation over a long timescale. The approach has the advantage of providing a reasonable assessment at regional scale without the need for very detailed documentation or analysis of each individual karst system. It is highly empirical and should be restricted to annual assessment; otherwise, real evapotranspiration and runoff processes should be addressed in a more precise way, requiring more sophisticated models and data. The simple nature of the approach includes the assumption that the elevation of the autogenic recharge areas (considered as the average elevation of the catchment area) is the most significant factor affecting annual recharge together with precipitation distribution, which is a valid assumption for mountainous regions but not for more level regions.

The novel features of the approach are the monitoring-based calibration using reference sites with high data reliability and the regional generalization. The results therefore enable estimation of a benchmark of total nnual recharge over a whole region in addition to deduction of recharge/discharge information for any additional karst system in the given region. The presented application of the approach in Switzerland demonstrated its feasibility and contributed to system characterization of Swiss karst aquifers by providing specific recharge rates between 20 and 46 L/km^2s for the geological domains within the region, corresponding to infiltration ratios between approximately 0.6 and 0.9. The procedure can be transferred to many other mountainous karst regions. Regarding water availability and considering the large number of factors influenced by karst groundwater recharge, new and more integral assessment and management schemes must be developed in the future. These will probably require the adjustment of existing methods and regulations. Approaches as the presented are believed to make useful contribution in that field.

ACKNOWLEDGEMENTS

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7.2. Evolution of water resources in karst aquifers with climate changes

7.2.1. Effects on groundwater recharge

Climate is notably changing in Switzerland (Beniston [2012]) as demonstrated by the general retreat of glaciers over the past decades and the global rise of the temperatures by up to 2°C since 1900 – especially at high elevations which is a three-times higher rate than the global-average warming of the century elsewhere in Europa. The project CCHydro (report BAFU [2012], chapter: Köplin et al. [2012]) demonstrated that until 2085 the hydro-meteorological regime of most of areas in Switzerland will move to a **more pluvial regime** than actually. The amount of precipitation is not supposed to significantly change but the distribution within the year will be modified. Karst areas will globally evolve the same way. Karst regions in the Jura Mountains will evolve toward a pluvial regime of transition while systems of the Prealps will evolve toward a Jurassian pluvial regime and systems from the Alps toward a more nival regime than nivo-glacial or glacio-nival. Karst regions from Austroalpin domain will evolve toward a southern nivo-pluvial regime (see Figure 7—1).

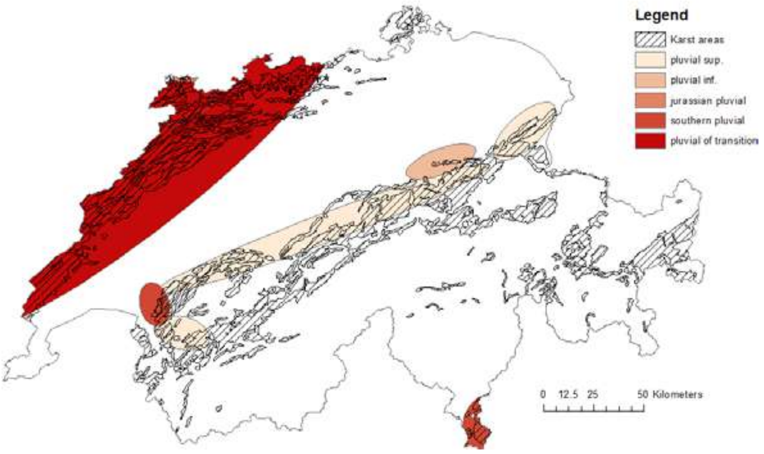

Figure 7—1. Karst regions of Switzerland and their expected hydroclimatic regime in 2085; regions with glacial, glacio-nival, nivo-glacial or nival regimes will become more pluvial; most of the Jura Mountains will move from a pluvial to a "pluvial of transition" regime, which is characterized by less recharge in winter/spring and an aggravated water deficit in summer.

Actual hydro-meteorological regime	2085 hydro-meteorological regime	Evolution of water resources in karst
Glacial glacio-nival nivo-glacial	nivo-glacial alpine nival nival of transition	- Winter droughts will be reduced - Alimentation by glacier melting will sustain the hydrologic regime of the systems for a time - Seasonal high-water discharge will appear sooner in summer - Seasonal droughts may appear in late Autumn
alpine nival	southern nivo-pluvial southern pluvio-nival	- Seasonal variations will be smoothed - Winter recharge will increase and summer high-flow discharge will decrease
prealpine nivo-pluvial prealpine pluvio-nival	jurassian nivo-pluvial jurassian pluvio-nival	- High-flows will appear sooner in the season - Droughts may appear in summer
jurassian nivo-pluvial jurassian pluvio-nival	pluvial of transition	- Summer droughts will become longer - Spring recharge will be reduced - Lower minimal discharge rate than today - Intensification of flash flood events

Table 7—1. Qualitative trend in the evolution of water resources in karst aquifers depending on changes in hydro-meteorological regimes

As winter (freezing) seasons become shorter in the future, **alpine flow-systems** will evolve to a nivo-pluvial or pluvio-nival regime. Summer droughts in these mountainous areas are expected to be shorter and less severe than actual winter droughts (see also Gremaud and Goldscheider [2010b]). Even more, regarding the progressive melting of the glaciers, specific discharge rates of these alpine karst systems will be boosted for a time. As glaciers in karst regions of Switzerland will soon disappear (horizon 2090), this observation will only be valid for a few decades. A special attention should be paid to these systems as their new regime may generate more frequent and intense floods in intermediate seasons.

As demonstrated by Weber et al. [2012], the flow regime of the alpine Tiert spring (Flims, GR) in 2085 should move from a nivo-glacial to a nival type, with a less pronounced drought in winter and a low-flow period in late summer. Summer drought should be less extreme than today's winter drought. The authors also mentioned that the annual discharge rate of the system will be reduced by about 30% after the glacier will have completely disappeared.

Regarding flow-systems of **lower elevation**, these are already affected by long periods of droughts in summer for which no recharge occurs. An increase of temperature and a decrease in precipitation over the summer will probably not further affect the recharge (as demonstrated by Caballero et al. [2015] for karst flow systems in eastern and southern France). However, recent time-series analyzes on the Milandre karst flow-system do not evidence significant trend in the groundwater discharge forr the last 30 years. If a trend does exist it is less than the precision of the discharge measurements.

Globally, the effect of temperature rising will surely modify the evaporation rate, leading to less infiltration to the aquifer. This phenomenon is certain, but potential losses for groundwater resources are difficult to assess as it depends on soils, vegetation and urbanization which will clearly change along the next decades.

7.2.2. Effect of increasing extremes

7.2.2.1. Prolonged periods without recharge (droughts)

Conclusions of the CChydro project (BAFU [2012]) show that seasonal drought periods will increase in frequency and duration in the next future. Summer droughts like in 2003 or in 2011 will be more frequents (one ever two-three years) which will surely have a consequence on environments and water resources, especially for low-elevated environments.

In karst regions, potential effects of repeated and prolonged drought periods will impact recharge areas (soils and plants) as well as groundwater flows. Nevertheless contrasted effects are expected depending on the hydroclimatic regime and on the characteristics of the systems: water resources, quality, catchment's environment, etc.

Existing discharge measurements of karst springs in Western Europe and in Switzerland indicate that for usual low-flow periods (= time duration without any recharge, i.e. summer droughts or winter freezing) the **specific discharge rate (Q_{347}) is of a few liters/sec/km^2**. Registered values range between 1 L/s/km^2 in the low-land areas (comparable to the tabular Jura) and 5 L/s/km^2 in high elevated areas, as in Jura and the Alps. Such differences may be explained by the following reasons:

- **Contrasted vegetation cover** which withdraws a part of the infiltrated water in order to satisfy vegetative processes;
- **Contrasted nature and thickness of soils** which retain and delay a part of the infiltration through the aquifer;
- **Contrasted sizes of the catchment areas**; larger catchment areas display higher specific discharge rates;
- **Contrasted development of the epikarst** (weathered part at the top of the limestone bedrock) which is an intermediate and efficient storage between the soil and the lower zones of the aquifer;

Contrasted values of specific discharge are also related to uncertainties about dimensions of the catchment areas which remain mostly high (up to 20%). As a consequence, the duration of periods without recharge cannot be easily compared from one system to another.

Moreover, differences in specific discharge rates may also result from other factors; for instance springs that are active under low-flow conditions are not well known nor measured: devices are often difficult to install, flow may be widely dispersed along the river bed or even directly injected into an alluvial aquifer (see for instance the Schlichenden Brünnen, SZ).

The combination of these parameters explains the wide range of observed low-flow specific discharge rates. In most case, low-flow specific discharge is underestimated as a significant proportion of the discharge could not be measured.

However, observations clearly indicate that base-flow emerging from karst aquifers do not turn dry - even during long drought periods - although outflowing discharge rate may be considerably reduced, and even become negligible for small flow-systems (e.g. of a few square kilometers).

Simple observation of long karst springs time-series in Switzerland (Ajoie, folded Jura, Helvetic Alps) indicates that over the same period of monitoring, small karst systems (a few square kilometers) in Ajoie have been more exposed to prolonged periods without recharge than systems with more mountainous catchment areas. Low-land karst flow-systems of moderate extension therefore appear to be more sensitive to droughts. This observation comes from the fact that the occurrence of precipitation (or recharge events) is statistically more frequent on a larger area than on a smaller one. However, the storage capacity of low-land karst systems is not negligible and they remain active through several months without recharge.

Application of recession methods to existing sites in Switzerland (Milandrine in Ajoie, Areuse in context of folded Jura and Schlichenden-Brünnen in the Helvetic Alps) showed that the extrapolation of the discharge rate remains strongly influenced by the start of the recession (i.e. by the amplitude of the previous recharge event) and do not fit very well the tailing parts of the curves. The recession of the spring discharge is adequately described for about ten days after a recharge event, but it cannot be extrapolated over a period of several months. Experiments showed that after 10-12 days without recharge, the divergence between the extrapolated signal and the real observation is already as large as 30%! Applications to large systems tend to be even less precise than for smaller ones because the recession part of the curve which is fitted by the model is in fact still controlled by the previous flood-release. As a consequence **extrapolations tend to overestimate the recession coefficients** and thus to underestimate discharge rates after extreme drought periods… Another problem is that even a short recharge event – a few mm of precipitations – already considerably disturbs the “strict” recession trend. In such cases it appears difficult to extrapolate the recessions observed at most karst springs, especially for springs with a large catchment area.

Recessions observed during long drought periods shows that **models always underestimate** long term discharge rates (e.g. overestimate the rate of discharge decrease). Models thus forecast shorter spring persistence than actually observed. Recession models applied to several karst springs in Switzerland models predicted at least 6 months before the discharge really turns negligible (persistence). This must therefore be considered as minimal persistence for karst springs in Switzerland.

Considering that only a few systems are well monitored in Switzerland, preliminary results indicate that soils (thickness and characteristics) play a determining role in the slowdown of the recession. In a similar context this effect seems to be more significant than the size of the catchment area.

Recession of karst springs impacts the rivers regime as a lot of rivers are fed by karst springs during low-flow periods. In the Jura Mountains for example contribution of karst groundwater lies between **24 to 74% of rivers discharge** draining more than 50% of karst areas (see Table 7—2). Thus, even if karst aquifers present a strong persistence to droughts, the increase of such periods will affect the regime of the rivers. Repeated and prolonged periods of drought would involve a significant reduction of the surface rivers regime.

Considered rivers	catchment [km²]	Karst %	Min. karst low-flow discharge / river low-flow discharge	References
Promenthouse (Gland)[1]	137.8	(77/138) = 56	(57/240) = 24 %	OFEV, ISSKA [2012b]
Aubonne (Allaman)	187.4	(140/187) = 75	(200/460) = 43 %	OFEV, Luetscher and Perrin [2005], ISSKA [2012b];
Orbe (Chalet)	308.5	(189/309) = 61	(1051/2370) = 44 %	OFEV, ISSKA [2012b]
Areuse (Boudry)[2]	377	(130 + 72 + 49 + 46 +20)/377 = 84	(690 + 170 + 150 + 200) / 1640 = 74 %	Burger [1959], OFEV, Bouzelboudjen et al. [1998]
Suze (Pery)	176	(112/176) = 64	(600/1200) = 50 %	AWA Bern, OFEV

Table 7—2. Examples of contribution from karst groundwater to the rivers low-flow discharge (Jura)

7.2.2.1.1. Increase of flood events in karst regions

Conclusions of the project CChydro (BAFU [2012]) mention that events of floods may increase in the Jura regions which are typical karst areas. This characteristic has to be taken into consideration as flood dynamics in karst are singular and cannot be approached with methods developed for surface hydrology.

This high probability of flood-events intensification reinforces the necessity of a systematic documentation of karst aquifers and of simulation tools to assess hydrological and hydraulic components – especially in the Jura region. This documentation should serve as a basis for assessing high-flow characteristics of the systems and their related hazards for environment and construction.

The study related to the assessment of flood-hazards of the Beuchire-Creugenat flow-system (§. 6.3) demonstrates the efficiency of combining the KARSYS approach with hydrological recharge model plus pipe-flow simulation tool to reproduce the floods.

A special attention should also be paid to alpine karst systems which are going to change from a glacio-nival toward a nivo-pluvial regime as their new regime may generate more frequent and intense floods in winter.

7.2.3. Effects on water quality

It is expected that climate changes lead to a global rising of temperature as well as to repeated and prolonged drought periods which may affect the quality of karst water. However, studies are missing on this topic. It should be mentioned that NAQUA dataset is relatively short to observe the evolution of the groundwater quality over the last decades. Additional data (cantons, communities, universities, etc.) should be collected in order to track mid-term evolutions of the groundwater quality.

7.2.3.1.1. Temperature

Temperature of groundwater in karst aquifers is expected to increase as a consequence of the global rising of air temperature in Europa. Increase of groundwater temperature is already observed in a few sites in Switzerland. Jeannin et al. [2015b] show that in the Jura Mountains, groundwater temperature increase of about +0.0205°C/y, i.e. +0.45°C over the period 1989-2011. The trend is supposed to evolve the same way as for other geological media (see Menberg et al. [2014] for instance). However, studies are missing for the expected evolution of the groundwater temperature in the next decades. This topic should be further investigated as it may affect water quality (chemical and microbiological content).

[1] Montant spring Q_{347} (E-Dric 2010)
[2] Springs of Noiraigue, Raies, Raisse and Sourde

7.2.3.1.2. Hydrochemistry

The quality of groundwater in karst aquifers is supposed to evolve as a consequence of the climate changes and of human activities. Observations on a few sites along the last 25 years indicated a clear **increase of water mineralization** and significant changes for **compounds related to human practices** (Jeannin et al. [2015b]).

7.2.3.1.2.1 Compounds related to climate warming, CO_2 and dissolution of the carbonates

This trend is expected to be a consequence of an increase of the biological activity in soils resulting from the global increase of the air/soil temperature under the current climate warming.

The most significant change of groundwater quality in karst aquifers is related to the increasing mineralization which is represented by the bicarbonates (+1-2 µS/cm/year) and to other parameters related to carbonate dissolution: electrical conductivity (+10 % over the last 22 years), hardness, Ca^{2+} and HCO_3^- and decrease in pH.

7.2.3.1.2.2 Compounds related to human practices

Analyses from Jeannin et al. [2015b] show a decrease of NO_3^-, K^+, Cl^-, SO_4^{2-} and NH_4^+, an increase of Na+. Relation of these compounds with climate warming is unclear. The decrease of K+ is related to fewer inputs of potassium-based fertilizers. For the decrease in NH_4^+ improvements in sewage treatment for both domestic and industrial waste waters is certainly the main reason. For NO_3^-, the opposite trend observed in France and in Switzerland may be explained by differences in application of the fertilization practices.

7.2.4. Effects on soil and vegetation

Soils in karst area are usually thin and of high permeability. Effective infiltration usually represents 50 to more than 80% of raw rainfall. Water retention in soil is low. This limits the variety of plants and their growth. Plants living on karst are persistent and survive to actual drought periods with limited damages. Nevertheless, extreme and repeated drought periods may produce such a **water deficit in soils** that vegetation will suffer, reduce or even die. Forest fires may become more frequent, accelerating the reduction of the vegetation. In extreme cases **soil erosion** could be enhanced leading to a barren and infertile landscape (i.e. karrenfelds)…

In Switzerland, issues related to maintain soils and vegetation should focused on high-elevated Jura (shallow soils covered by pastures and forests), and locally on the alpine karst environments where the vegetation is sparse. Regions of low-elevated Jura (shallow to thick soils covered by prairies, forests and cultures) are slightly less sensitive, as long as vegetation can be maintained.

Karst regions where soils are of moderate or high thickness (moraine or molassic cover) may present a surface drainage. This is common in synclines valleys of the folded Jura Mountains (Saint-Imier (BE), Val de Ruz (NE), Vallée de Joux (VD), etc.). Here the sensitivity to drought periods may be comparable to non-karst environments.

7.3. Perspectives for karst water management

7.3.1. Specific management rules for karst environments

One of the main highlight of Swissskarst is the awareness of karst groundwater significance at the scale of the country. Before the Swisskarst project starts, the significance of groundwater reserves and resources at the scale of Switzerland and as agent of natural hazards: floods, collapses, landslides, etc. was underestimated from most hydrogeologists, hydrologists and stakeholders.

It is hoped that consideration of this significance will increase and that all aspects related to the management of karst environment will be taken into account in an integrated way.

Identification of water resources, optimization of the water catchment protection areas, prevention of karst flood hazards, collapses, contamination, preservation of natural heritage in karst are questions, which should be managed in a coordinated way. The idea of a water management organized by river catchment areas instead of administrative borders, and including groundwater would be an important milestone in this direction.

7.3.2. Survey and investigation

Along these 4 years, the project highlighted a lack of data related to karst hydrology all over the Swiss territory:

- Lack of a federal central database which gathers and shares data and metadata; even if a lot of sites are monitored and studied by various institutions, private companies or organisms, the knowledge of these data and their accessibility remain hard to manage!
- Existing monitoring of karst aquifers over the Swiss territory does not reflect all contexts diversity given their respective significance. **Recommendations would be to increase monitoring in alpine and lowland karst areas**; alpine as this context provides most of the resources (Malard et al. [2016]) and lowland as they are expected to experience more droughts in summer (BAFU [2012])…
- The project also demonstrated that spring data are often not usable, because only one part (often a small part) of the effective outflow of a karst system is monitored. This makes some datasets completely useless (at least from the point of view of a hydrogeologist). This leads sometimes to wrong catchment areas and to completely wrong protection zones or management strategies. Monitoring strategies should therefore be reassessed (or at least criticized) in regions documented with the KARSYS approach.

In the perspective of a sustainable management of water resources in Switzerland, it would be important to address these lacks.

7.3.3. Direct water exploitation

Observations and discussions with groundwater managers and stakeholders in the investigated areas (Bernese Jura, Jura, Valais, etc.) evidenced that a lot of existing extraction strategies are far from being optimal. Recurring problems with karst groundwater are:

- Turbidity: deterioration in the water quality and of the facilities because of particles loads after some rain events;
- Conflicts related to the application of large protection zones;
- Water scarcity in summer;

However it was observed that better strategies could be developed to face those problems. If summer droughts become more frequent, adjustments have to be done. The recent federal report (OFEV [2012]) about adaptation to climate changes identified actions in the field of water supply (GE1). Objectives are to insure capacities of water extraction devices, storage and distribution during low-flow conditions and droughts.

Concerning karst, SISKA recommends to develop new tapping strategies such as (i) **deep wells** in confined parts of aquifers (for instance in synclines or along the border of the Swiss Plateau) instead of tapping springs, (ii) **overexploitation** of groundwater during low-flow periods. However details on these were beyond the scope of the Swisskarst project.

7.3.4. **Indirect exploitation**

7.3.4.1. <u>Heat</u>

Geothermal flux and thermal gradients are very special in karst aquifers compared to less heterogeneous systems (see §. 3.1.3.1). As a consequence, for being efficient, heat extraction devices should take these characteristics into consideration when dimensioning. Besides, impact on groundwater (quality and quantity) must be avoided.

In this perspective, recommendations at a federal level are clearly incomplete and not applicable. KARSYS is a relevant approach to support implantation of geothermal probes in karst aquifers as it provides concrete characteristics for probes dimensioning (i.e. the thickness of the covering formations, the depth of the saturated zone, the existence of superimposed aquifers, the fluctuations of the groundwater table, etc.), it makes possible to make decisions on a consistent and explicit base. The application of KARSYS in cantons Sankt-Gallen and Fribourg in order to set criteria for authorization/rejection of the large number of demands for geothermal heat pumps is the best example of such support.

7.3.4.2. <u>Hydropower</u>

Karst represents a non-negligible source for hydropower production. In many cases, such exploitations remain challenging, especially concerning the tapping location, but also regarding environmental issues.

A good knowledge of karst flow-systems is therefore required in order to take appropriate decisions concerning the expected success (resp. risk of failure) and the impact on the environment. In this perspective, KARSYS is a prerequisite for designing and optimizing this type of project, but further extension of the approach should be developed to address this issue in a more straightforward way.

8. *Conclusion*

Thanks to the 61th Swiss National Research Program, the Swisskarst project made possible to formalize procedures of the KARSYS approach via different applications in Switzerland and abroad, and to develop pragmatic and relevant extensions which base on concepts and information resulting from KARSYS: generation of conduit network, simulation of recharge and of hydraulics, and mapping processes. Such work was applied to a large panel of issues which require spatial and temporal information in karst environments / aquifers. Depending on the karst-context, the issues, the available data and the scale, KARSYS and related extensions may be systematically applied on a site, thus providing a large set of information within a limited effort. Applications of KARSYS since the thesis starts were achieved for various applied questions. The applicability of KARSYS could thus be refined according to usual constraints in the field (available data, time, reliability, conditions of application, etc.) and user's expectations (understandability of the interpretations, sustainability and exploitability of the results).

The Swisskarst project was also the opportunity to work on recharge and storage processes in karst aquifers in Switzerland. In the context of climate changes, changes in groundwater recharge and storage in karst aquifers are expected. Thus, actual processes have to be better understood before addressing forecasts for the coming decades. Dedicated approaches have been developed for being applied at Swiss scale with scarce data. In spite of uncertainties related to data, to the sites and to climatic variability, key-values about recharge and storage have been provided as well as insights regarding their evolution with expected climate changes.

Developed approaches and results (i.e. spatial characteristics, key-values, etc.) are of great interest for the institutions in charge of managing groundwater resources and land-uses. These should be presented through understandable and pragmatic documents for being adopted and further used by the authorities. As the review of existing hydrogeological maps proved that no clear consensus guided the realization of hydrogeological maps in karst areas, innovative concepts and guidelines for mapping karst hydrogeology have thus been developed in order map characteristics resulting from the KARSYS approach and to provide usable information for decision-support. Unlike most existing maps, advantages of the KARSYS hydrogeological maps are to explicitly locate and describe the phreatic zones of the considered aquifer, the expected flow-paths and the boundaries of the underground flow-systems and their catchment area at land-surface.

Finally, in Switzerland, both cantonal services and federal offices support the development and the application of KARSYS for the sustainable management of groundwater resources in karst aquifers.

This work provided two main contributions: a methodological development of the KARSYS approach, including extensions, and an outlook as well as key-values for karst aquifers and flow-systems in Switzerland. These two contributions are summarized in the next sub-chapters.

8.1. Improvements of KARSYS and extensions

Existing procedures related to the application of KARSYS have been described in details and further formalized. As of today, this dissertation presents the most complete instructions for applying KARSYS. Advantages, limitations, validation methods, reliability and conditions for application (contexts, data, scale, issues, etc.) have been specified and discussed.

In addition to technical improvements made on the existing approach (concepts and procedures formalization, database implementation, tasks automatization, etc.), three main extensions have been implemented to KARSYS in order to address specific questions in karst.

The first extension concerns the **generation of a conduit network**. Starting from the KARSYS model and the delineation of the catchment area (for which a systematic procedure has been proposed), a tool has been developed to generate a consistent conduit network in three dimensions. Processes of conduits generation are controlled by the size of the catchment, the position of the main outlet, the geology and the hydraulic gradient in the different zones of the aquifer. The conduit generation process is based on four distinct sub-models: 1) the **infiltration** sub-model which provide the conduit inputs over the ground surface (allogenic recharge or autogenic concentrated or diffuse recharge), 2) the sub-model of the **vertically-controlled conduits** which generate the vertical conduits in the vadose zone, 3) the sub-model of the **basement-controlled conduits** which generate a vadose conduit network according to the topography of the aquifer basement, and at last 4) the **phreatic conduits** sub-model which provide the geometry of the conduit network developing in the phreatic zone. The modeling of phreatic conduits is adjusted by some empirical parameters, which could be customized by the users in order to adjust the generated network to their idea of the expected geometry, depending on the guiding-effects of the inception horizons or on the intensity of the hydraulic gradient. The model then ensures a sufficient drainage capacity of the aquifer and can be validated by using additional investigations, field observations or data which were not integrated in the process. Although the model parameters may be adjusted by the user, two main limitations do exist: (i) the model cannot separate itself two flow-systems which drain a common phreatic zone, (ii) the model does not consider the effect of previous phases of karstification resulting from paleo-conditions. This last point is problematic only for the generation of the epiphreatic conduits which activate for high-flows. The proposed model is thus first valid for low-flows. However, flow processes for high-flow conditions may be inferred in a second phase and latter integrated in the conduits model as illustrated by the case study of the Beuchire-Creugenat (BC) and the Bonnefontaine-Voyeboeuf (BV) karst systems (Malard et al. [2015a]). Resulting conduit network from the generation model must thus be constantly confronted (and improved) by considering new data. After some iterations of the generation model and after conduits have been adapted for high-flow conditions thanks to new data and observations, the user obtains a ready-to-use field of parameters (conduit lengths, equivalent diameters, thresholding conduits, etc.) which may be later implemented in conduit-flows simulation models.

The second extension is related to the assessment of **karst groundwater recharge**. During the Swisskarst project, different hydrological semi-distributed models (RS3.0, Minerve) have been tested on various test sites, assuming that computed surface runoff (out of these hydrological models) reflects infiltration into the karst aquifer. These models are able to properly spatialize equivalent precipitation, snow-melt and glacier-melt processes in function of the size and the relief of the catchment. Tests conclude that such models are fairly well adapted for alpine flow-systems with prominent elevation contrasts, little soil covers (i.e. scarce vegetation), i.e. where recharge processes are dominated by snow and/or glacier-melt. On the opposite, these models fail in assessing recharge processes for karst flow-systems of lower elevation and lower relief contrasts. In low-land environments, recharge processes are more dominated by the vegetation and the presence of soils. Then, an alternative semi-distributed model has been developed. **KRM_1** focus on surface interception (forests, cultures, etc.), soils and sub-soils (epikarst) processes and on conduit-surrounding storage. Application of this model to the BC and the BV flow systems provided a much better assessment of recharge rates, in compliance with realist values of interception depending on the vegetation cover, RET, epikarst storage and expected storage in the conduits surrounding zones. Although KRM_1 provides satisfactory results, some parameters could be further refined – especially regarding interception reservoirs. Following conclusions were drawn from these applications:

- The use of the appropriate recharge model (RS3.0 or KRM_1) is governed by the relief and the hydroclimatic regime of the catchment area. A map of recommendation has been established for Switzerland; it gives the places where RS3.0 - or respectively KRM_1 – could be applied with confidence.
- The calibration of a recharge simulation model in lowland karst area is much more complex compared to environments of highest relief amplitude, as in the Alps. This complexity results from the lack of a dominant process which controls the recharge in lowland area, as for instance the seasonal snowmelt as in the Alps. RET is a parameter which becomes more and more important and complex to evaluate as the environment is flat and of lower elevation.
- The land-use in lowland environments should be explicitly taken into consideration as parameters in the simulation as it greatly controls the recharge processes (forest covers, type and rotation of crops, urban development, etc.). This is a strong difference compared to mountainous environments, where the land-use may be neglected.
- The use of spatially distributed precipitations over catchment areas in lowland karst environments does not provide significantly better results than using non-distributed precipitations. This is a significant difference compared to mountainous environments, where precipitation rates may notably vary with the elevation.

The third extension is related to **pipe-flow simulation**. Recharge calculated by the second extension can be used as input for a pipe-flow model using the conduit network generated within the first extension to KARSYS. This modelling makes possible to reproduce the evolution of the hydraulic heads within the conduits and the discharge rates at permanent and overflow outlets. Various tests have been realized, considering a simplified conduit-model and a more complex one obtained with the conduit generator. The application to the BC and BV karst systems made it possible to validate the low-flow conduits model and to adapt the geometry of the expected active conduits for high-flow conditions (using additional data, observations and hydraulic relationships) in accordance with the KARSYS model and with speleogenetic interpretations. Finally, simulations made it possible to reproduce all measured head and discharge rates at a given place (permanent and overflow springs, borehole, cave, etc.). This was only possible by introducing thresholds and by-passes in the conduit network. The final model is concrete and physically realistic. As demonstrated via the simulation of the flood event of August 2007, this extension reveals relevant for assessing flood hazards in karst environments. The two main learnings from this application are the following ones:

- Hydraulic relationships between measured hydraulic heads or discharge rates at various location of the flow-system (springs, boreholes, caves, etc.) provide crucial indications for refining the geometry of the active karst conduits for high-flow conditions;
- Most of the flow-dynamics is controlled by a few hydraulic obstacles (thresholds, narrowing or by-pass conduits). Thus, flow-dynamics may be fairly well simulated by designing a minimalist hydraulic model with a restricted number of conduits, focusing on the main hydraulic obstacles. The application to BC and BV flow-systems shows that a complex hydraulic model with a high discretization of conduits does not bring better results for understanding the flow-system compared to a minimalist hydraulic model which focuses on the aforementioned obstacles.

Figure 8—1 summarizes the actual workflow for the application of KARSYS and extensions, including conditions for application. The first condition is to assess if the karst to be investigated is telogenic of not. If yes, the 4-steps procedure of KARSYS Original 3D is applied. Then, if the initial question(s) require(s) it, the newly-developed extensions (conduits generation, recharge and hydraulic simulations) can be applied based on the original KARSYS model plus additional models (infiltration models, Speleogenetic model, etc.). This systematic workflow can be applied for any issue requiring spatial and temporal information on the aquifer and on the flow-system (e.g. resources, hazards and energy).

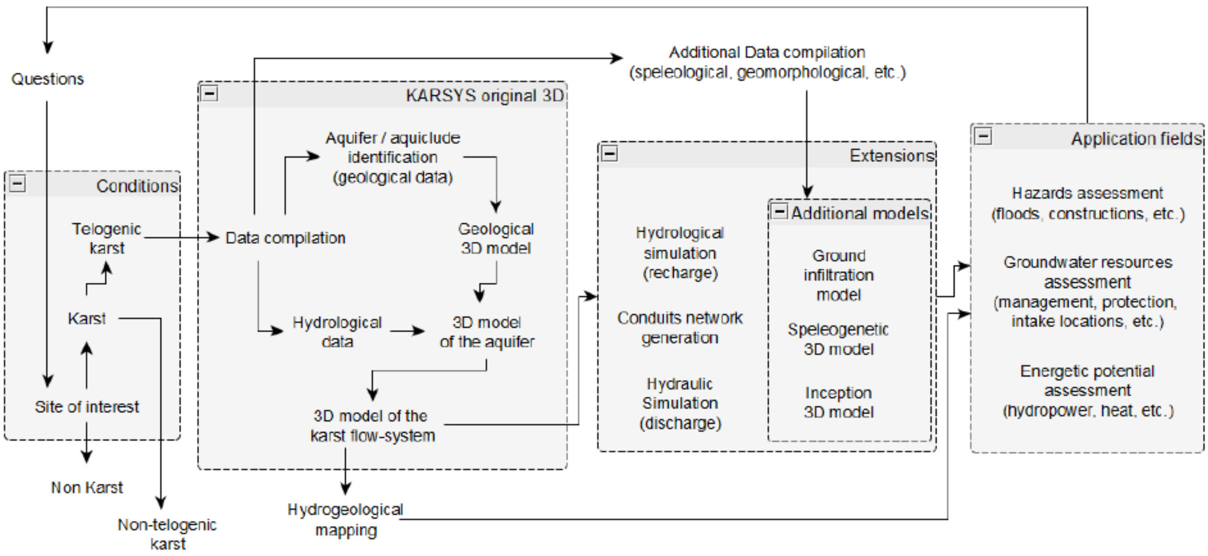

Figure 8—1. Synthesis of the KARSYS workflow including newly-developed extensions for a large range of applications

8.2. Swiss karst aquifers, key-values of actual dynamics and expected evolution

The Swisskarst project was also the opportunity to address general questions concerning karst aquifers in Switzerland in order to provide insights, key-values or recommendations regarding groundwater resources and their expected evolution with climate changes. Three questions have been addressed: (i) the annual recharge of Swiss karst aquifers, (ii) the minimal low-flow storage and the seasonal storage, (iii) the expected evolution of karst water resources with climate changes.

A dedicated approach has been proposed for assessing recharge of karst aquifers in Switzerland (Malard et al. [2016]). Assessed values range between 6.9 and 9.9 km^3 (average 8.4 km^3), which in turn represents nearly 40% of the total annual groundwater recharge in Switzerland, although karst outcrops cover only 20% of the country's territory. Depending on a pessimistic or optimistic scenario, the averaged recharge rates vary between 29 and 42 Lkm^{-2}s^{-1} over the swiss karst areas. In lowland karst areas, the recharge is about 20 Lkm^{-2}s^{-1} while in alpine karst areas it may often exceed 100 Lkm^{-2}s^{-1}. Globally, this corresponds to 60 or even 90 percent of the precipitation falling on the catchment, the rest being retrieved by RET. Such high rates mean that infiltration into karst is complete. In these regions water supply and ecological services related to water are completely or dominantly depending on karst waters.

Regarding the storage capacity of the karst aquifers, two types of storage are relevant for groundwater management: (i) the seasonal storage which refers to the stored amount of groundwater in the aquifer between low- and high-flow seasons and, (ii) the minimal low-flow storage which reflects the released amount of groundwater after a prolonged period without recharge. Results show that seasonal storage represents 40 to 70 mm of (i.e. 3 to max. 10% of the annual recharge of the aquifer). At the scale of Switzerland, the seasonal storage in karst aquifers ranges between 0.23 and 1.1 km^3 depending on the scenarios; the mean storage being about 0.4 km^3. A rough estimation for a karst system indicates that most of the seasonal storage capacity seems to take place in the epikarst and in the karst conduits of the epiphreatic zone, meaning that seasonal storage in the low permeability volumes of the aquifer is *a priori* negligible. Minimal low-flow storage ranges from 20 to 50 mm, depending on the type of the aquifer. Nearly 50% of the storage seems to take place in the soil and epikarst and the other 50% in the saturated zone (conduits + low permeability volumes). At the scale of

Switzerland, the total estimated low-flow storage ranges between 0.2 and 0.4 km^3. These values are site-specific and may considerably vary from an aquifer to another.

Thanks to these analyses, the dynamics of the karst aquifers in different regions of Switzerland have been better understood making possible to assess the evolution of groundwater resources in the frame of the climate changes. Preliminary results suggest the following changes within the next decades. Changes in recharge conditions of karst groundwater in Switzerland will be very different depending on regions. In the regions dominated by jurassian and prealpine pluvio-nival and nivo-pluvial regimes, late summer drought is expected to become more severe in the future, and extreme flood-events are expected to be reinforced as well. Changes in other areas will lead to less contrasted conditions (less drought and less floods) than today. For instance, in alpine regions dominated by a nival regime, seasonal recharge variations will be smoothed. Winter recharge is expected to increase and summer high-flow discharge will probably decrease as the melting period will be longer. In other alpine regions dominated by nivo-glacial, glacio-nival and glacial regimes, winter droughts will be reduced, high-flow periods will appear sooner on summer and seasonal droughts may appear in late autumn, they will however be less severe than today's winter droughts! The very large spectrum of recharge conditions in Switzerland is the main reason for this large palette of expected changes (see the map on Figure 7—1). Our study, however showed that the evolution related to climate change, i.e. increase in temperature (mainly in summer) and a slight increase in rainfall quantity (mainly in winter) will probably have less impact on water than changes directly related to human activities, which will modify recharge conditions. Mainly agriculture, but also urban development and increased water abstraction, or even artificial snowing will have more impact on recharge than only the effect of temperature and rainfall changes. Impacts due to climate changes will also concern the vegetation that covers the ground surface in karst areas as well as the water quality (as demonstrated by our recent publication: Jeannin et al. [2015b]).

Consequences of these modifications should be anticipated in order to think about groundwater strategies to be adopted in the coming decades. Strategies of development regarding energies, land-planning, water resources, ecosystems, etc. should explicitly take into account aspects related to groundwater in karst region (uses, resources, vulnerability, etc.). In this view, the KARSYS approach should be extended to non-documented areas of Switzerland (see Figure 10—1) in order to provide a consistent documentation for supporting such decisions.

8.3. Outlook: Visual KARSYS

Research and development conducted in the frame of this thesis are going to continue. Mid-2016, SISKA started a new project as a follow-up of NRP-61 Swisskarst project. The Visual KARSYS project[1] is funded by the FOEN (grant for the "Promotion of Environmental Technologies") and aims at developing a web- tool for making KARSYS more accessible, i.e. more usable. The web-application provides a practical guideline on the way to prepare the data, to build the KARSYS 3D models and to produce specific outputs. The user-interface will include the necessary tools either build the models directly or to import models from other software packages. It will also include a visualization module as well as export files for being manipulated with other existing tools.

Visual KARSYS will promote the approach worldwide and by providing pragmatic tools that most karst hydrogeologists may perform by themselves using their own working environment. End-users (stakeholders) will also benefit of this development by having access to all outputs, including 3D-models directly on-line.

[1] visualkarsys.isska.ch

9. *Bibliography*

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10. *Appendices*

As mentioned in the introduction, several publications have been realized all along the Swisskarst project. Some of them are only mentioned in this thesis (Appendix 10.1) as they are not strictly related to the development of KARSYS or its extensions but rather to applications. For example, the papers related to KARSYS applications in Slovenia or in Spain (resp. Turk et al. [2013]; Turk et al. [2014], Ballesteros et al. [2013]; and Ballesteros et al. [2015a]) are not compiled here as they are not indispensable for the understanding of the approach.

The following papers: Vouillamoz et al. [2011] and Jeannin et al. [2013] are considered as the state of knowledge before the thesis starts. Although I participated to the redaction of these papers, these are more considered as teamwork in whihc each collaborator brought its personal input.

Papers related to the progresses and the dissemination of the Swisskarst project are also not compiled here; they are only mentioned in the §. Appendix 10.1. These are the following references: Malard [2013]; Malard and Jeannin [2013a]; Malard and Jeannin [2013b], as well as the following technical reports which have been addressed to the Swiss National Research Fundation: ISSKA [2012c]; ISSKA [2013c] and ISSKA [2014c]. These annual reports have been written in parallel to the thesis and some elements of these reports have been integrated in the previous chapters (especially in §. 7). Two technical reports to the attention of the FOEN have been written on the following issues: assessment of the Swiss annual karst groundwater resources (ISSKA [2013d]) and assessment of the dynamic storage in karst aquifers in Switzerland (ISSKA [2015a]). Elements from these reports have been integrated in the §. 7.1 in a form of a published paper (Malard et al. [2016]).

Regarding the improvements of the KARSYS approach, the following papers and reports have been published depending on the thematic:

- In the field of mapping processes; the papers Malard et al. [2014b] (Appendix 10.9) and Malard et al. [2014c] (Appendix 10.10) describe the improvements which have been realized in the field of karst hydrogeological mapping and could be read in addition to the thesis.
- In the field of flood hazards assessment, two papers have been written and published as conference in-proceedings. The paper Vouillamoz et al. [2013] presents a first application of KARSYS on the Beuchire-Creugenat karst system which has been partially reviewed and integrated in the §. 6. In Appendix 10.3, the paper Malard et al. [2014a] presents another case studies of karst enhanced flood-hazards in the Bernese Jura as well as the concepts and the approach for assessing hazards and risks related to the karst overflow.
- In the field of karst related hazards during constructions in karst area, two papers have been produced in teamwork and may be consulted in addition to the thesis as concrete case studies of a KARSYS application combining 3D conceptual model and hydraulic simulations for hazards prevention: Malard et al. [2015b] in Appendix 10.6 and Jeannin et al. [2015b].
- In the field of simulation, the paper Weber et al. [2011] provided a base for the recharge assessment in alpine karst aquifers using RS3.0. This paper is considered as the state of the simulation progresses before the thesis starts. This paper brings additional information on the recharge simulation for an alpine karst aquifer partially fed by a glacier. The second paper from Weber et al. [2012]) discussed the differences between recharge processes between alpine and lowland systems. This paper point out the fact that effects of coming climate changes are more difficult to forecast in lowland areas even though they are expected to be more significant than in alpine systems.

10.1. Appendix 1: Swisskarst, a project of the 61st National Research Program

10.1.1. The 61th National Research Program

The National Research Program 61[1] - supported by the Swiss National Science Foundation[2] - focuses on the sustainable water management in Switzerland. The program entails 16 research projects grouped in two interacting clusters. Cluster 1 is related to Hydrology – Glaciers, groundwater and extreme events regarding climate changes and anthropogenic activities while Cluster 2 deals with Water management, especially the socio-economic changes on hydrological services.

The research phase of the Program started in January 2010 and ended in December 2013. The closure ceremony of the project took place in November 2014 in Solothurn.

Outputs of the Program - including highlights of the Swisskarst project - are synthetized into four scientific and thematic syntheses and an overall synthesis summarizing the key findings of the 16 projects for a larger audience. These documents are available for download on the NRP61 website.

The scope of the Program is to promote a modus of integrated and sustainable water management in Switzerland. Through the results of the different involved projects, final documents (outputs of the Program) aim at providing recommendations to improve the actual water management according to: development of the Swiss society, water uses and climate changes.

10.1.2. The Swisskarst project

The Swisskarst project finds its origin from the observation that karst aquifers – and more broadly karst environments – pose problems to water managers and stakeholders who do not have a sufficient knowledge about the hydrological functioning of these specific areas. Historically, this lack of knowledge was the main reason for many projects in karst to be abandoned or to be subjected of modifications inducing additional costs because of the non-consideration / underestimation of the potential incidences related to the karst aquifers functioning.

In the frame of the national Research Program 61 (NRP61) - which was dedicated to the sustainable water management in Switzerland - the Swisskarst project was supported because karst aquifers were considered as a major issue regarding groundwater reserves and resources.

Indeed, in 2008, prior to the implementation of the Program, the Swiss Federal Office for the Environment (FOEN) launched an assessment of the groundwater reserves in the different aquifers types. The preliminary results show that most of the Swiss groundwater is stored within karst aquifers (ISSKA [2008]; Jeannin et al. [2013]). Approximately 120 km^3 of groundwater are stored within the Triassic, Jurassic and Cretaceous dolostone and limestone which outcrop over 20% of the territory. This result was an additional argument to consider the relevance of the Swisskarst project as a full part of the NRP61.

As mentioned in the proposal, objectives of the Swisskarst project were:

1) The development and the improvement of a specific approach for the documentation of the karst aquifers (KARSYS);
2) The application of this approach to the whole territory to gradually increase the knowledge relative to karst aquifers and to test and still improve the approach;
3) The formalization of indicators which could be used to evaluate and compare these aquifers;
4) The promotion of these formalized information though a communication support (Internet) accessible to the largest audience

[1] www.nfp61.ch
[2] www.snf.ch

The results of the Swisskarst project can be consulted via a series of papers and reports (§. 10.1.2.2 and 10.1.2.3.3) and some representative results of the project are presented in this thesis.

The author of the thesis represented the main workforce of the project staff. Besides, a 50% position during three years was added in order to support application of the method (technical support mainly in geology and GIS). Additional funding from FOEN and from several Cantons made it possible to reinforce the working team during the whole project duration.

10.1.2.1. Status of implementation

A wide range of public projects have benefited of developments made in the Swisskarst project along these four years, and vice-versa. Many of these projects have been concluded with cantonal administrations or with the FOEN. Others have been conducted in collaboration with universities or hydrogeologists groups (CHYN[1], UNIBE[2], etc.). In addition, collaborations have been organized with institutions in Slovenia and Spain in order to apply the KARSYS approach in these countries. Methods and results of most of these projects have been published as public reports, book-chapters or articles (see §. 10.1.2.2 hereafter). Main collaborations in Switzerland for applying the KARSYS approach have been the following ones:

- **Karst Natural Hazards Haute-Ajoie (canton Jura):** Thanks to additional subsides from the Jura Canton; karst flood hazards have been assessed in the region of Porrentruy (Ajoie) by using KARSYS. This project clearly supported the development of the approach with a concrete application aiming at characterizing flood mechanisms and their incidences. Results of the project were published and presented to the Sinkhole Conference, Carlsbad (NM) in May 2013 (Vouillamoz et al. [2013]).
- **Montanaqua (UNIBE):** Collaborations with UNIBE in the frame of the Montanaqua project (also part of the NPR61) led to the application of the KARSYS approach to the Plaine-Morte glacier karst region (BE-VS) in order to characterize the incidence of the karst in the hydrology of the massif. Results were used to predict the pathways of the underground drainage of the glacier melt. A tracing experiment was designed and organized based on this model. Results have been integrated to the final report of the Montanaqua project and published in a peer-reviewed paper (Finger et al. [2013]).
- **Hydrovaud (canton Vaud, service Energie):** The project aimed at documenting and characterizing the main karst systems in the Vaud canton in order to assess their potential for hydropower and low temperature heat production. KARSYS was applied to 80 karst systems of Vaud (VD) canton (in total ~600 km2 of karst terrain) and led to the selection of 39 potential sites. Based on KARSYS 3D models and according to various capture scenarios (capture of perched springs, capture of perched underground streams or perched phreatic groundwater bodies) the potential energy production was assessed for each site (Jeannin et al. [2010a]). The overall potential was estimated to about 40 GWh/year. Seven sites were recognized as being of economic interest within the short/middle term. A closer study of three of them started at the beginning of 2015. Fifteen other sites have been also recognized as manageable but would require more investigation. Results of this work are now being expanded for the integrated management of karst environments in the Vaud canton, including natural hazards and the assessment of geothermal heat pumps.
- **KarstBern (AWA, canton Bern):** The KarstBern project was initiated in early 2011. The project entailed two parts: (1) the documentation of the groundwater reserves and karst systems organization in the Bernese Jura by the application of the complete KARSYS approach (this region represents around 540 km^2 and encloses more than 50’000 inhabitants who are supplied for a part or totally by karst water) and (2) a first documentation of the main karst systems and their expected catchments in the Bernese Oberland without applying the full 3D procedures of the KARSYS approach. The study in the Bernese Jura identified and characterized 17 significant karst systems and their associated catchment areas. Seven regional karst groundwater bodies have been identified and their geometry was depicted

[1] Centre for Hydrogeology and Geothermics, University of Neuchâtel, Switzerland *(www.unine.ch/chyn)*
[2] University of Bern, Switzerland (*www.unibe.ch)*

in 3D: Saint-Imier, Tavannes, Moutier, Bellelay, Diesse, Orvin and Mont-Sujet. The main drainage axes have been sketched for each system as well as interactions between the systems. The final results have been synthetized by Malard et al. [2012].

- **Karst im Hoch-Ybrig** (OGH, Ostschweizerische Gesellschaft für Höhlenforschung): The aim of this project is to document the massif of Hoch Ybrig in canton Schwyz in order to design a future multi-tracing experiment by predicting the groundwater flow paths and the connections which will be later verified by tracer's experiments. This prediction improves the monitoring design and the selection of appropriate injection points.
- **Karst St-Gall** (AFU Kanton Skt-Gallen): The project was initiated at the end of 2012. The aim was to obtain a systematic documentation of karst aquifers and karst systems of the region enclosing the Alpstein-, Alvier- and Churfirsten massifs. Results of the KARSYS 3D models are used for the formulation of practical recommendations and guidelines concerning the implantation of geothermal heat pumps in karst environments. Karst aquifers develop here within the Seewerkalk, Schrattenkalk, Kieselkalk and Quintnerkalk formations. Ten groundwater bodies and 32 karst systems have been identified and documented. Results of the approach are now being translated into a prescription map by the AFU stakeholders. In the frame of this project a collaboration with the UNIBE was initiated in order to exchange 3D geological models of the Säntis massif. Geological modelling was quite a challenge in this project.
- **Karst Fribourg** (SEn Fribourg): the project was initiated at the end of 2012. The aim was to assist the cantonal institution in the establishment of clear guidelines for the implantation of geothermal probes in karst regions. As for St-Gallen, the KARSYS approach was applied on a territory of 880 km^2 enclosing the median plastic Prealps and the Ultrahelvetic nappes. The main goal was to map the distribution of phreatic bodies and the unsaturated zone as well as the position of the main drainage axes. 24 groundwater bodies and 54 systems have been described in this area. This document is now being integrated in the process of establishing guidelines for the implantation of geothermal probes in the canton. The complexity of the geology and the number of karst systems were initially underestimated nevertheless the approach could be applied with some more effort than expected.
- **Projects FOEN**: Since the beginning of Swisskarst, the FOEN expressed a high interest for the documentation of karst aquifers. Numerous collaborations have been initiated with different sections (Hydrology department) in order to integrate results of the Swisskarst project in the federal processes of documentation. By the mean of the following projects, karst information is being progressively integrated into the official data of the Confederation (official migration scheduled for 2016). These projects are briefly listed hereafter:
    - **Karst maps, FOEN (2013)**: The aim of this project was to discuss and to formalize the possible integration of karst hydrogeological data and information resulting from KARSYS into the federal hydrogeological supports (maps, GIS and database). Existing Federal hydrogeological maps were discussed from a karst point of view and compared to the karst hydrogeological map resulting from KARSYS. A consensus was proposed in order to combine this information in a GIS database. This makes it possible to display a formal and pragmatic overview of karst aquifers and systems according to the scale of visualization.
    - **Karst resources FOEN (2013)**: the aim of this project was to develop an approach for the assessment of the annual karst groundwater resources in Switzerland. By taking into account the spatial heterogeneity of karst aquifers recharge, the assessment leads to a value ranging between 6.9 and 9.9 km^3 per year (i.e. benchmark of 8.4 (±1.5) km^3/year). A detailed description of this analysis is presented in §. 7.1 in a form of a published paper (Malard et al. [2016]). By comparing with values estimated by Sinreich et al. [2012], karst aquifers represent nearly 40% of the total renewable groundwater resources in Switzerland (18 km^3 per year). The authors also assessed the sustainable yield, i.e. the renewable resources that could be used in a sustainable manner. For karst aquifers, the assessed sustainable yield was 3.8 km^3, i.e. 35 to 55% of the annual renewable karst groundwater resources.

  - o **Storage in karst aquifers in Switzerland, FOEN (2015)**: the aim of the project was to assess variations in groundwater storage in the karst aquifers at the scale of Switzerland. Two types of storage have been distinguished: (i) the base-flow and (ii) the seasonal storage. The base-flow storage encompasses the groundwater volume that could be released by the system once the discharge rate of the system is lower than Q_{347} – corresponding to the seasonal minimal flow stage of the system. The seasonal storage corresponds to the groundwater volume temporary stored in the aquifer between the low and the high seasonal flows. The analysis has been performed over 4 different karst systems in the tabular and folded Jura and in the Alps.
  - o **Karst catchment areas, FOEN (started in 2010)**: Along with the application of KARSYS in the Jura Mountains (i.e. Vaud, Bern), results rapidly evidenced that the official catchment areas (based on topographic delineations) provided by the Swiss Administration are very imprecise or even wrong in many karst areas. Based on this observation and after a series of discussions, FOEN decided to use regions documented with KARSYS as samples for assessing differences between karst catchment areas and topographic ones, as well as the feasibility to include karst catchments into the federal database. This also required to criticize and to adjust the official basis stream network of Switzerland. Work is ongoing and results will be included in the official data in the coming years.
- **KARSYS in Slovenia**: This project was supported by the Swiss Contribution to new UE countries. The aim of the project was to assess the applicability of KARSYS in other contexts. Two distinct sites of Slovenia were selected, both being used for drinking water supply: the Trnov Forest site and the Kanin massif. Maps of groundwater reserves were established in both areas revealing unknown groundwater reserves which could be exploited in the future. Catchment areas were proposed and the understanding of hydrogeological mechanisms was significantly improved. Results have been presented to local authorities that are responsible for the management of water resources. Two scientific papers were published as outputs of the project, respectively in Acta Carsologica (Turk et al. [2013]) and Hydrological Processes (Turk et al. [2014])
- **KARSYS in Spain** (Picos de Europa): The project was operated in collaboration with the Oviedo University (Spain). The objective was to apply KARSYS on the Picos de Europa Mountains in order to understand the organization of groundwater flow at the scale of the massif before addressing further investigation like spring/cave monitoring, work on karst and cave genesis, etc. The approach provided the first picture of the main aquifer and its organization in systems as a prerequisite for designing future tracer tests and hydro-chemical investigations. Results of the KARSYS application were published in different journals (Ballesteros et al. [2013]; Ballesteros et al. [2015a]; Ballesteros et al. [2015b]).

10.1.2.2. State of documentation

Late 2014, the Swisskarst project made it possible to document nearly one-third of karst territories in Switzerland (cf. Figure 10—1). Several cantons have been fully documented (Friboug, St-Gallen, Appenzell, Vaud) while some other have been solely partially documented (Neuchâtel, Bern, Jura, Schwyz, Valais). Discussions with other cantons are in progress for applying KARSYS in the coming years.

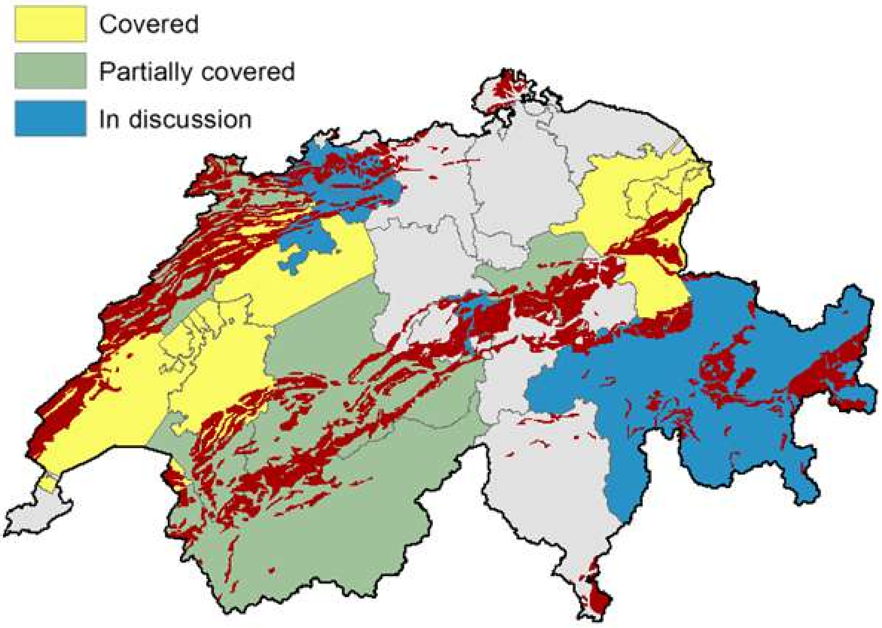

Figure 10—1. State of the documentation of karst aquifers in Switzerland at the end of the Swisskarst project

10.1.2.3. Communication

10.1.2.3.1. Publications

A considerable number of publications have been realized in the frame of the Swisskarst project during these last four years. As required by the NRP61, publications are addressed to institutional domains, scientific community, engineering sector, karst-interested people (i.e. cavers) in order to consider the wider audience that are in touch with karst environment.

Institutional domains journals: the project was presented through different articles in various journals dedicated to stakeholders in the frame of water and environmental management:

- Jeannin P (2012) Améliorer la gestion des ressources en eau du karst. Aqua & Gas 2: 8-9.
- Malard A, Jeannin PY (2013) Characterisation of karst aquifers in Switzerland: the KARSYS approach. European Geologist 35: 59-63.
- Malard A. (2013) Swisskarst Project (NRP61); comprendre et documenter les systèmes karstiques de Suisse. Geosciences Actuel 1: 15-18.
- Malard A, Jeannin PY (2013) Swisskarst: aquifères karstiques de Suisse. une approche pour une meilleure gestion et exploitation des eaux souterraines karstiques. Aqua & Gas 7/8: 22-27.

Scientific publications: a series of scientific publications have been realized along these four years. They are related to various aspects of the KARSYS approach (3D model, hydrological simulation, mapping processes, cases studies, etc.) and have been published in peer-reviewed journals and/or in congress-proceedings. The following list gives an outlook of the main ones by chronological order:

- Vouillamoz J, Jeannin PY, Demary S, Weber E, Malard A et al. (2011) KARSYS, un concept de caractérisation des systèmes karstiques pour une gestion durable des ressources en eau. Proc. H2Karst, 9th Conference on Limestone Hydrogeology, Besançon (France) 1-4 sep. 2011. 475-478.
- Weber E, Jeannin PY, Malard A, Vouillamoz J, Jordan F (2012) A pragmatic simulation of karst spring discharge with semidistributed models. Advantages and limits for assessing the effect of climate change. Akten des 13. Nationalen Kongresses für Höhlenforschung. 220-224.

- Malard A, Vouillamoz J, Weber E, Jeannin PY (2012) Swisskarst Project – toward a sustainable management of karst water in Switzerland. Application to the Bernese Jura. Actes du 13e Congrès National de Spéléologie, Muotathal, Suisse. 29 sept.au 01 oct. 2012. 215-219.
- Jeannin PY, Eichenberger U, Sinreich M, Vouillamoz J, Malard A et al. (2013) KARSYS: a pragmatic approach to karst hydrogeological system conceptualisation. Assessment of groundwater reserves and resources in Switzerland. Environmental Earth Sciences 69(3): 999-1013.
- Vouillamoz J, Malard A, Schwab-Rouge G, Weber E, Jeannin PY (2013) Mapping flood related hazards in karst using KARSYS approach. Application to the Beuchire-Creugenat karst system (Ju, Switzerland). Proceedings of the 13th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, held in Carlsbad, New Mexico, May 06-10, 2013. 333-342.
- Turk J, Malard A, Jeannin PY, Vouillamoz J, Petrič M et al. (2013) Interpretation of hydrogeological functioning of a high karst plateau using the KARSYS approach: the case of Trovsko-Banjška planota (Slovenia). Acta Carsologica 42(1): 61-74.
- Malard A, Jeannin PY, Sinreich M, Weber E, Vouillamoz J et al. (2014) Praxisorientierter Ansatz zur Kartographischen Darstellung von Karst-Grundwasserressourcen - Erfahrungen aus dem Swisskarst Projekt. Grundwasser – Zeitschrift der Fachsektion Hydrogeologie, 19(4): 237-249.
- Turk J, Malard A, Jeannin P, Gabrovšek F, Petrič M et al. (2014) Hydrogeological interpretation of the alpine karst massif by application of a Karsys approach (Kanin case study, Julian Alps). Hydrological Processes, Published online in Wiley Online Library: DOI: 10.1002/hyp.10313
- Ballesteros D, Malard A, Jeannin PY, Jiménez-Sánchez M, García-Sansegundo J et al. (2015) KARSYS hydrogeological 3D modeling of alpine karst aquifers developed into geological complex areas: Picos de Europa National Park (Spain). Environmental Earth Sciences, : DOI 10.1007/s12665-015-4712-0
- Malard A, Jeannin PY, Rickerl D (2015) Impact of a tunnel on a karst aquifer: application on the brunnmühle springs (bernese jura, Switzerland). In: B. Andreo et al., editor. Hydrogeological and environmental investigations in karst systems. Environmental Earth Sciences. Springer. pp. 457-463.
- Ballesteros D, Malard A, Jeannin PY, Jiménez-Sánchez M, García-Sansegundo J, Meléndez-Asensio M, Sendra G (2015) Influence of the rivers on speleogenesis combining karsys approach and cave levels. picos de europa, spain. In: B. Andreo et al., editor. Hydrogeological and environmental investigations in karst systems. Environmental Earth Sciences. Springer. pp. 599-607.
- Malard A, Jeannin PY, Vouillamoz J, Weber E (2015) An integrated approach for catchment delineation and conduit-network modeling in karst aquifers: application to a site in the Swiss tabular Jura. Hydrogeology Journal, 23(7): 1341-1357 p.
- Malard A, Sinreich M, jeannin PY (2015) A novel approach for estimating karst groundwater recharge in mountainous regions and its application in Switzerland. Hydrological Processes, DOI: 10.1002/hyp.10765

Book chapters for engineering sectors: two book chapters have been produced in the frame of the project. Both of them deal with the consideration of karst aquifers in engineering projects:

- Ballesteros D, Malard A, Jeannin PY, Jiménez-Sánchez M, García-Sansegundo J, Meléndez M, Sendra G (2013) Geometría y direcciones de flujo de agua subterránea preliminares de acuíferos kársticos mediante el método KARSYS. Picos de Europa, norte de España. In: Berrezueta E, Domínguez-Cuesta MJ, editors. Técnicas aplicadas a la caracterización y aprovechamiento de recursos geológico-mineros. Red Minería Siglo XXI, CYTED, Instituto Geológico y Minero de España - 2013. pp. 51-60.
- Jeannin PY. (2014) Karst hydrogeology. In: Saied Eslamian, editor. Handbook for engineering hydrology. Fundamentals and Applications. CRC Press, Taylor & Francis Group - 2014. p 379-406

Journal dedicated to speleology or caves sciences: two recent papers related to the KARSYS approach have been published:

- Malard A, Jeannin PY et al. (2014) Apport des outils 3D pour la caractérisation des aquifères karstiques: l'approche KARSYS. Karstologia 2: 31-40.
- Malard A, Jeannin PY (2015) Estimation des écoulements souterrains du système Siebenhengste (BE) / Schrattenfluh (LU) par l'application de l'approche KARSYS. Stalactite 2: 38-53.
- Jeannin 2015: KARSYS, KarstALEA, la spéléologie et le canton de Neuchâtel. Cavernes

10.1.2.3.2. Meetings and conferences

All along these four years, the SWISSKARST project and the KARSYS approach were presented in the frame of several congresses; in Switzerland and abroad. Most of them have been accepted for oral presentations. The list of these congresses is available on the webpage (www.Swisskarst.ch).

Here are listed the most important congresses:

- June 2015: IAH Karst Groundwater Conference, Birmingham, England
- November 2014: 12th Swiss Geoscience Meeting, Fribourg
- October 2014: 5th International Symposium on Karst, Malaga, Spain
- September 2014: XII Congress *IAEG.* International Association of Engineering Geology, Torino, Italy
- June 2014: International Conference “Karst Without Boundaries”, Trebinje, Bosnia Herzegovina
- November 2013: 11thSwiss Geoscience Meeting, Lausanne
- October 2013: Annual meeting of the Geological Society of America, Denver (CO)
- September 2013: International Symposium on Hierarchical flow systems in Karst Regions “Karstflow”, Budapest. During the Symposium the Swisskarst project was awarded by the Karst commission of the International Association of hydrogeologists (IAH).
- July 2013: 16thInternational Congress of Speleology, Brno (Czech Republic)
- May 2013: 13thInternational Sinkhole Conference, Carlsbad, New Mexico, U.S
- March 2013: European Geomodeller User Meeting, Orleans (France)
- November 2012: 10th Swiss Geoscience Meeting, Bern
- September 2012: 13th National Swiss Congress of Speleology “Speleodiversity”, Muotathal (Switzerland)
- April 2012: Annual meeting of the European Geosciences Union, Vienna, Austria
- November 2011: 9th Swiss Geoscience Meeting, Zurich
- September 2011: 9th Conference of the Limestone Hydrogeology “H2karst”, Besançon (France)

10.1.2.3.3. Dissemination

The Swisskarst website: Results of KARSYS applications are available on the www.swisskarst.ch web site. As mentioned in our 2011 and 2012 reports, the technical standards of the website are not very high because time was invested to the hydrogeological part rather than to fine website design. However the layout and the structure of the website has been improved and updated in 2013. In the future it is expected that results will be included in cantons or Federal web-sites in order to benefit from the technology developed for those platforms and to be accessible to a large number of users. The web site summarizes the results for following cantons: VD, BE, FR and SG. The update process of the available data and products will be discussed and organized along the coming years. Information and results concerning the cantons Fribourg and St-Gall have been added to the website in December 2013.

A brochure related to the Swisskarst project has been published in “International Innovation” Journal in November 2013. This brochure was sent to the community of Hydrogeologists and to the geological surveys from European states. We hope that this brochure will contribute to the promotion of the Swisskarst project and the KARSYS approach.

The document is available for download on the following link:

http://Swisskarst.ch/images/stories/brochure/Pierre-ves_Jeannin_Brochure_High-Res.pdf

Two video clips about the Swisskarst project and the significance of karst groundwater in Switzerland in 2010 were shot. These clips are available on the Swisskarst website as well as on the NRP61 website. It is dedicated to the wider audience, outside Hydrogeologists.

10.2. Appendix 2: review of classifications of porosity in carbonate and karst aquifers

In carbonate aquifers, authors (e.g. Choquette and Pray [1970] or Moore [1989]) usually define the porosity as resulting from some specific processes. The **primary porosity** results of pre-depositional and depositional stages of the sedimentation (due to the shape and the arrangement of the deposed particles). The **secondary porosity** results from dissolution processes that occur during the diagenetic phases of the sedimentation. This definition – adapted for deep and *a-priori* non-karstified carbonate - does not explicitly consider the development of a "**macro-porosity**" due to the karstification. Lucia [1983] defines a petrophysical classification of carbonate porosity based on pore types. The classification entails two main types of porosity: the **"interparticle porosity"** which refers to pore-space between grains and crystals and the **"vuggy porosity"**. The vuggy porosity may be subdivided in vugs that are interconnected only through the pore network ("separate vugs") and vugs that form an interconnected pore system which may be assimilated to a karst conduit network ("touching void").

Castany [1984] proposes a classification of the porosity based on the void types: the **intercrystaline porosity** refers to microscopic voids, **interstitial porosity** refers to the voids between poorly cemented particles (example for a chalk), **microfissure porosity** refers to voids formed by microjoints, fissures or beddings while the **macroscopic voids** refers to enlarged fissures, conduits and channels (= channel porosity) that result from karstification processes. The author also proposes a model of hydrograph recession based on the successive drainage (release) from these zones of various porosities.

The common classification of porosities in karst aquifers usually defines two types of porosity; the **primary** or **matrix porosity**, which refers to the pore voids between grains and/or beddings and the **secondary porosity**, which refers to faults and fissures resulting from tectonics forces and/or to enlarged conduits resulting from dissolution processes (see detailed definition in Kresic [2007]). Alternatively, other authors (Worthington [1994], Taylor and Greene [2001]; Gunn [2004];) redefine this last classification by separating the porosity due to karstification (voids enlargement by dissolution) as **tertiary porosity**… In their definition, the secondary porosity only entails fractures and bedding plan partings. Bonacci [1987] complete the classification according to the dimension of the change in the cross-section "d". Regarding the matrix porosity, d<0.1 mm, for the secondary porosity, 0.1 mm<d<1 cm and for the porosity due to enlarged conduits, d is higher than 1 cm.

The **total porosity** – defined as the geometric average of the different classes of porosity – in various karst aquifers over the world ranges from less than one percent to more than 30% (Wolff [1982], Castany [1984]; Bonacci [1987]; Ford and Williams [2007];). Such range shows the large diversity of these aquifers from the strictly carbonate ones to the extremely karstified ones (or non-cemented carbonate aquifers).

Because previous definitions may significantly vary from an author to another, comparison of values coming from the literature may reveal difficult. Existing measurements published in the literature (see Manger [1963]; Wolff [1982]; Worthington et al. [2000], Jerry Lucia [2007], etc.) show a wide range of porosities that have been measured in various karst aquifers developed in chalks, limestones or dolomites (see Table 10—1, using the classification proposed by Worthington [1994]).

Refs.	Sites	Matrix (or primary) porosity [%]	Fissures (or secondary) porosity [%]	Dissolution enlarged-conduits (or tertiary) porosity [%]	Total porosity [%]
Chalk					
Schoeller [1962] (in Wolff [1982])	Northern France, Upper Cretaceous	29.2 (mean value, 16 samples)			
Worthington et al. [2000]	Southern England, Cretaceous	20 to 45	0.01	0.01 to 0.03	
Dolomite					
Manger [1963]	Llano County, Texas, lower Ordovician	4.3 (mean value, 23 samples)			
Manger [1963]	Permain Basin, Texas, lower Ordovician	1.51 (mean value, 36 samples)		1.79 (mean value, 36 samples)	3.30 (mean value, 36 samples)
Manger [1963]	Wood County, West Virginia, Ordovician	0.4 (mean value, 56 samples)			
Manger [1963]	Coldwater field, Michigan, Devonian	2.5 (mean value, 16 samples)			
Worthington et al. [2000]	Smithville, Southern Ontario, Silurian		0.017	0.0003	6.6 (mean value, 1043 samples)
Worthington et al. [2000]	Kentucky, Upper Paleozoic	2.4	0.03	0.063	
Limestone					
Manger [1963]	Kansas, Upper Cambrian and lower Ordovician	10.3 (mean value, 26 samples)			
Manger [1963]	W. Edmond field, Oklahoma, upper Silurian	7.3 (mean value, 545 samples)			
Manger [1963]	Midlands, England, Carboniferous	5.7 (mean value, 24 samples)			
Manger [1963]	Germany, Muschelkalk	15.5 (mean value, 19 samples)			
Manger [1963]	Germany, Solenhofen formation, Jurassic	3.9 (mean value, 23 samples)			
Manger [1963]	New Hope field, Texas, Cretaceous	12.9 (mean value, 61 samples)			
Manger [1963]	Asmari formation, Masjidi Sulaiman field, Iran, Miocene	5.6 (mean value, 140 samples)			
Atkinson [1977]	Mendip Hills, England, Carboniferous	0.18	0.59		0.92
Sauter [1992]	Swabian Alps, south Germany, Jurassic	1 to 2		0.01 to 0.03	
Worthington et al. [2000]	Yucatan, Mexico, Cenozoic		0.1	0.5	17

Table 10—1. Porosities in karst aquifers (listed values from literature)

According to this table, the higher porosities are found in matrix (primary porosity). These seem related to the depth of the diagenesis. Basically, the greater is the depth (resp. the burial time) of diagenesis, the lower is the primary porosity. The measured values show that Paleozoic carbonates which have been buried to great depth compared to younger Cretaceous limestone or chalks show lower porosities (a few percent). In “non-diagenetically mature” rocks, such as reef limestones or chalk, matrix porosities may reach 15 to 40% (Gunn [2004] DiFrenna et al. [2008];). Fissure porosity is up to hundred times lower than the matrix porosity (up to 0.1%) while the porosity generated by karst dissolution is usually less than 0.5% and even negligible for certain aquifers.

10.3. Appendix 3: Malard et al. 2014 - Assessing the Contribution of Karst to Flood Peaks of the Suze River, Potentially Affecting the City of Bienne (Switzerland)

Assessing the Contribution of Karst to Flood Peaks of the Suze River, Potentially Affecting the City of Bienne (Switzerland)

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Arnauld Malard, Pierre-Yves Jeannin, and Eric Weber

Abstract
The city of Bienne (BE, Switzerland) located downstream of the Suze River is exposed to flooding caused by the River overflows. Although the infrastructures were designed for a maximal discharge rate of 100 m^3/s (return period of 100 years), it appears that the River threatened to flood the city more than 6 times during the past century. The frequency analysis of the River discharge rates shows an abrupt increase for discharge rates >75 m^3/s and a plateau at 95 m^3/s; in other words discharge rates for return period events between 30 years and 150 years appear to be almost the same… Such a plateau could be produced by a significant storage upstream of the city, which smooth extreme discharge peaks. This storage was assessed to about 17 millions of cubic meters for a T_{100} flood. However, the storage is not visible along the river and it was suggested that karst aquifers may be responsible for it. The questions are (1) "Does such a storage exist in the karst aquifer?", (2) "What is its capacity and how does it work?", (3) "What could happen if this capacity is suddenly exceeded?",
(4) "What is the real contribution of karst water to the flows peak in Bienne?" In this view, a pragmatic approach is proposed to assess the contribution of the karst systems in the River flood generation. As the work is ongoing only the conceptual approach is here presented.

Keywords
Karst aquifer Flood Storage Jura Suze Switzerland

Introduction

Flood hazard assessment in a karst environment implies to consider a conceptual and a simulation model of karst hydraulics in addition to a usual rain-runoff model. The reason is that the flood intensity may be enhanced (or reduced) by the functioning of karst systems interacting with the investigated river. This may be done at a mesoscale (Jourde et al. 2007) or more locally for flash floods (Bonacci et al. 2006). Such models—even simplified ones—require a good documentation/understanding of the karst systems: position and hydraulics relationships of the outlets, discharge capacities, etc.

In Bienne, infrastructures on the Suze River (especially a bridge at the town entrance) are designed for a flood return period of 100 years (□peak discharge rate of 100 m^3/s). However, since the bridge was made the river rose many times close to the bridge's deck and threatened to pass over the channels. These events clearly evidence that the dimensioning of the infrastructures was underestimated as a result of a misunderstanding of the floods dynamics.

The Suze River is partly fed by at least five significant karst springs emerging from the Malm aquifer, which is the most productive aquifer in the area. Although based on only

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a few (and not accurate) measurements it turns out that the significant discharge rate of the karst springs represents at least one third of a T_{10} flood of the Suze river in Bienne. This observation shows that contribution of karst systems have to be considered in the flood processes.

The aim of this paper is to present the role of the karst systems and to suggest an approach for estimating their contribution in the flood generation of the River. Four main questions have been proposed: (1) "Does such a storage exist in the karst aquifer?", (2) "What is its capacity and how does it work?", (3) "What could happen if this capacity is suddenly exceeded?", (4) "What is the real contribution of karst water to the flows peak in Bienne?"

Addressing questions (1) and (2) requires an assessment of the geometry of the karst aquifer and its hydrogeological flow-systems. A 3D model of the aquifer was built according to the KARSYS approach (Jeannin et al. 2013). In next steps, the probability distribution of karst- conduits (inception horizons) as well as of potential overflow horizons will be implemented (speleogenetic model); because they represent the potential storage and release capacities of the karst system. For question (3) a hydrological model of the systems catchments (semi distributed routing model) as well as a hydraulic model which considers the storage/release capacities of the systems (pipe flow model) will be set up for each main karst system feeding the Suze river. These models will be coupled as input to the runoff model or the river, in order to assess the contribution of the karst groundwater to peak flow.

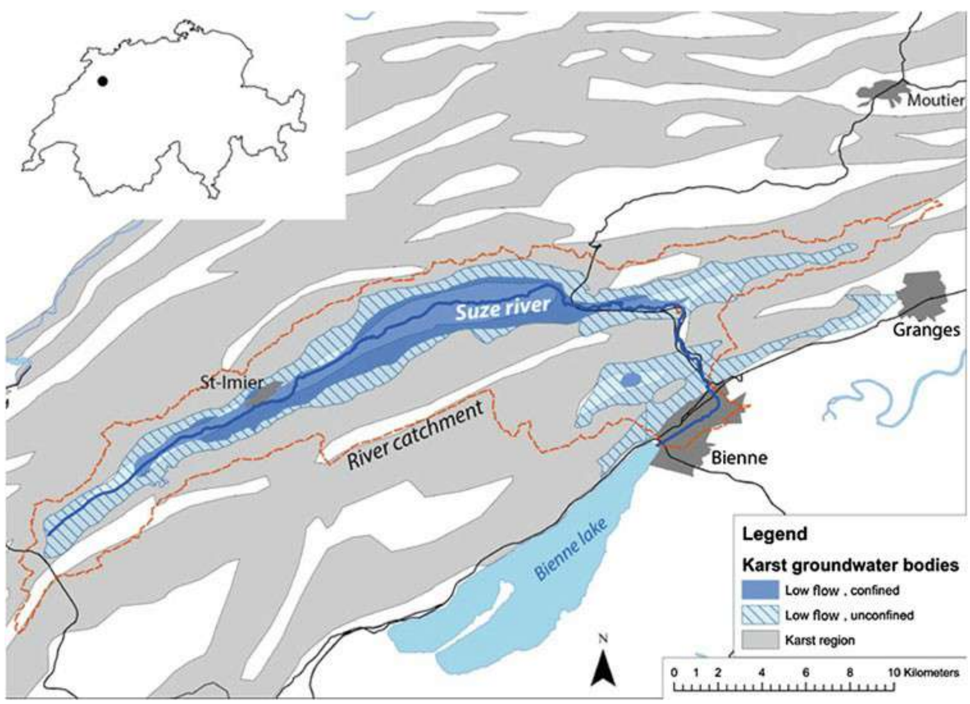
Context and Flood Analysis

The city of Bienne (Bernese Jura) is traversed by the Suze River. This stream drains the St-Imier (molassic) valley of the Jura Mountains surrounded by two anticlines formed by karstified Malm limestones (Fig. 35.1). The river flows into Lake Bienne located directly South-West of the city. The river topographic catchment covers a surface area of 213 km^2 with an elevation ranging from 429 m (Bienne) to 1607 m a.s.l.

Due to the lack of measurements in the past, the channels crossing the city, as well as the bridge at the entrance of the city were designed for a maximal discharge rate of 100 m^3/s. This was considered as the value with a return period of 100 years. During the 20th century, the river rose 6 times close to the bridge's deck and threatened to pass over the channels. Along the last 30 years, five other high water events of the Suze reached the city with unexpected discharge peaks and threatened to flood the center by submerging the channels (1987, 1990, 1991, 1999 and 2007). Peak discharge rates were only measured for the 2007 event (74 m^3/s). Events of Feb. 1990 and Dec. 1991 clearly demonstrated the limitations of the existing infrastructures, which is a delicate situation for the city of Bienne because damages may induce very considerable costs.

Previous authors distinguished two types of events: the "winter" events and the "summer" ones. The winter events (1990, 1991 and Feb. 1999) are related to a combination of heavy rainfalls, snow melting and frozen ground which

Fig. 35.1 The Suze River drains the St-Imier basin and flows through the city of Bienne (Biel) where it enters the Lake Bienne



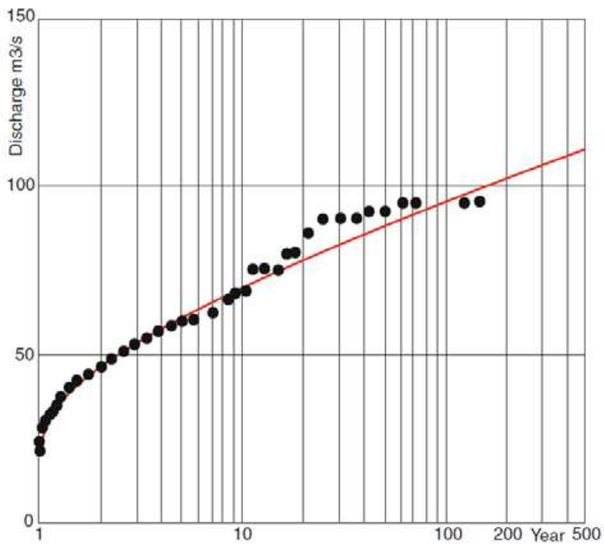


Fig. 35.2 Peak discharge frequency curve of the Suze River in Bienne (Naef and Frauchiger 2009). For T larger than 10 years peak discharge drops from 68 to 75 m^3/s and flattens by about 85 to 95 m^3/s for T between 30 and 150 years

enhances the surface runoff coefficient and then discharge concentration. Summer events of Sept. 1987 and Aug. 2007 resulted from huge rainfall quantities falling during several days.

The profile of the peak discharge frequency curve from the last 150 years (Fig. 35.2) shows a storage/threshold functioning of the river basin, which may be related to karst hydrology. Indeed, discharge measurements in the city since the late 19th show a singular stepwise increase of the peak discharge rate between T_{10} and T_{25} and an attenuated plateau from T_{30} to T_{150} which is an unusual profile for surface-runoff dominated floods. The stepwise increases of the discharge rates suggest successive releases from parts of the catchment while the plateau suggests a storage (or buffer) capacity of the basin, which was estimated to 17 millions of cubic meters for T_{100}. It was suggested that storage in karst could be one possible explanation for this unusual shape.

Is the Contribution of Karst Water to Peak Discharge Significant?

The first step was to validate the concomitancy of river peak discharge events with peaks at karst springs in order to assess the influence of karst hydrology which was considered by previous hydrologists as delayed, i.e. as not really contributing to peak flow.

The catchment area of the Suze River is mainly composed by karst formations (Jurassic limestone) and extends along the St-Imier molassic basin. The river mean annual discharge rate reaches 8 m^3/s in Bienne. Five significant karst-springs emerging from the Malm aquifer and two other systems emerging from the (lower) Dogger aquifer feed the river. Although most springs are not monitored, their discharge rates have been punctually or indirectly assessed showing that their mean annual discharge rate is at least 3 m^3/s which is nearly 35 % of the river annual mean discharge in Bienne (ISSKA 2012). High-flow discharge rate of the springs was estimated at 28 m^3/s; i.e. more than the third of corresponding peak flow measured in Bienne (74 m^3/s). Hydrographs of the river and karst springs were compared using existing measurements. Because of poor-quality data, the comparison could only be performed for 1999. It appears that hydrographs of the main karst spring (Dou-Raissette) is comparable to that of the River, at least in responsiveness and duration (3–4 days). Older events suggest the same proportion but data quality is really poor (1987, 1991). The karst discharge evaluation and the concomitancy of river and karst peaks clearly suggest that the karst contribution to river peaks is not negligible and must be better quantified in the flood-risk assessment.

Geometry of Karst Aquifers and Sketch of Karst Flow-Systems

The application of the KARSYS approach (Jeannin et al. 2013) to the main karst systems of Bernese Jura (including the Suze catchment) was performed in 2012 in the frame of the Swisskarst project (Malard et al. 2012). The catchment areas of these karst systems were delineated in this context. It was therefore demonstrated that the whole catchment of the Suze river—including the karst systems—encompasses 263 km^2, which noticeably exceeds the value of the topographic watershed (213 km^2, Naef and Frauchiger 2009). A very recent dye tracing expanded the hydrogeological catchment boundaries even further to the South. The whole catchment of the Suze River may therefore approximate 300 km^2 with at least 150 km^2 lying in karst areas.

Assessing the Storage Capacity in Karst - Conceptual Model [Questions (1) and (2)]

Temporary water storage in karst can be produced by the flooding of significant conduit network, which are reached by water only at high flow conditions. Such storage in the epiphreatic zone can take place if (i) the hydraulic heads rise within the system and (ii) the discharge capacity of the permanent base-flow spring/conduits is overpassed (see Fig. 35.3). In many situations, conditions (i) and (ii) lead to the activation of overflow overflow springs (b on Fig. 35.3). If the storage volume between levels (a) and (b) is large, a significant lag on the total hydrograph may be produced. If the flow capacity of level b is exceeded, heads may continue to rise until the water reaches a more elevated conduit level (overflows c.). In case of such significant rises of the hydraulic heads one part of the water often leaks and leaves the karst system to a nearby one, or the opposite (comes from a nearby system). This may lead to an enlargement (or reduction) of the system catchment area with the discharge increase and may explain abrupt steps in the observed frequency distribution curve.

Assessing the storage distribution and threshold functioning of the systems implies:

(i) The establishment of a geological 3D model of the aquifer and the implementation of the hydrological low-flows information (base springs, hydraulic gradients), which define the systems boundaries. This work was already carried out but still needs some refinement (Malard et al. 2012);

(ii) The assessment of karst inception features as defined by Filipponi (2009): stratigraphic and tectonic hori- zons controlling the development of the karstifica- tion must be identified in the field and placed in the 3D model. These structures define the position of the most probable karstified horizons;

(iii) The establishment of a speleogenetic model, which provides indication on the characteristics of karst conduits in the massif along the inception horizon. This makes it possible to identify and localize potential paleo-conduits, which could still be reactivated as overflow galleries or/and springs in case of extreme high-flows. These mechanisms have been clearly supposed for two karst systems for which the Dou spring (+25 m/Raissette) and the Bez supérieur spring (+35 m/Bez inférieur) are the systems' overflows. These features have to be associated with a karstification density model in order to assess the spatial distribution of the potential storage volume (type of conduits, diameter, etc., see Fig. 35.4). It is hypothesized that the volume of such epiphreatic conduits could correspond to the storage capacity of the aquifer and could explain the observed discharge frequency curve of the Suze river;

(iv) The presence and location of underground overflow passes. These passes may be activated at high-flow and lead to considerable water exchanges between adjacent karst systems. This mechanism has been suggested in the upstream part of one of systems (Cuchatte-Tournedos): In high-flow conditions, the nearby upper Birse karst system probably overflows towards the Suze system by an underground threshold (col de Pierre Pertuis).

The 4 previous steps provide an assessment of the storage capacity of the karst aquifer as well as a sketch of the reservoirs geometry within the catchment area (answers question (1)).

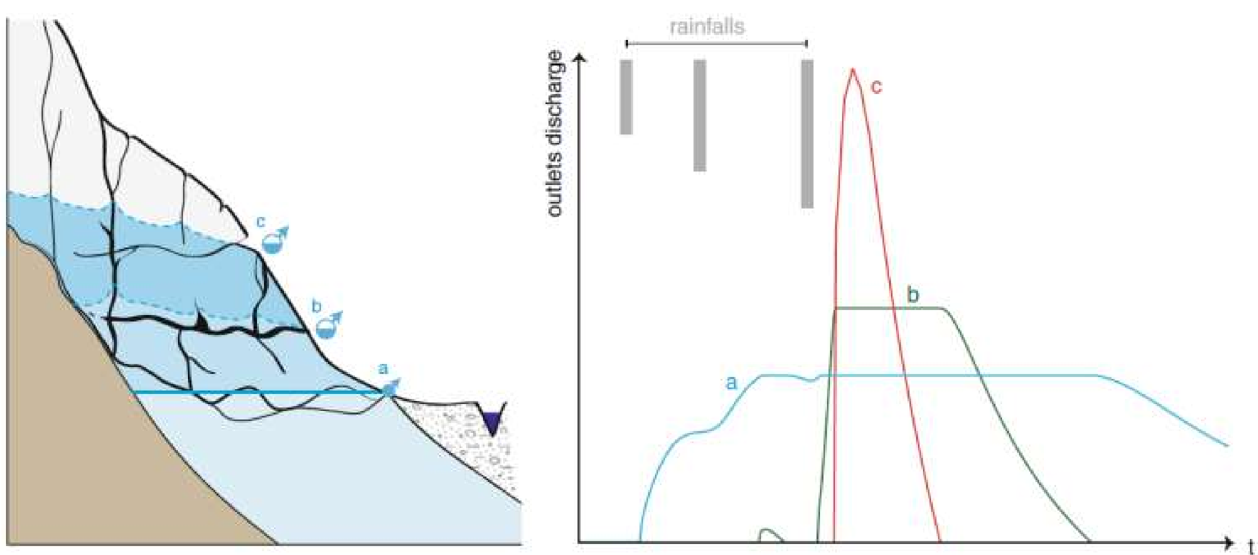


Fig. 35.3 Conceptual model of floods evolution in karst aquifers. While the hydraulic gradient rises in the epiphreatic zone, one part of the coming water is released downstream by overflow springs, and the other part is stored and released later. The position, elevation, discharge capacity and volume of the epiphreatic conduits are the main controlling factors. Depending on the geometry of the aquifer and the rise of the hydraulic heads, water may be exchanged with adjacent karst

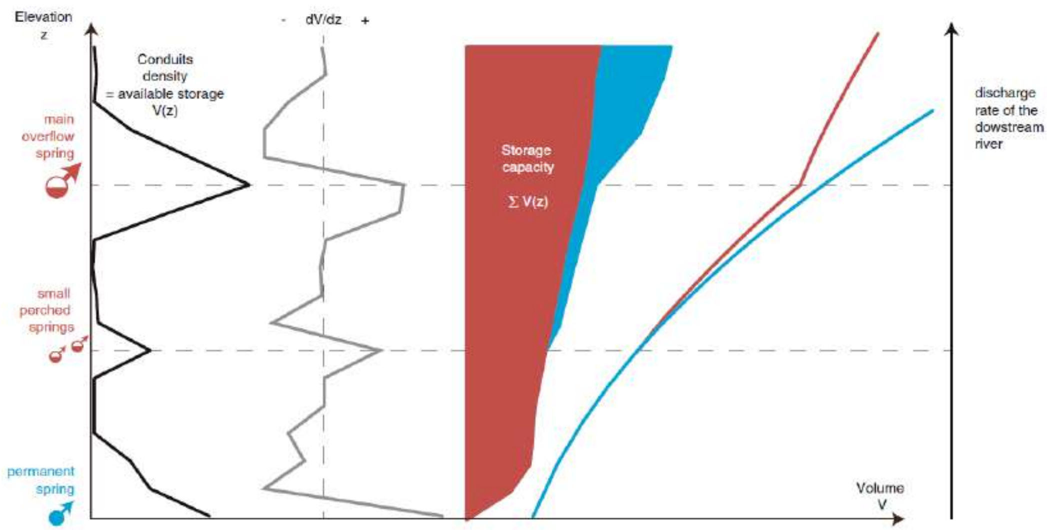


Fig. 35.4 Conceptual model of the relationship between the conduits density (*black line*), the position of overflows springs, the evolution of the storage capacity and the downstream water release (*blue* and *red curves*). If no overflow springs do exist, the storage capacity in the karst massif increases and less water is released downstream

Hydrology of the Karst Systems: Recharge and Discharge Processes [Question (3)]

In this step, one or several karst system(s) of the Suze catchment will be considered as test sites for the simulation of extreme hydrological events by using a semi-distributed routing model (R.S. 2012, e-dric.ch) as this type of model reveals appropriate to reasonably simulate recharge of karst systems at catchment scale (Weber et al. 2011). Based on the respective catchment areas of the karst springs given by the KARSYS approach, a numerical model is calibrated. As previously mentioned the consideration of the karst systems as tributaries of the Suze River leads to significantly enlarge its catchment area compared to the purely topographic one. However, two types of karst systems must be distinguished: convergent and divergent ones. Convergent parts include areas where recharge integrally flows to one signle outlet (one spring or one group of springs), while divergent parts recharge two or more karst systems depending on flow conditions (e.g. Birse and Cuchatte-Tournedos. The discretization of the recharge areas considers a several parameters such as: (i) elevation zones of the catchment (200 m bands), (ii) the north-south flank exposure and (iii) the snow accumulation.

Various reservoirs will be added in order to reproduce the effect of the storage capacities. The work is still ongoing and we hope that simulations will address questions related to storage capacity and its limitation by overflows thresholds.

Uncertainties will also be considered by weighting uncertainties of each parameter. A clear assessment of the karst contribution for various conditions will thus be estimated as well as the probability of a flood larger than 95 m^3/s in Bienne. Various meteorological scenarios—but still reasonable—will be tested in order to extrapolate the behavior of karst systems during extremely high recharge events, including several storage scenarios in karst. The modelling work will only be possible if better field data are measured than the existing ones.

Karst Contribution to the River Discharge Peak [Question (4)]

Once the previously exposed steps will have been carried out, the modelling of the karst contribution to Suze will be possible. The dynamics of karst systems will be compared to the contribution of surface runoff to the river peak for any flood event. To do it, each karst system will be coupled to the stream routing procedure used for surface runoff along the Suze and the respective contribution and time transfer of each system will be assessed. The influence of karst systems to peak discharge rates does not exclusively depend on their peak discharge but on their responsiveness and retardation capacity. Fast reactive karst systems with a low or moderate storage capacity may really contribute to the peak discharge. Systems with more storage may explain the flattening of the discharge frequency curve. The routing procedure will make it possible to assess the respective "impact-weight" of each karst system to the flood generation.

Discussion and Perspectives

Understanding the flood generation processes of the Suze River requires the identification and the assessment of the main contributive karst systems in a pragmatic way. A combined approach considering the density and distribution of the karstification (speleogensis), and the evolution of the hydraulic heads as well as the position of the discharge outlets or underground passes (hydraulics) is suggested. In other words, the proposed approach combines a 3D geo- logical model, karst hydraulics and speleogenetic concepts. This approach therefore takes in account the major characteristics of karst hydraulics and tries to quantitatively model them. It establishes consistent relationships between a series of known facts such as: successive activation of overflows springs, water exchanges between adjacent sys- tems by overflowing underground thresholds, enlargement of the catchment areas of the karst systems during high-flow conditions, and variation with time of the storage and release processes. Routing modelling of the Suze river hydrology will provide the respective contribution of the systems with time in the generation of the flood peak in Bienne. This allows to discuss the effective influence of the karst systems

and to possibly envisage adequate protection measures.

One disadvantage of this approach is that it requires a considerable amount of investigations in the field, which is time consuming (and thus expensive). The quality of the existing data is poor leading to considerable uncertainties. −A better monitoring is required to reinforce the quality of the diagnostic.

Conclusion

An approach is proposed to describe and quantify the con- tributions of karst systems to the peak flow of the Suze River (Bernese Jura) in Bienne, because pure surface-hydrology modelling fails at explaining the profile of the discharge frequency curve. Observations suggest that karst aquifers may act as storage and/or intermittent inputs, which flatten or increase the flood peaks. Preliminary analyses assess a karst contribution of about 35 % during usual flood events, which is much more than what was considered in hydro- logical models so far. Conceptual ideas on the way how karst hydrodynamics should be included are presented. We suggest a 4-steps approach: (i) Assessment of the geometry of the karst aquifers, the systems and their catchments, (ii) Assessment of the storage capacities of the systems by the combination of the hydraulic heads oscillations and the inception/speleogenetic model, (iii) Assessment of all exchanges with nearby karst systems, which may increase or reduce the peak intensity(iv) Assessment of the karst systems' contributions using a surface runoff model for the flood propagation along the river.

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10.4. Appendix 4: additional information on karst groundwater quality

Different authors already discussed the topic of karst groundwater quality, especially Van Beynen [2011] who made a detailed review on the main features of karst groundwater quality. In a more formal way, Vesper [2008] identifies three types of contaminants: Inorganic, Microbes and Pathogens (bacteria) and Anthropogenic Organic Compounds. Depending on their nature, contaminants may be dissolved or transported along with sediments when they are associated with solids. These three types are detailed and discussed in the following sections. Water temperature is another parameter with a strong influence on groundwater biology.

10.4.1. Groundwater temperature

Because of the presence of a vadose and/or saturated zone and the organization of conduit networks, the evolution of the groundwater temperature in karst aquifers is more heterogeneous than for other geological environments (Drogue [1985]) - even if globally temperature also increases with the depth.

Mechanisms of heat transfer in karst are further discussed in §. 3.1.3.1.1., with respect to geothermal energy. Roughly, regarding a borehole, a vertical cave or a spring, the evolution of the groundwater temperature (average values and seasonal variations) depends on the following factors:

(i) The geographic context, mainly the elevation of the saturated zone;
(ii) The thickness of the unsaturated and saturated zones of the aquifer;
(iii) The presence / proximity of active karst conduits and their hydrological regime (flow velocity, water renewal, etc.).

At a large scale, the principal control on the karst groundwater temperature is the elevation of the saturated zone.

In the frame of the Swisskarst project, late 2014, nearly two hundred flow-systems representing one third of the Swiss territory have been documented as well as more than 800 karst springs. When they exist, temperature measurements of the springs have been compiled, representing nearly 160 karst springs that are distributed over the whole territory in different contexts and for different elevations. This makes it possible to establish the following figure relating groundwater temperature of the springs to their elevation (Figure 10—2).

Regarding Figure 10—2, the relationship formulated by Jeannin [1990], between the elevation of the karst systems springs (considered as the elevation of the phreatic zone) and the groundwater temperature is confirmed. Moreover, even if the trend is well visible, temperature may fluctuate by up to 3°C for the same elevation. For elevation lower than 500 m, the range even seems more extended (up to 5°C). They could be related to wrong measurements or to local geothermal influences (for example thermal karst springs, see Vuataz [1982]).

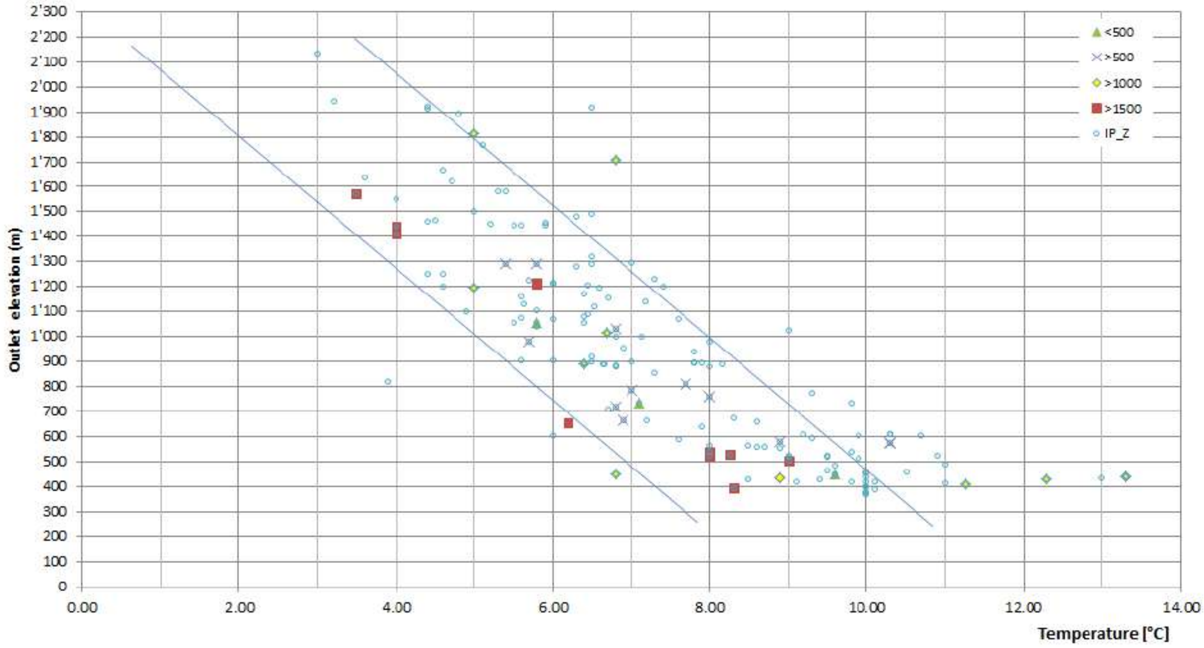

Figure 10—2. Relationship between karst groundwater temperature and the elevation of the spring (~160 karst springs); the correlation is significant although for similar elevation the difference in temperature may reach 3°C. Thermal springs could be identified from this relation. Systems for which the catchment area is well known are labeled separately giving an indication of the elevation-classes of the catchment area feeding the spring (<500 m, >500 m, >1000 m, >1500 m). Horizontal deviations in the temperatures distribution do not significantly depend on the elevation of the catchment. For instance, systems where elevation-classes exceed 1500 m are not closer to the min. than to the max. boundaries.

According to the literature (Jeannin [1990]; Lütscher and Jeannin [2004]) this 3°C-delta for presumably comparable karst flow systems may be related to:

- The geographic location of the system (difference between Alps and Jura, or between northern and southern parts of Switzerland) and the exposition of the catchment (toward the north or toward the south) are probably the most significant factors;
- The hydrological regime of the karst flow-system; for a similar system and under comparable hydrological conditions, it could be expected that springs from deep karsts may present a higher temperature than ones from shallow karsts as circulations are expected to be deeper. It is therefore not a general rule.
- The proportion of concentrated infiltration; as demonstrated by Brandt [1982], the presence of a surficial lake in the recharge zone of the Orbe karst system which may fast infiltrates is responsible for temperature oscillations up to 4°C within the same season. The presence of glaciers in the catchment may also have the same incidence on the groundwater temperature (Gremaud [2011]). This is partially evidenced on the graphic when looking systems for which the catchment extends higher than 1500 m a.s.l as they present colder groundwater than the other systems for which springs lie at a similar elevation. Excepting these particular cases, the temperature of the groundwater is not expected to significantly depend on the elevation of the catchment area (as demonstrated by Jeannin [1990]);
- Seasonal fluctuations of the temperature: Measurements displayed on Figure 10—2 result sometimes from single values, sometimes from average values. Karst systems with a significant part of concentrated recharge, temperature may fluctuate by several degrees along the year. This increases the range of variation of temperature for a given elevation;
- The ventilation of the aquifer; as demonstrated by Lütscher and Jeannin [2004]; the temperature gradient is higher in ventilated caves (0.5°C/100 m) than in non-ventilated ones (~0.3°C/100 m). It is

then demonstrated that the groundwater temperature is higher where the vadose zone is thick and ventilated.

- High elevation catchments are mainly fed by snow melt, meaning that the temperature of infiltrated water is higher than outside air temperature over the catchment area. This may lead to a deviation towards warmer springs for high elevations, as can be seen on Figure 10—2.

As demonstrated by Jeannin 1990, the temperature fluctuations of karst springs are a good indicator of the degree of concentrated recharge. Systems with a phreatic zone located close to the surface (less than 5 to 70 m are also expected to show more variation than those located deeper (Figure 10—3 and Table 10—2). The Milandrine underground stream (Kovács and Jeannin [2003]) has no known sinking stream or swallow-hole (~100% diffuse recharge). The Brunnmühle spring (Jeannin et al. [2015a]) has less than 10% of recharge through swallow-holes. Schlichenden Brünnen (canton SZ, CH), Areuse (canton NE, CH) and Malagne (canton VD, CH) have 10 to 20 % of concentrated recharge. For Orbe spring, nearly 40% comes from Lac de Joux (ISSKA [2015b]).

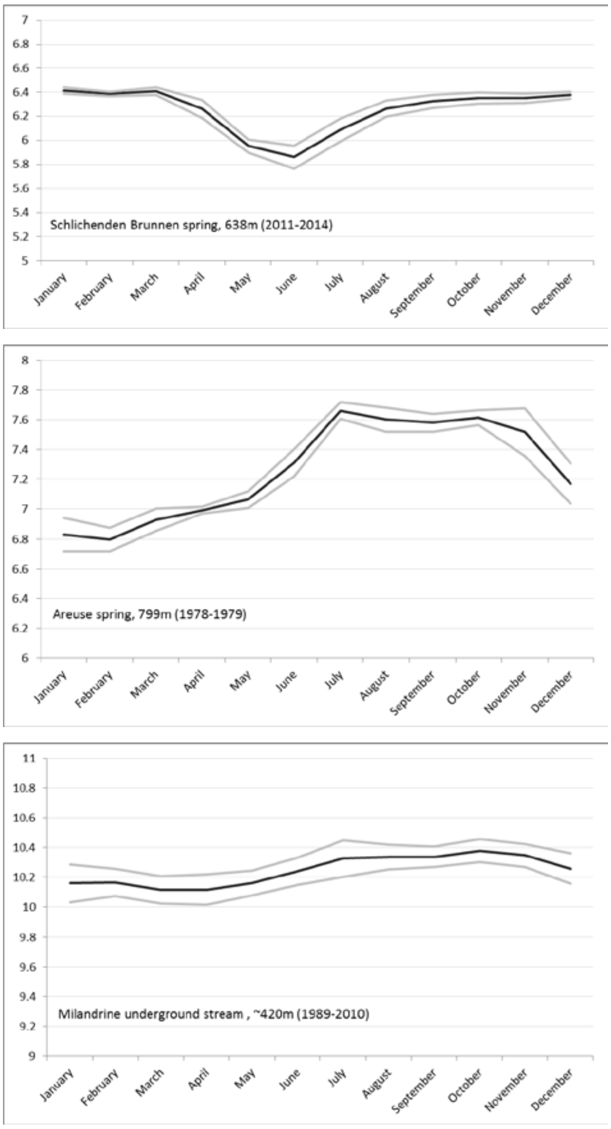

Figure 10—3. Seasonal variations of the groundwater temperature (monthly average) for selected karst flow-systems; a. the alpine Schlichenden Brünnen spring (Hölloch karst system, SZ), b. the elevated Jurassian Areuse Spring (NE), c. the low-elevated Jurassian Milandrine underground river (JU). The mean temperature fluctuates over the year of few degrees tenth (± 0.5°C for Schlichenden Brunnen and for Milandrine, ±1°C for Areuse, ± 0.8°C for Brunnmühle and up to 2.5°C for Malagne). The Orbe spring is a singular case as the seasonal amplitude of the temperature may reach 6 to 8°C…

Karst flow-system	spring elevation	Winter time temperature	Summer time temperature	Source
Orbe (VD)	445 m a.s.l	4.6°C	Up to 12.5°C	Brandt [1982]
Brunnmühle (BE)	433 m a.s.l	8.9°C	9.7°C	Kellerhals + Haefeli [2014]
Malagne (VD)	720 m a.s.l	5°C	7.5°C	AQUITYP

Table 10—2. Spring temperature of karst flow-systems is not constant over the year but displays seasonal variations depending on the degree of concentrated recharge (examples for flow-systems of the Swiss folded Jura).

From the previous graphics and table, it could also be observed that:

- According to specific events, groundwater temperature may fluctuate by several degrees for a few couple of days (Orbe is an extreme example with fluctuations up to 5-10°C more or less than the average value). These fluctuations will be not further discussed.
- Low temperature and high temperature periods do not occur the same months depending on the geographic context of the system: low-temperature periods in alpine context occur between May and July, while in Jurassian context low-temperature periods occur between March and April. This shift is a priori related to the snowmelt lag that starts earlier in low-elevated contexts than in the high-alps.

Thus, it appears that the average temperature of the groundwater is conditioned by the elevation of the phreatic zone while the seasonal fluctuations are controlled by proportion of concentrated infiltrations.

Evolution of groundwater temperature in karst aquifers over the last decades is expected to follow climate warming. In the Milandre groundwater stream (JU) the average water temperature increased by about +0.42°C over the period 1989-2011 (Jeannin et al. [2015b]).

10.4.2. **Suspended sediments**

Suspended sediments in karst groundwater result from soil erosion. Concentrated points-recharge is expected to introduce more particles than diffuse recharge. However, the Milandre system, which is fed only by diffuse recharge experience turbidity in a similar degree as other systems. Thus, the amount of transported material may presumably be close related to the type of soils, to the associated land-uses (agriculture, urban areas, etc.) and to the frequency and intensity of recharge events (climate). Materials forming turbidity may be solid and mineral fragments (rock sediments) or organic matter, which is a complex mixture of organic compounds resulting from the litter or humus decomposition. This litter (or humus) decomposition is also the main source of DOC (Dissolved Organic Carbon) which can compose complexes with some metals or adsorb hydrophobic organic compounds and facilitate their migration in the groundwater (Hunkeler and Mudry [2007]).

10.4.3. **Inorganic contaminants**

Among inorganic contaminants, the most frequent are: nitrates, phosphorous, chlorides and sodium. The latter are highly soluble compounds and may result from agricultural practices or road-salt practices. Heavy metals are also considered as Inorganic contaminants, although they are not soluble. These are mainly transported by suspended sediments or by organic matter.

10.4.3.1. Nitrates

Compared to other countries such as France, England or Germany where elevated nitrate concentrations are found in karst aquifers (Coxon [2011]), sometimes over-passing the regulation of 50 mg/L NO_3 fixed by the Water Framework Directive (2000/60/EC), measurements in Swiss karst aquifers show minor concentrations of this pollutant. The requirements of the federal directive (OEaux [1998]) for the nitrate is by 25 mg/L NO_3.

During the 90's, the trend of nitrates globally decreased by about 20%. However, these last 10 years, in most of the above-cited countries, it has been observed that the trend of nitrates is closely related to the aquifer recharge. During wet years the concentration is low while it increases during dry years. It should be noticed that no specific study has been compiled on nitrates in karst aquifer in Switzerland.

High concentrations of nitrates are usually the consequence of agriculture fertilizers and may concern some karst areas. In Switzerland most karst areas are not intensively farmed or cultivated, and recharge is quite high (>500 mm/year). This keeps nitrate concentrations to a relatively low level. As observed in the Jura (Jeannin et al. [2015b]), nitrates do not show a specific trend over the last 20 or 25 years. Regional variations are however observed: a decrease in Ajoie (Swiss part of the tabular Jura) and an increase in the French part of the Jura Mountains.

10.4.3.2. Phosphorus

As for nitrates, increase of phosphorus contents in surface freshwaters is responsible for the eutrophication of rivers and lakes (Coxon [2011]). Most of the Phosphorus input results from agricultural input (fertilizers) and the domestic use of phosphate detergents (washing powder). However, since 1986, domestic phosphate detergents are prohibited in Switzerland and, since 2007 regulations in European countries aim at prohibiting Phosphorus in all domestic detergents (Abirached et al. [2008]).

Observations in the Jura region of Switzerland do not evidence any clear trend in groundwater Phosphorus content between 1990 and 2011 (Jeannin et al. [2015b]). As for Nitrate, Phosphorus content in the French Jura Mountains is still growing. It can thus be expected that the restriction of phosphate detergents imposed in 1986 in Switzerland had a benefic impact on the Phosphorus groundwater content. Situation in France is thus expected to improve soon.

10.4.3.3. Chlorides and Sodium

Chlorides and Sodium mainly originate from winter road-salt practices. By the way, concentration of these compounds often increases in the springtime due to the seasonal snowmelt.

As observed by Jeannin et al. [2015b], annual concentrations of chlorides in groundwater in the Jura Mountains show a negative trend since the beginning of the 90s (-25% these last 25 years). This probably results (i) from a better management of road-salt practices and (ii) from a clear warming and a reduction of snowfalls in this region, as observed in climatological data.

According to the same authors, and regarding the Sodium compound, it appears that its concentration in groundwater slightly increased over these last 20 years. This surprising increase in content is contradictory with the one observed for the chlorides. More research is required about this surprising trend.

10.4.3.4. Heavy metals

Most of the metals may be seen as "natural" compounds as they are present in sedimentary rocks at various concentrations (Fe, Mn, Zn, As, Cr, Al, Cd, etc.). However, some industries or waste deposits (including wild and unauthorized deposits in caves or sinkholes) may be a considerable source of these compounds leading to environmental problems.

Heavy metals are frequently associated with solids and they are transported with suspended sediments (Vesper et al. [2001] Vesper and White [2004];). As the pH of karst waters is neutral to alkaline, most of the transported metals are insoluble.

10.4.4. Microbes and Pathogens

Microbes and pathogens represent one of the most frequent contaminant to human health over the world, especially in developing countries (Montgomery and Elimelech [2007]). Microbes and pathogens result from bacterial contamination from urban areas (sewage) or agricultural and farm lands (manure spreading) which migrate toward the groundwater. In Swiss karst aquifers, microbes and pathogens are the most frequent and most problematic contaminants (Auckenthaler and Huggenberger [2003]). Indeed, it has been demonstrated that coliforms are able to survive up to four months in the aquifer (Davis et al. [2005], for temperate climate conditions) which is longer than most of karst groundwater circulations.

Regarding karst springs, it often appears that concentration of microbes and pathogens may vary from several orders of magnitude depending on the hydrological regime. Concentrations evolve non-linearly depending on a multitude of parameters: seasons, production rate, spreading modalities and frequency, degradation rate, etc. These contaminants are also difficult to measure as continuous and real-time monitoring still not exists, or if they may exist, they are too expensive for routine analysis. Thus, it remains difficult to predict and to prevent the magnitude of the groundwater contamination emerging at springs. This is one of the main issues regarding the management of drinking water quality.

Bacterial contamination is often associated with the organic matter content. Pronk [2008] found a clear positive relation at a spring between fine particles transport (0.9 to 10 µm) identified as allochtonous – meaning they come from the surface via point-recharge features – and the concentration of pathogens (fecal bacteria).

Microbes and pathogens are present in karst aquifers in Switzerland. Sinreich et al. [2011] give an overview of the type and the occurrence of microbiological contents found in the Swiss groundwater monitoring network (NAQUA) in addition to the conventional “Fecal Indicator Bacteria (FIB)” and suggest a microbiological classification for karst aquifers. Indeed, authors indicate that 5 out of the 7 monitored karst springs (Jura, Prealps and Helvetic Alps) reveal FIB with significant concentrations of E. Coli and Enterococci (as well as few Clostridium perfringens) while only 5 out of 37 monitoring stations in granular aquifer are affected… Protozoa has been only enumerated in karst springs while viruses could be found both in karst springs and in porous or fissured aquifers. In addition to E. Coli and/or Enterococci, pathogens have been also detected in very few samples. The results of this pilot-study confirm the high vulnerability of karst groundwater to contamination and the fluctuation of microbiological contents according to the hydrological conditions. It also revealed that FIBs only represent a small proportion of the total bacteria load present in the groundwater. Usual enumerations of TCC (Total Cell Count) range between 3.10^3 and 5.10^5 cells/mL for karst groundwater (depending on the flow dynamics of the system). This is more or less 5 orders of magnitude higher than the measured concentration of fecal bacterial. The classification of the karst systems according to microbiological content is then based on the spring dynamic, the occurrence of FIB and TCC and the correlation FIB-TCC (see Table 10—3).

Vulnerable springs	▪ High spring dynamics ▪ Occurrence of FIB ▪ High TCC ($10^5 – 10^6$ cells/mL) ▪ FIB-TCC correlation
	▪ Moderate spring dynamics ▪ Occurrence of FIB ▪ Moderate TCC ($10^4 – 10^5$ cells/mL) ▪ No FIB-TCC correlation
Low spring vulnerability	▪ Low spring dynamics ▪ Absence of FIB ▪ Low/stable TCC ($10^3 – 10^4$ cells/mL)

Table 10—3. Classification of the karst springs vulnerability according to microbiological contents (Sinreich et al. [2011])

Although it is technically possible to disinfect tapped groundwater before distribution, for instance by using chlorination of UV treatment, these methods show a maximal concentration which cannot be exceeded (see the Swiss regulations regarding admissible characteristics for drinking water). When bacterial components exceed the limit concentration, groundwater cannot be treated and distributed. Then water managers have to switch to a substitute supply-device.

Actually, for Switzerland, microbes and pathogens have to be seen as the most important contaminant for karst groundwater.

10.4.5. **Anthropogenic Organic Compounds**

This type of contaminants covers a wide range of chemical characteristics and phases (gases, dissolved, adsorbed on organic or solids, etc.) which makes their complete description highly difficult. In addition, their comportment may be greatly modified depending on their association with other contaminants or also depending on the chemico-physical properties of the aquifer. Organic compounds may also change their composition or they may be degraded under certain conditions. Resulting products may become harmless or may still be hazardous for consumers.

10.4.5.1. NAPLs

Anthropogenic organic contaminants may be distinguished in two groups (Vesper et al. [2001]): (i) light, non-aqueous phase liquids (LNAPLs) and (ii) dense and slightly soluble organic compounds (DNAPLs). LNAPLs entails mostly gasoline, fuel, oil composed of aromatic hydrocarbons while DNAPLs gather chlorinated or brominated compounds, volatile compounds used as solvents or dry cleaning agents (TCE and PCE) and some polychlorinated biphenyls (PCBs) used as component for electrical transformers.

Most of LNAPLs move as floating “free-products”. Ewers et al. [1991] detailed the mechanisms of the LNAPLs migration, which are function of karst aquifers properties. According to the authors, LNAPs may be trapped for two conditions: first the active phreatic conduits must remain in a completely water-filled condition in order to “dam” the lighter product; secondly the velocity of the groundwater must remain slow in order to not-mobilize the products… This is unfortunately not often compatible with turbulent flows which may be observed in the karst systems. In other conditions, LNAPLs are supposed to migrate within the aquifer and to possibly reach the spring.

DNAPLs migration is mostly driven by gravity even in the phreatic zone. They thus migrate vertically rather than in the direction of the groundwater flow and they usually accumulate at the bottom of the aquifer. Usually the concentration of both NAPL contaminants increase during storm events as the increase of hydraulic activities release the previous trapped contaminants (Vesper [2008]).

10.4.5.2. Pesticides, herbicides

The use of pesticides and herbicides for agricultural practices also greatly increased these last decades. These are of various chemical compositions which affect their migration properties. In addition, a lot of these compounds may be degraded in secondary products within the aquifer (for example glyphosate is readily degraded by soils bacteria to AMPA “aminomethylphosphonic acid“, atrazine is also metabolized to deethyl atrazine or deisopropylatrazine, etc.). Such resulting products may be present in higher concentration than the original compounds and may differently modify the groundwater quality.

The problematic of pesticides and herbicides migration within karst aquifers have been addressed by Pasquarell and Boyer [1996], Groves et al. [2013]; or Hillebrand et al. [2014]. This last author observes that the concentration of Metazachlor (herbicide) increases at the Gallusquelle karst spring (Germany) during rainfall events and rapidly decreases below the limit of detection. On the opposite, atrazine and its metabolites are diluted during such rainfall events, after which their concentration returns to their pre-event value. Atrazine is here suspected to be stored within the rock matrix and could be continuously release to the groundwater for a long time as the compound has been prohibited twenty years ago… In Switzerland, the spreading of atrazine (and also of simazine which is another herbicide) in karst regions is banned since 1998.

10.4.6. **Evolution over the last decades**

In many areas of Switzerland (and of the world), withdrawals during droughts will become an increasing challenge in the future, according to climate change scenarios (see Björnsen Gurung and Stähli [2014], synthesis of the NRP61 concerning water resources for the future). The groundwater quality is also supposed to evolve conjointly to climate warming.

Investigations undertaken within other projects provided the opportunity to analyze the evolution of groundwater quality in karst aquifers in the Jura Mountains (Jeannin et al. [Submitted])[1]. Statistical trend analyses were performed on three different datasets with the aim to discuss the evolution of temperature and chemical parameters of karst springs between 1990 and 2011 (i.e. over more than 20 years). Parameters related to carbonate dissolution and other parameters were analyzed over the three datasets. The first dataset is made of chemical analyses of samples taken every 3 months at 40 springs in the Ajoie region (JU, Switzerland). The second set of data comes from data loggers recording discharge rates, temperature and electrical conductivity along the Milandre cave stream (JU, Switzerland). The third set of data comes from a monitoring network of several karst springs in the Doubs department (France). All data thus come from the Jura Mountains.

By applying Mann-Kendall trend tests, authors demonstrate that clear trends for compounds related to groundwater mineralization: increase in temperature (by about 0.5°C/25 years), decrease in pH, increase in bicarbonate (by about 5%), and positive or negative trends for major ions directly related to human practices. some of them display a clear increase or a clear decrease in content (Figure 10—4 and Table 10—4).

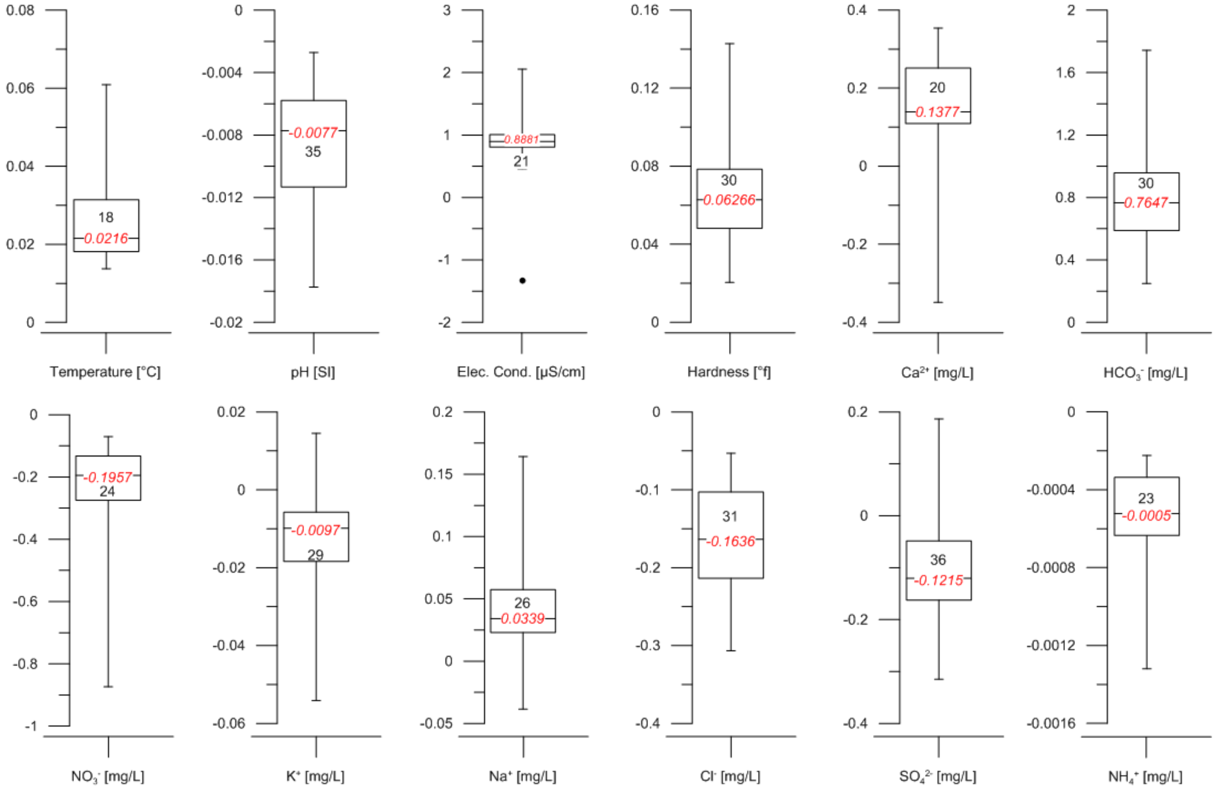

*Figure 10—4. Whisker-Box plots showing the evolution of groundwater compounds in Jurassian karst aquifers for the first dataset (*Jeannin et al. [Submitted]*); the upper graphics refer to parameters related to carbonate dissolution while the lower graphics refer to other parameters showing a meaningful trend. For each parameter, plain values refer to the numbers of stations where the trend*

[1] The study was carried out in close collaboration with MFR SA Géologie (Delémont, JU) and data come mainly from the environmental impact study related to the construction of A16 Motorway (Ponts-et-Chaussées du canton du Jura and OFROU).

was identified (over a total of 40 stations), italic value gives the estimated rate of change (/year).Trends are further detailled hereafter.

Parameter	Trend (per year)	Nb. of sources	Time period
Temperature	+0.022 °C	18	1992-2011
Electrical conductivity	+0.89 µS/cm	21	1984-2011
HCO_3^-	+0.76 mg/L	30	1989-2011
pH	-0.008 pH unit	35	1992-2011
SO_4^{2-}	-0.12 mg/L	36	1989-2011
Cl^-	-0.16 mg/L	31	1985-2011
Na^+	+0.034 mg/L	26	1990-2011

Table 10—4. Trends assessed for 7 selected parameters out of the Figure 10—4 (values have been rounded compared to those previously displayed)

By analyzing the three independent dataset, the following main evolutions could be confirmed:

- **Temperature**: positive trend of nearly +0.5°C over the last 22 years.
- **Hardness**: positive trend of nearly +10 % over the last 22 years. A similar trend is observed for the electrical conductivity. Logically, pH displays a trend in the opposite direction.
- **Nitrates**: negative trend
- **Sodium**: clearly positive trend
- **Chlorides and Sulfates**: negative trends (-30%)

Climate warming is obviously responsible for the increase of. Concerning the other parameters reasons for the observed trends are not easily identified: they may be related to climate warming, but also to changes in land-use, in urban development or in farming practices. Further investigations are being carried out on this topic. They will provide a useful background for assessing changes of karst groundwater quality for the next decades.

10.5. Appendix 5: examples of karst-related problems for tunnels in Switzerland

Karst hazards in tunnel are frequent and represent a major issue in Switzerland, since they lead to economic, social, security-related and environmental problems. The following list give an overview of the main Swiss cases (see also Filipponi et al. [2012], Tab. 2.1).

Engelberg Tunnel, canton Obwalden (2001-2010): large water inflows (up to 1.1 m^3/s) and high hydraulic heads (at least 50 bars above the roof) under un-drained conditions (Anagnostou and Ehrbar [2013]). Due to snowmelt in June 2004, 2'000 m^3 of debris and muds invaded the tunnel and partially destroyed the installations. The costs of the construction has been increased by at least 70 mio CHF due to the karst-related problematic (Filipponi et al. [2012]).

Concise Tunnel, canton Vaud/Neuchâtel (2000-2004): due to the intersection of a large cave (50 m length), 3 months of additional work and huge consolidations have been required to pass through the cave zone. All the collected water inflows have been re-injected in the downstream parts of the intersected conduits (see in Anagnostou and Ehrbar [2013]).

Flimserstein Tunnel, canton Grisons (1998-2007): unexpected water inflows (up to 0.8 m^3/s) and high hydraulic heads (up to 50 m above the roof) have been encountered during the construction (October 2002, see in Anagnostou and Ehrbar 2013). The diversion of the water out of the tunnel provoked environmental damages on the plateau above (cf. Jeannin [2007]). At this stage of the construction project, the mitigation measures were difficult to implement and induced considerable costs. This could probably have been avoided if the karst components were taken into consideration at an earlier stage of the project.

Kerenzerberg Tunnel, canton Glarus (1986): a cave has been intersected during the construction of the road tunnel (Jeannin [1986]). Under high flow conditions, the entrance conduit becomes active and the water may overflow in the tunnel (up to several hundreds of liters per second). A door has been installed at the entrance of the cave in order to prevent the flood from the cave overflow. The door has been destroyed a first time under the high pressure-flows; boulders and gravels were spilled over the road.

Mont d'Or Tunnel, France and canton Vaud (1910-1915): the construction led to a de-clogging of conduits and to large water inflow into the tunnel (up to 10 m^3/s! while the engineers expected less than 0.5 m^3/s). French springs dried up and considerable damages have been recorded in the Swiss part as the built zone has been swept by the flows. The significance of the flows within the tunnel did not allow to work as initially planned and the costs of the construction considerably increased (Anonymous [XXXX]; Filipponi et al. [2012]).

Ölberg Tunnel, canton Schwyz (90ies): a cave was intersected during the construction of a roadway tunnel, parallel to the existing railway tunnel but slightly below. The groundwater flow in the cave was responsible for frequently flooding the railway tunnel until it was diverted by the roadway tunnel toward the lake (+18 m of hydraulic head and discharge up to 0.5 m^3/s, Wildberger [1994]).

Raimeux Tunnel, canton Berne/Jura (1999-2007): active karst conduits have been intersected and the amount of water inflows within the tunnel during the construction reached up to 1 m^3/s (Anagnostou and Ehrbar [2013]).

Rawil exploration drift (BE/VS): the construction of the exploration drift (started in 1976) - prior to the drill of a future road tunnel - was stopped in 1978. The drift was supposed to affect the stability of the Tseuzier dam. Indeed, a partial subsidence at the edge of the dam was registered in the meantime the drift intersected the malm aquifer. Numerous water inrushes were also encountered in this zone (Wildberger [1979], Schneider [1980];). As a precaution, the drift was not further excavated. Badoux [1982] brings into question the relationship between the excavation of the drift and the partial subsidence of the dam. For the author, the subsidence of the Tseuzier dam resulted from an earthquake – without direct relation with the excavation. The project is still stopped.

Sauges Tunnel, canton Neuchâtel (1997-2002): the tunnel intersected a series of voids which have been considered as dry. In reality, under high-flow they discharge up to 1 m^3/s (Jeannin and Blant [1999]).

Twann Tunnel, canton Berne: several water inflows have been intersected in 1989 in the pilot drift (up to 2 m^3/s). The prolongation of the existing Ligerz Tunnel has been abandoned due to technical and costs complication related to the groundwater management (cf. Bollinger and Kellerhals [2007]). As so much water was unexpected by the engineers, various technical solutions have been envisaged in order to prevent the gallery from the inflows. Hydraulic tests have been carried out by closure of the pilot gallery but the rise of the hydraulic heads threatened the portal area. Cracks and fissures appeared in the structure recently concreted. By consequence, as the mitigation measures required considerable additional costs and technics which could be not applied without difficulties, the drill work has been stopped in the pilot gallery and the tunnel has been shortened compared to the initial project.

Vue des Alpes Tunnel, canton Neuchâtel (1999): the tunnel intersected a karst chamber during the drill (Jeannin and Wenger [1993]). In order to pass through the chamber, a small bridge has been constructed, inducing non-expected costs and serious delays in the work. The cave is now inscribed as a geotope of national significance (Nr. 138).

10.6. Appendix 6: Malard et al. 2014 - Impact of a Tunnel on a Karst Aquifer: Application on the Brunnmühle Springs (Bernese Jura, Switzerland)

Impact of a Tunnel on a Karst Aquifer: Application on the Brunnmühle Springs (Bernese Jura, Switzerland)

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Abstract Tunnel drilling in karst regions often leads to major disturbances in the hydrogeological functioning of aquifers and flow-systems. Numerous examples are documented in Switzerland and induced significant costs, which were not or rarely anticipated (e.g.: Flims, Jeannin et al. 2009). The Ligerztunnel is one of these example. The tunnel was built a few hundreds of meters upstream from the Brunnmühle spring, which contributes to the drinking water supply of communities of Twann and Ligerz. During the construction, a major karst conduit with a huge discharge rate was intersected in a side exploration tunnel. Overflowing water was diverted into the Twannbach canyon. In the main section, smaller conduits were found and drained outside by pipe leading water close to the Brunnmühle spring. Actually, authorities want to add a safety tunnel parallel to the main tunnel. In this view, SISKA is in charge of evaluating the hydrological disturbances on the spring regime. The paper presents the approach applied to assess the potential effect of the drilling of a new tunnel near to a group of karst springs and pumping wells. The approach combines available spatial information and a hydraulic model. The KARSYS approach is first applied on this system in order to set up a 3D geological and hydrogeological model of the karst aquifer and the related systems. The spatial distribution of karst conduits within the massif is assessed based on a speleogenetical and inception horizons model (KarstALEA method). Inferring from these models, a karst conduits network is generated. The hydraulic model of the downstream part of the conduit network, which concerns the close vicinity of the safety tunnel project, is precisely calibrated using head and discharge data. Flow in this conduit network is then simulated using SWMM 5.0 in order to reproduce the hydrological responses of the different outlets (permanent springs, drainage devices, overflow springs, etc.).

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Introduction

Communities of Twann and Ligerz (Bernese Jura, CH) obtain water from the Brunnmühle spring, which is a karst spring emerging from Malm karst aquifer. In 1980s the construction of the Ligerztunnel, which crosses the karst aquifer 100 m upstream from the spring induced serious hydrological disturbances to the karst hydraulics. Active karst conduits have been intersected in the tunnel and required the drilling of a pipe to discharge karst waters out of the tunnel, close to the spring (Bollinger and Kellerhals 2007). This considerably modified the dynamics of the karst aquifer: the seasonal regime of the spring as well as the functioning of the overflow springs located 40 m above the permanent outlet. Nowadays the construction of a safety gallery parallel to the tunnel raises the question of new hydrological disturbances on the spring. The communities already considered to replace the actual supply device by two wells drilled further upstream in the same aquifer. The question to be addressed is therefore to assess the potential disturbances of the new gallery on the spring and wells.

As the study is still in course, only the steps of the proposed approach are presented in the following note. This approach is an extension of the KARSYS approach (Jeannin et al. 2013). The evaluation is based on five main steps:

i. Build a geological and hydrogeological 3D model of the site in order to characterize the underground drainage zone of the system and its catchment area over the surface using the KARSYS approach;
ii. Establish a speleogenetic model of the site to assess the potential organization of the karst conduit network. At the same time, the analysis of existing caves and karst features will be used to identify the inception horizons;
iii. Design a hydraulic model of the system using the hydrological karst features (permanent and overflows springs, catchment areas), the artificial drainage devices (tunnel, drainage pipes) and the results of the speleogenetic and inception models;
iv. Reproduce the discharge regime of the Brunnmühle permanent springs and the overflow outlets;
v. Test various scenarios of hydrological disturbances on the spring regime caused by the tunnel construction. As far as possible, disturbances will be extended to pumping wells, which are being equipped as the future drinking supply for the communities;

Context

The site is located at the foothill in the Eastern part of the Jura Mountain (canton of Bern) along Lake Biel (see Figs. 1 and 2). The geological context is composed of South-East dipping pile of Jurassic and Cretaceous limestone, underlain by Oxfordian Marls (aquiclude). The tunnel develops approximately along the strike

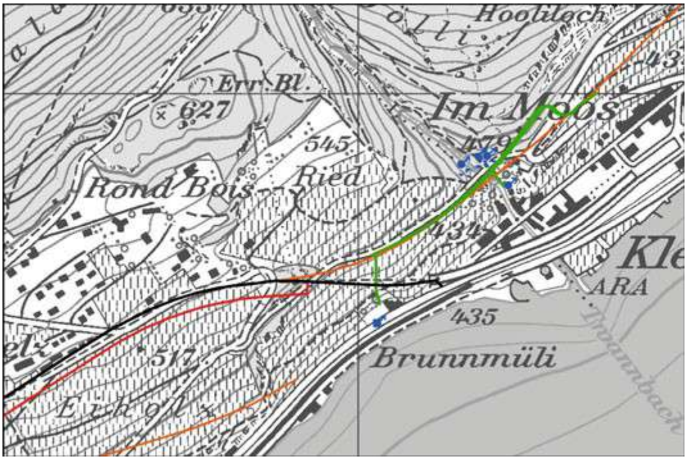


Fig. 1 Site location *Black line* existing main tunnels; *Green line* existing exploration tunnel; *Red line* security gallery (project), *Orange lines* future railway and road tunnels. The Brunnmühle spring (*blue*) emerges at 433 m a.s.l close to Lake Biel. Other springs are visible in the Twannbach canyon (Im Moos)

of bedding planes and the Brunnmühle spring emerges at the base of the massif, close to the elevation of the lake Biel, but at the top of the limestone series. Several other springs emerge in the Twannbach canyon. Due to the existing exploration tunnel, which intersected a major karst conduit, the natural hydrological regime of the karst system was very probably modified. This must be considered in the perspective of a hydraulic simulation and impact assessment.

As sketched on Fig. 2 the Brunnmühle spring emerges at the contact between the Portlandian limestone and the Purbeckian marls. It is mainly fed by the Malm aquifer (upper Jurassic limestone, from Sequanian to late Portlandian, □600 m of thickness) and partially dammed by the Purbeckian marls. All tunnels are located within the Malm aquifer, close to the groundwater table.

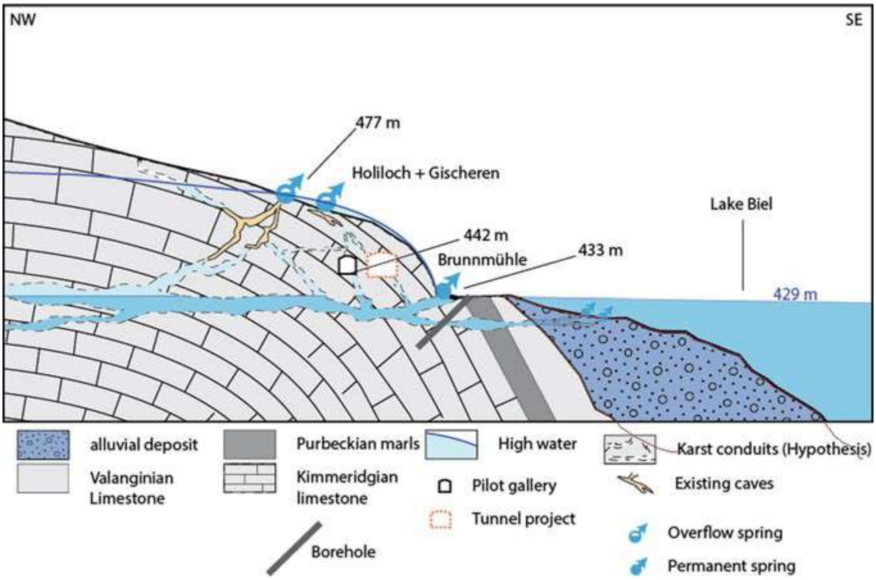
Holiloch and Gisheren are emissive caves, which become active during high-flow events. They act as overflow springs of the system, especially during the spring melt period (https://www.google.ch/maps/@47.093352,7.151663,3a,75y,331.https://www.google.ch/maps/%4047.093352%2C7.151663%2C3a%2C75y%2C331.3h%2C77.88t/data%3D%213m4%211e1%213m2%211snPY6RkNP2cjiAKW9Pb2xEA%212e0%3Fhl%3Dfr).

Their entrances are located 44 m above the elevation of the Brunnmühle spring indicating that the hydraulic head considerably rises during high-flow conditions.

Approach

The first step of the KARSYS approach (Jeannin et al. 2013) consists in building a geological 3D model of the site depicting the geometry of the Malm aquifer. Figure 3 depicts the geological structure of the site. The existing and projected

Fig. 2 Schematic cross-section of the site, the Jurassic and Cretaceous units plunge toward the



South-East. The Brunnmühle spring emerges at the contact between the portlandian limestone and the purbeckian marls

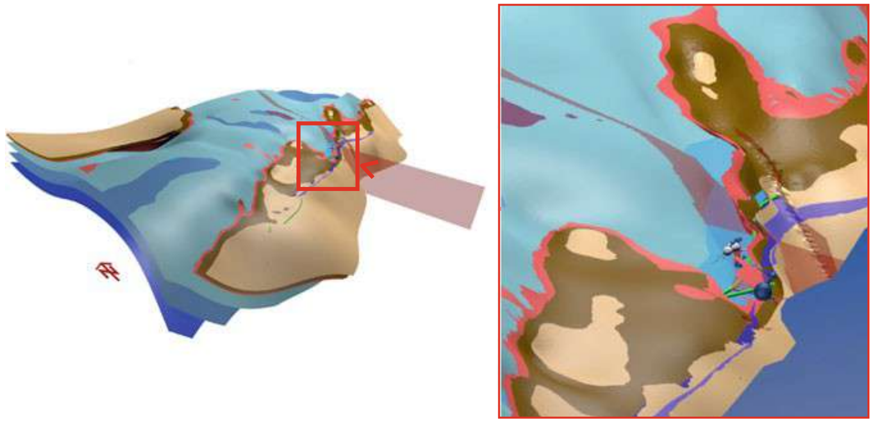


Fig. 3 Perspective view of the geological 3D model of the site (8km along the east-western axe and 6km along the north-southern axe); the tunnel (*green pipe*) develops along the bedding planes below the Purbeckian marls (*red layer*)

tunnels (green pipes) all develops within the Malm limestone, i.e., Purbeckian Marls (red layer on Fig. 3).

Hydrological features (mainly springs, but also boreholes and caves indicating the position of the water table) are added to the model in order to build a hydrogeological 3D model of the site. The model shows that the Brunnmühle

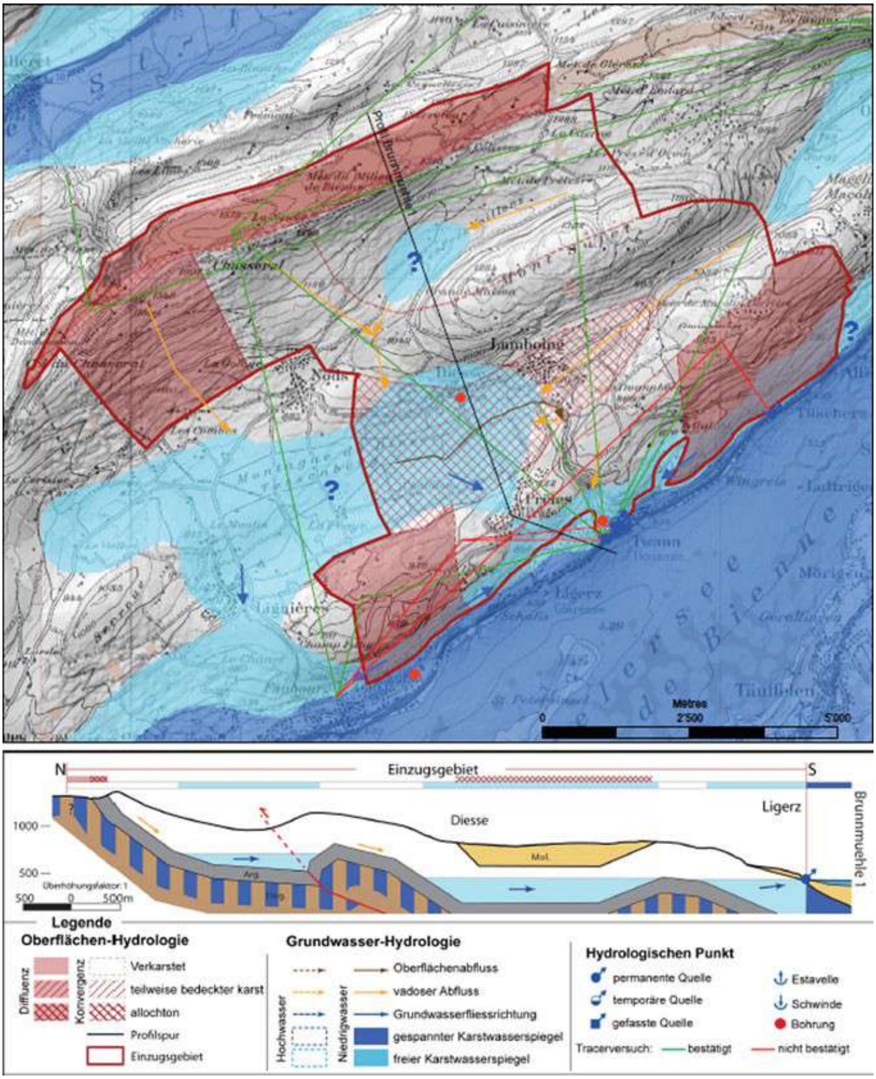


Fig. 4 Preliminary catchment area of the Brunnmühle karst system; the area is 66 km^2 wide but presents divergent parts with the adjacent karst systems

spring emerges at the lowest outcrop of Malm limestone, confirming the damming effect of the Purbekian marls (red layer). Knowing the geometry of the aquifer and assuming an almost horizontal water table at low water conditions, the extension of groundwater bodies, the underground drainage zone, and the respective catchment area feeding the system can be delineated (Fig. 4).

The second step of the approach is to set up a speleogenetical model of the site in order to hypothesize the organization of the karst conduits within the massif.

The density and the geometry of existing caves and karst evidences in this area will be analyzed and compared with the geological model in order to assess the main horizons of karstification (called ‘‘inception horizon’’, Filipponi 2009) along some specific stratigraphic limits or due to tectonic disturbances. Such model makes it possible to assess the supposed organization of the karst network. This approach is known as the KarstALEA method (Filipponi et al. 2012).

The aim of the third step of the approach is to generate a pipe network according to the 3D hydrogeological and speleogenetical models, and to make a first guess of the flow parameters of the generated pipes. A series of hydraulics and speleogenetical principles are used to generate a conduit network linking the catchment area according to its topography and infiltration characteristics to the main outlets (springs) of the system. The generator provides files directly compatible for SWMM 5.0 (Rossman 2004), which is a robust pipe-flow modeling tool.

For the fourth step, the model will be calibrated using first existing head and discharge data acquired in the neighboring of the spring. The hydraulic characteristics and the topology of the pipes in the vicinity of the spring will be calibrated using a series of various hydraulic situations (e.g., overflow conditions of the respective springs, measured heads, and discharge rates). This network will be included into the pipe network generated at catchment scale. This model will be calibrated using a recharge model assessing infiltration on various parts of the catchment area.

The fifth step will include the simulation of the intersection of various karst conduits (pipes) by the projected tunnels. The first simulations show that the effect can range from almost insignificant to very considerable depending on the topological position of the intersected karst conduit.

Discussion

One main uncertainty of the proposed approach is related to the lack of discharge rate measurements (short or incomplete hydrographs) of the different outlets. This is especially true for artificial tunnels, where discharge rates have not been measured correctly until now (April 2014).

Another difficulty is that no data are available for all springs before the construction of the first tunnel, making a comparison with the natural situation almost impossible.

Conclusion

The KARSYS approach was then applied to the Brunnmühle karst system in order to define the underground drainage pattern and the catchment area of the spring. In a second step a speleogenetical model was established in order to design the organization of the karst conduits within the massif. Then, these parameters are being injected within a hydraulic model—SWMM 5.0® to simulate the regime of the Brunnmühle spring and its overflow springs in the Twannbach canyon. According to the speleogenetical model, several scenarios of potential disturbances will be tested to assess the effects on the springs' regime, as well as on the future borehole.

As a preliminary discussion, it appears that simulating such systems may be quite complicated as data and measurements do not exist for all outlets. These data and measurements may also be obsolete as artificial galleries (or drainage) probably modified the natural functioning of the aquifer.

As the study is still in progress, results could not be discussed yet. Only the approach was presented here. Results will be presented during the conference and compared to the initial approach.

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10.7. Appendix 7: Malard et al. 2012 - toward a sustainable management of karst water in Switzerland. Application to the Bernese Jura

Swisskarst Project – toward a sustainable management of karst water in Switzerland. Application to the Bernese Jura

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Abstract: Karst groundwater represents about 80 % of Swiss groundwater reserves and about 50 % of groundwater resources. Paradoxically these reserves/resources are badly documented which leads to a non-optimal management of karst systems. In the framework of the NRP61, supported by SNF, SISKA develops and applies a dedicated and systematic approach (named KARSYS) for documenting karst system in Switzerland. This approach is currently applied in the frame of the SWISSKARST project (started in 2010) to cover the Swiss territory.

We focus here on a recent application of KARSYS in the Bernese Jura, which represents around 540 km^2 of karst area and encloses more than 50 000 inhabitants. This region strictly depends on karst water for drinking supply and industrial purposes. Seventeen strategic karst springs emerging from the Malm aquifer are harvested by communities for drinking water. In addition, pumping wells have been recently drilled to reinforce this supply. In spite of many hydrogeological studies , delineation of the respective spring catchment areas remains unclear inducing difficulties in the implementation of protection rules.

Thanks to the additional funding provided by the AWA (Amt für Wasser und Abfall des Kantons Bern), SISKA applied KARSYS on the Malm aquifer and built a 3D geological model of the regional aquifer basement. Hydraulic features have been analyzed and added into the model to highlight the location and extension of groundwater bodies. Seven main karst groundwater bodies have been identified and their geometry was depicted in 3D: Saint-Imier, Tavannes, Moutier, Bellelay, Diesse, Orvin and Mont-Sujet. The total capacity of karst groundwater reserves reaches about 2.2 km^3 assuming an average porosity value of 2 %. This is twice the water volume of Lake Biel.

Results provide an understanding of flow mechanisms at regional scale as well as interactions occurring between adjacent or even between remote systems. It also reveals new questions and identifies places where investigation should be conducted in order to precise the proposed delineation of the karst systems and improve the protection of these water resources.

Key words: KARSYS, SWISSKARST; karst aquifer, karst groundwater body, Jura, Bern, Switzerland

Intoduction

Many studies have been dedicated to the hydrogeology of the Bernese Jura, especially in connection with tunnel constructions (Grenchenberg: Buxtorf & Bram, 1916, Pierre Pertuis: Kellerhals, 1992, Twann: Kellerhals, 1976 and further...), highway management (Transjurane: Kellerhals, 1985, and others), water supply (deep bore-holes and hydrogeological prospection: Schindler, 1977, MFR Géologie-Géotechnique SA, 1998, delineation of S zones: Kellerhals & Tröhler, 1979…) or academic works (Häfeli, 1964, Aufranc, 1985). They provide good geological and hydrogeological materials to under- stand groundwater mechanisms. However there is no consensual work which gathers these data or interpreted information at the scale of the entire massif in order to give a systematic and pragmatic overview of karst groundwater reserves and flow. In the framework of the SWISSKARST project (NRP61), SISKA applied the KARSYS approach to the entire territory, and could therefore document these aquifers by the mean of a systematic process based on relevant literature and data, which were compiled and synthesized.

The Bernese Jura – a complex karst area

The Bernese Jura belongs to the Northern part of the folded Jura (cf. Figure 1) jammed between the French boundary and Lake Biel and oriented along the ENE-WSW direction. Three main valleys expand within the massif according to the main regional thrusts and folding: St-Imier, Tavannes and Moutier. They include most of activities and residents. Surface stream networks show a multi-directional drainage. The most southern part (Diesse, Tüscherz-Alfermée) is drained towards Lake Biel while areas of Saint-Imier, Cortébert, la Heutte and Orvin are drained by the Suze river. North-eastern parts are drained through the Birse River (Tramelan, Tavannes, Court, Moutier) or the Sorne river (Souboz, Bellelay) towards Basel. Both belong to the catchment of the Rhine River and meet together in the Delémont region. The most North-western part of the Bernese Jura

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(La Ferrière) is drained towards the Doubs River (Rhône catchment). These rivers are mainly fed by numerous perennial karst springs (Table 1) which contribute signifi- cantly to their discharge.

Despite a large number of studies and deep investigations (boreholes, tunnels…) catchment areas of these springs are still not well defined and several boundaries remain very unclear.

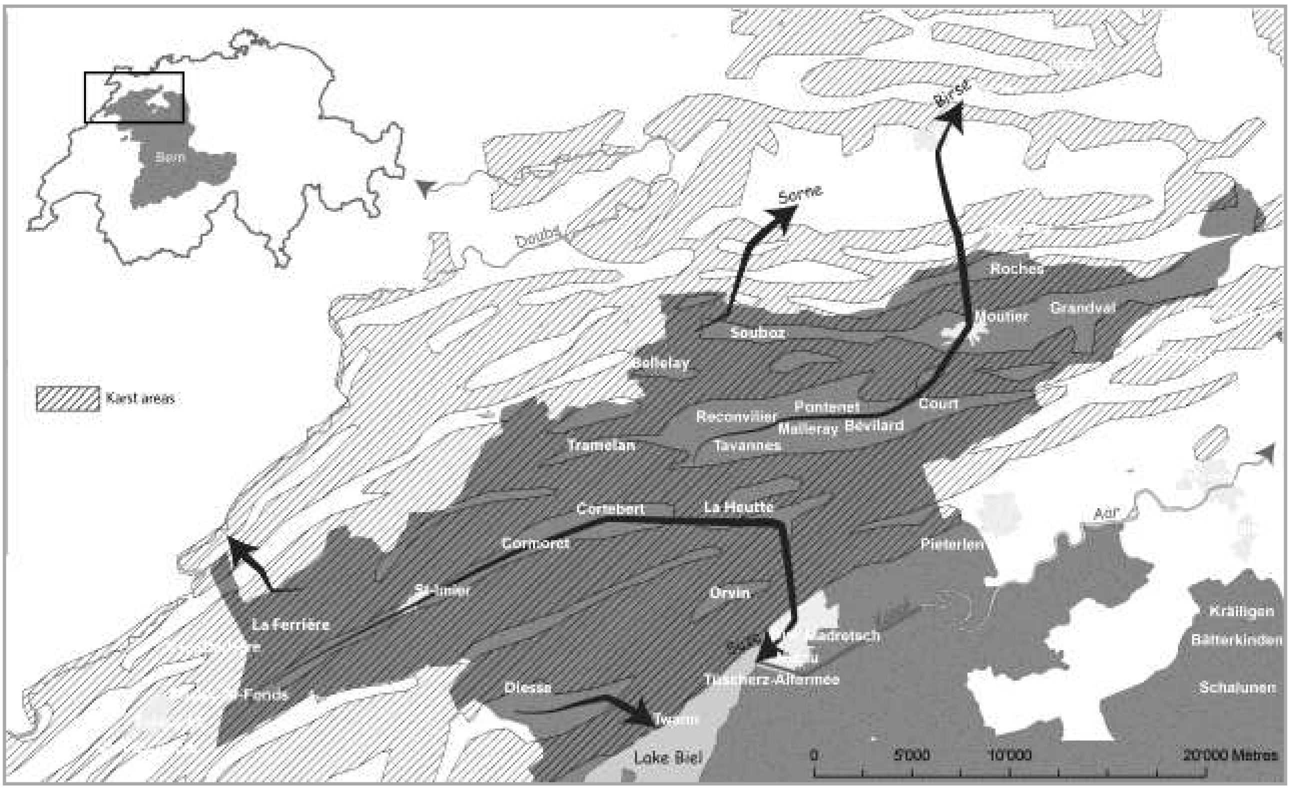


Fig. 1: Three main rivers drain the Bernese Jura: the Birse, the Suze and to some extends the Sorne. Locally flows are driven underground directly towards the lake Biel and the Doubs River.

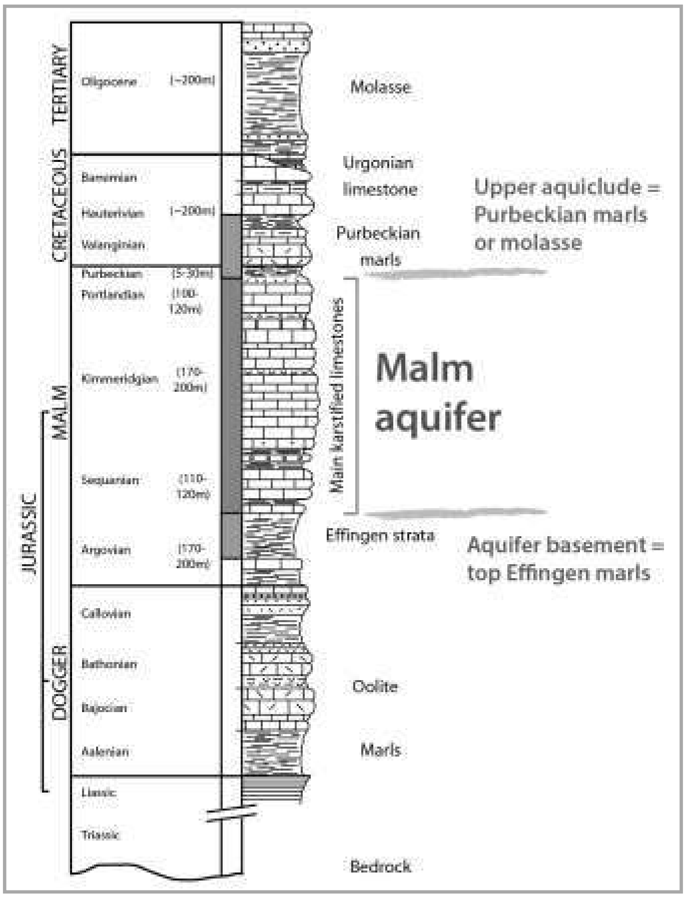
Springs	Coord X (m)	Coord Y (m)	Elevation (m a.s.l)	Mean discharge rate (L/s)	Supplied rivers
Bez	576992	225585	710	200 to 500	Suze
Dou	569590	224215	746	More than 1000	
Merlin	585863	224381	530	200 to 500	
Romerquelle	585310	221325	455	50 to 200	
Torrent	570084	224153	719	50 to 200	
Cuchatte	580890	226551	636	50 to 200	
Raissette	570725	224845	725	200 to 500	
Foule	593538	235338	559	200 to 500	Birse
Birse	581555	229221	771	50 to 200	
Envers	591915	231193	733	50 to 200	
Gore	601389	237855	744	50 to 200	
La-Tu	602473	238057	744	50 to 200	
Etang	600430	236279	638	50 to 200	
Blanches-Fontaines	583663	237656	580	500 to 1000	Sorne

Table 1: Rivers of the Bernese Jura are mainly fed by various karst springs.

Identification of the main regional aquifer

Springs emerge from a limestone series limited at its bottom and possibly also at its top by aquiclude formations (usually marls). The first step is therefore to identify from which limestone series one particular spring emerges and, based on the geological litera- ture to identify what impervious formation is expected to limit the bottom and the top of this aquifer. In the considered area springs of Blanches-Fontaines and Gore (sup) are the only ones emerging at the inter- face of the aquifer basement. Other springs overflow close to the top of the aquifer, where the overlaying Cretaceous or Molasse formations dam the lime- stone aquifer. This is the case for Brunnmühle, Moulin, Römer, Bez, Birse, Cuchatte-Tournedos, Dou-Torrent-Raissette, Envers, Etang, Foule, Grabenbach and Merlin. The spring of the Grenchen tunnel is an exception where water flows out of karst conduits intersected by the tunnel.

The Bernese Jura is composed of an alternation of limestone and marls from the lower Lias to the upper Jurassic with at least three limestone series being potential karst aquifers: Lias, Dogger and Malm. At some places (southern part) Cretaceous limestone series are also present (isolated from the Jurassic one by the Purbeckian marls). At the top of these formations Molasse deposits covered the entire Jura (overlaying the cretaceous formation in the South and the Jurassic ones in the North). These Tertiary deposits were deformed together with the Jura folding and faulting. They were protected from erosion in synclines where they are still present and sometimes overthrusted by upper limestone masses. The main karst aquifer of the Bernese Jura is composed by series of the Malm limestones: Portlandian, Kimmeridgian and Sequanian. The aqui- fer basement (or aquiclude) is constituted by the Argovian marls, here labeled as Effingen strata (cf. Figure 2), which isolates the Malm aquifer from the lower Dogger aquifer. This lower aquifer is less productive but obviously exchanges water at some locations with the Malm aquifer.



Building up a 3D geological model to shape the aquifer basement

The Bernese Jura territory was divided into six square regions of 15 x 15 km. Each region was modeled with Geomodeller® software using 1/25 000 available geo- logical map and 98 geological cross-sections collected among the literature. Seven geological formations have been considered. As their lithologies and thickness change from one region to another some of these formations are sometimes not distinguished and/or gathered under a same label (cf. Table 2). This implies that models show limitations in their geological details and could not be used for other purposes than karst-related questions.

Mol, C1-C2	Molasse and Cretaceous limestone – Purbekian marls on basis
i8	Portlandian limestone (Twannbach formation)
i7	Kimmeridgian limestone (Reuchenette and Balsthal formations)
i6	Sequanian limestone (Court Vellerat and Günsberg formations)
i5	Argovian marls (Effingen and Birmenstorf strata)
i4	Undifferentiated Dogger limestone
i3	Indicative Lias Formation

Table 2: Geological formations considered in modeling the Malm aquifer bottom (top of the Argovian marls) and top (bottom of overlaying Cretaceous and/or molassic formations).

The whole model construction is focused on approaching the geometry of the Malm aquifer basis (Argovian Marls) and top (Cretaceous and/or Molasse). In many places (mainly in valley) the top of the aquifer lies below the groundwater level, i.e. water is confined. Faults are included as long as they influence the geometry of the aquifer. When geological information of two nearby cross-sections is significantly different, preference is given to the author who contributed to the geological mapping of the area. Models are mainly constrained by surface data of the 1/25'000 geological maps. Data from the few existing boreholes and tunnels have been included for constraining the model at depth. However the density and the precision of the geological data decrease with depth.

Implementing hydrological features to assess the geometry of the groundwater bodies (GWB)

Some hydraulics principles are assumed in the KARSYS approach (JEANNIN et al. in print): (i) the aquifer volume below the main perennial springs is water saturated,

(ii) the hydraulic gradient in the saturated zone is flat or inclined at most of 1 %. More than 70 karstic springs emerging from Malm aquifer and showing a significant discharge rate were implemented into the model. The elevation of each of them - as well as their relative discharge rate - were verified. Around 55 springs are considered as perennial, 15 as temporary or as estavelle.

21 deep boreholes reaching or passing through the aquifer and tagged with piezometric data (expected to give the level at low water stage) are also implemented. They are usually located in the core of the valleys, thus giving information on the thickness of the Molasse cover and the groundwater confinement.

From the perennial springs and water levels in boreholes horizontal plans are stretched through the karst media until they cross surface of the aquifer basement. They give the minimal extension of the saturated zone. In some cases the water table "overflows" over the top of the aquifer basis (e.g. over an anticline threshold or a pass) towards another karst system. Along one valley, if several springs are found at different elevation, and if there is no clear geological discontinuity which disconnects the groundwater body between them, the hydraulic gradient is adjusted to meet the elevation of each spring as far as the gradient remains lower than 1 %. The intersection between these water table plans and the top of the aquifer (non-karstic formations) gives the limit between unconfined and confined groundwater. The extension of the ground- water table is then controlled by emerging points (springs) on surface or subsurface (i.e. alluvial deposits) or by overflowing threshold over the aquifer basement.

Once groundwater bodies have been identified flows are determined. Two further characteristics of groundwater flow can be distinguished: (i) the catchment areas of surface runoff swallowing into the karst and vertical flow in the unsaturated zone, and (ii) main drainage axes at low (and high) water (solid lines in Figure 3) and drainage axes occurring only at high water stages. These flow lines are drawn according to the geometry of the aquifer basement in unsaturated areas and to the hydraulic gradient in the saturated zone. Most of them have been validated by results of dye tracer tests (226 connections or no-connections have been analyzed in the Bernese Jura). Organization of flows allows the delineation of catchment areas of all the main karst systems with well- defined boundaries when geological boundaries do exist and/or with diffluent areas where infiltrated water reaches a groundwater body (GWB) drained by two groups of springs or karst systems.

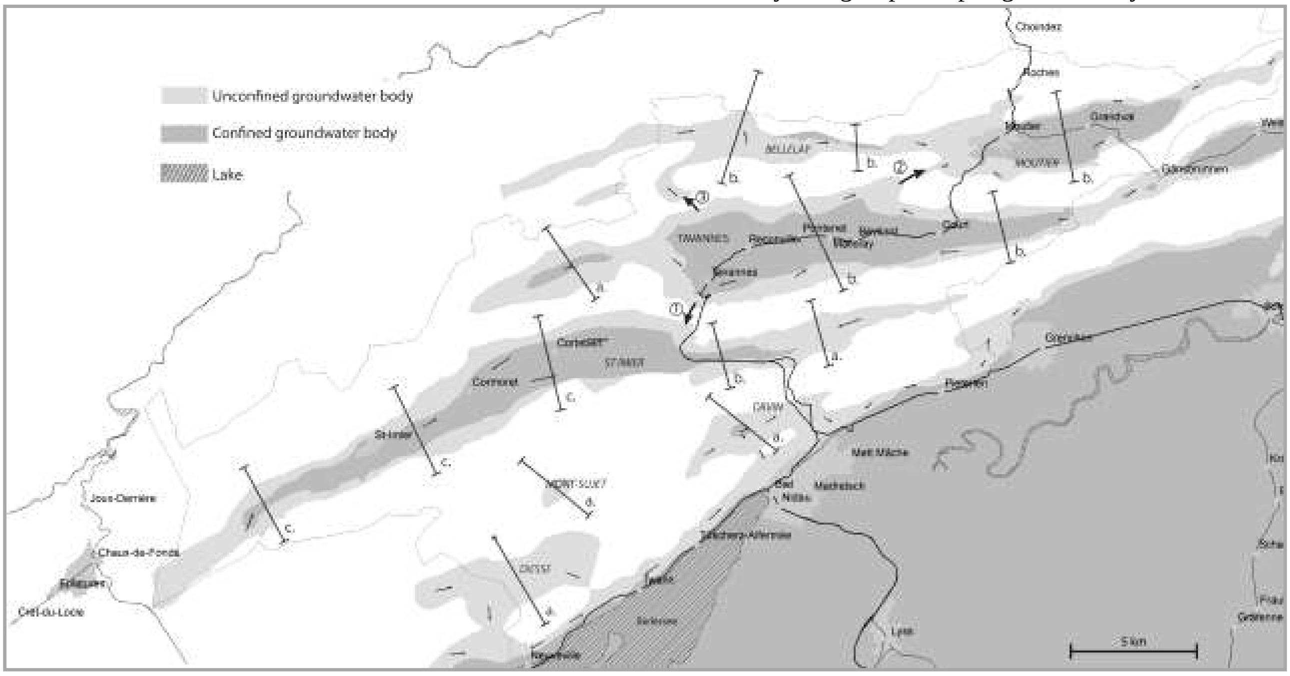


Fig 3: Location and extension of the main groundwater bodies identified in the Bernese Jura. Vertically three main profiles are distinguished (right): synform (a.) case of DIESSE, ORVIN, MONT-SUJET, west part of TAVANNES; simple faulted (b.) case of central TAVANNES, BELLELAY, MOUTIER; double faulted (c.) case of the west and central part of ST-IMIER. ①, ② and ③ represents overflow of the TAVANNES GWB over passes towards other GWB.

The application of the KARSYS approach allowed us to identify seven groundwater bodies in the Bernese Jura (without considering the one extending along the Jura foot). These are mapped on Figure 3. Three typical profiles are represented according to the structural geometry. The estimated water volume (reserve) strongly depends on the profile type. Table 3 summarizes characteristics of the seven groundwater bodies.

Flow lines show that MONT-SUJET and DIESSE GWB discharge toward Lake Biel while ST-IMIER and ORVIN GWB flow towards the Suze. The Northern BELLELAY and MOUTIER GWB discharge respectively towards the Sorne and the Birse rivers. Concerning the TAVANNES GWB, which is the upper one, flow arrows indicate overflow ① towards the ST-IMIER GWB over a threshold (or pass) in the Argovian marls at ~770 m a.s.l (back from the Birse spring) in the vicinity of the Pierre-Pertuis tunnel, Overflow ② leads water towards the MOUTIER GWB, over another pass in the Argovian marls under the village of Champoz at ~670 m a.s.l. Overflow ③ is a third threshold under the village of Le Fuet towards the Blanche-Fontaine GWB. The existence and elevation of this threshold is not confirmed and further investigations are suggested to understand hydrological mechanisms in this area. Therefore the TAVANNES GWB (the most elevated GWB) shows a multi-diffluent behavior in supplying both southern and northern valleys. These relations, except ③ have been confirmed by dye tracer tests (PFIRTER et al. 1989, MFR GÉOLOGIE-GÉOTECHNIQUE SA 2008). They bring new elements in the delineation of the Foule, Cuchatte-Tournedos and Blanches-Fontaines catchment areas, which are significantly enlarged, compared to previous studies which did suggest the ① and ② exchanges but did not predict the ③ one which may appear greatly significant for the groundwater management in the vicinity of Tavannes.

Conclusion

The application of the KARSYS approach to the entire Bernese Jura (540 km^2) documented and delineated 17 main karst systems draining the Malm aquifer, which are harvested by communities for supplying water. KARSYS made it possible to identify and delineate the extension of seven major groundwater bodies and precise their dis- charge outlets. The main underground flowpaths could be sketched for all systems, as well as interactions occurring between groundwater bodies. The TAVANNES GWB which is the central and most elevated GWB contributes to feed (i) towards the South the ST-IMIER GWB by overflowing over the Argovian marls threshold at the vicinity of the Birse spring (elevation ~770 m), (ii) towards the North-West to the MOUTIER GWB by overflowing the Argovian marls threshold under the town of Champoz and (iii) towards the North-East to the BELLELAY GWB by overflowing the Argovian marls threshold under the town of le Fuet. Further field investigations are encouraged to precise this third threshold and confirm this mechanism which may appear substantial to manage groundwater resources in the vicinity of Tavannes.

Results of this application to the Bernese Jura are available on the www.swisskarst.ch website.

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10.8. Appendix 8: Additional information on the limitations of the KARSYS approach

Scientific methods usually show three types of limitations: (i) method limitations, (ii) limitations in the application field(s) and (iii) limitations in the conditions of application. Limitations of KARSYS should be addressed in order to assess the validity range of the approach and the conditions for applicability. With the exception of the approach-independent limitations, approach-dependent limitations are of two types (Figure 10—5): those that are related to the concepts of the approach (principles, methods) and those related to the tools.

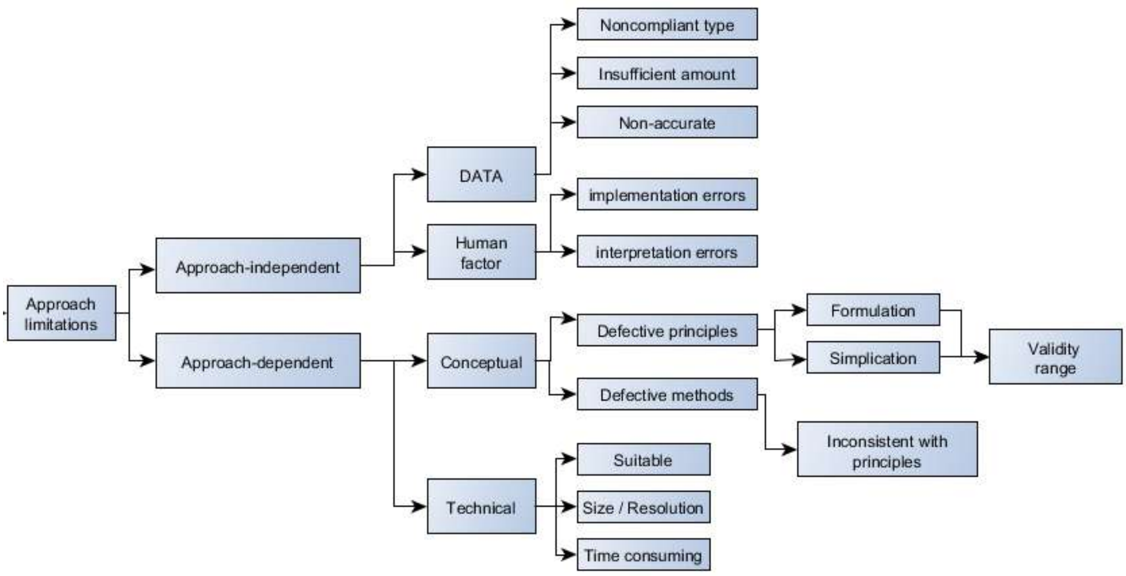

Figure 10—5. Limitations of the KARSYS approach are of two types; limitations that are specific to the approach (approach-dependent) and limitations which are inherent to a man-made work and based on quantitative and qualitative data (approach-independent limitations).

10.8.1.1. Approach-independent limitations

Approach-independent limitations are of general order. They mainly concern data and human factor. It is usually assumed that data and experience of the applicant are not limiting factors but whatever the approach; **poor data** and/or **man-induced errors** may greatly affect the reliability of the results.

Approaches are efficient and may be considered as pragmatic and applicable when (i) the required data are available and (ii) the applicant efforts (time and tasks) are conceivable whatever the environment. Approaches may be seen as non-pragmatic when (i) the required data are too large or impossible to assemble and (ii) the experimenters' efforts appear unconceivable (time consuming, abstraction or extreme degree of interpretation, etc.). Some approaches are more sensitive to such limitations as they require a considerable amount of data and/or a high degree of interpretation from the applicant. Data and human factor limitations for KARSYS are described in the following sections.

10.8.1.1.1. Data limitation

whatever the selected approach, all scientific approaches are based on a combination of data, hypotheses, experiments or models and observations (Gauch [2003]). Thus, type, amount and accuracy of the data are essential parameters that support the relevance of an approach. Any bias or gap in the data may increase the degree of uncertainty and may result in the approach failure.

Data that are used in KARSYS are of two types: **direct** and **indirect**, see §. 5.2.5.2. As the reliability of the direct data is higher, the reliability of the KARSYS models is therefore proportional on the ratio between direct and indirect data. As this ratio significantly decreases with depth, the reliability of the KARSYS also decreases with depth.

Globally, experiences of application demonstrated that dense and relevant geological data are the main limitations for building the geological model in step 2. These concern (i) information on the properties of the different lithologies on site making difficult to define the hydrostratigraphic model and (ii) spatial information on geological contacts, tectonic structures, etc. making difficult to build a consistent geological model in 3D! Hydrological data are usually not a limitation for applying KARSYS as they may be directly obtained by springs, caves, boreholes or indirectly inferred form the surface geomorphology.

Beside the fact that data may be sometimes inexistent on a site, usual limitations for the data are listed in the following Table 10—5.

Type of data		Usual data limitations
Geological data:	Maps	Karstification strongly depends on lithology; however, most of the existing maps and cross-sections depict stratigraphic units rather than lithological formations. In addition, even if at some locations outcrops are visible and clearly pointed out; contours on a map already reflect a geological interpretation…
	Cross-sections	As for the maps, cross-sections display an interpretation of the geological structures with depth for a given transect. Most cross-sections are perpendicular to tectonic fronts leading to higher resolution of geological models in this direction compared to the resolution in parallel to the main geological structures (i.e. anticline, etc.).
	Borehole logs	Borehole logs bring direct but punctual observations on a place. Accuracy of the observations may be questionable depending on (i) the nature of the excavated material (cores or cuttings) and (ii) the experience of the geologist who surveyed the drill.
Hydrological data:	Springs inventories	Existing database of springs in karst region does often not meet the minimal description requirements for being used in the approach. For being processed, spring descriptions must entail at least: - An indication on the nature of the spring (considered as karst or non-karst spring or porous / fissural spring that is influenced by the karst) - An indication of perennial or temporary regime. Temporary springs are often inexistent in most inventories or assimilated to caves or estavelles. It should be also mentioned that perennial springs may be unknown when emerging in a lake or in the bottom of a river; - A value (or even an assessment) of min., max. and average discharge regime. Experience shows that usually, estimated discharge rates of karst springs are far from being correct. Temporary springs are often neglected as rarely active and discharge rate of perennial springs is often restricted to the taped part of the water flowing out of the spring. Ideally, karst spring descriptions should also entail: (i) an indication of the supposed connections between the springs (main springs and overflow ones, etc. and (ii) a discharge time series
	Dye-tracer tests	Dye tracing tests data are used for validating the KARSYS hydrogeological 3D model. In karst regions it often appears that tracer-tests inventories are incomplete or deficient and even non-accurate. Most of the time, only positive connections are reported while negative connections which are of equal importance in terms of information are usually neglected. Because of possible diffluences and changes in the catchment boundaries depending on hydrological conditions, identified connections by dye-tracer tests may change. Meteorological conditions and hydrological regimes during the test have to be documented. Unfortunately, this is often not the case and results usually appear as a set of arrows on maps without more indications… Then, in spite of their great interest, such data have to be considered with a maximal precaution.
	Water table indications	Indications on water tables recorded in boreholes or in cave conduits have to be carefully considered before being assigned to the head of the groundwater in the phreatic karst conduits. Indeed, the low-flow connection of the borehole or the cave conduits with the phreatic conduit network has to be clearly demonstrated before being integrated in the process (see §. 5.2.1.3 and §. 6.3.2.2).
Speleological data:	Cave inventories	Existing database of caves in karst region usually entail the location of the caves entrance but do barely inform on the geological units (stratigraphy or lithology) in which the cave develops.
	3D cave surveys	3D cave surveys may bring input data for the establishment of the 3D geological or hydrogeological model when the caves have been described from a geological or hydrogeological point of view. If not, cave surveys cannot be considered as a data but rather as a validation mean for the established 3D models.

*Table 10—5. Main **data limitations** occurring when applying KARSYS*

The data limitation may be seen as the most important limitation when applying KARSYS.

10.8.1.1.2. Human factor limitation

Human factors encompass all the man-induced errors or misinterpretations that may occur when applying the approach. These are not dependent on the considered approach but rather dependent on the applicant (knowledge, experience, rigor in method, etc.). Such errors may occur during the implementation of the models or later when interpreting the outputs. These biases are common in all scientific methods whatever the hypothesis of the theory. Pre-existing beliefs or preference for one outcome or another may considerably alter the outputs interpretation (Bright Wilson [1952]).

This observation indicates that the respective significance of the data-limitation and human factor-limitation is inversely correlated. The more reliable data do exist, the less applicants may diverge in their interpretation and vice et versa. At the opposite, the more data diverge from a consensual interpretation - especially the indirect data - the more man-induced errors may occur.

Regarding KARSYS, as the approach is based on an interpreted 3D geological model; the **personal degree of interpretation** on the geological style may notably affect the resulting model. Besides the interpretative bias provided by the selected tools for geological modeling (= technical limitations), and especially when relevant data are missing, personal interpretation from the experimenters may diverge, leading to very different geological or hydrogeological 3D models…

Consequently, **experience** of the applicant and **knowledge** about the site are prerequisite for applying KARSYS.

10.8.1.2. Approach-dependent limitations

Approach-dependent limitations are of two types: **conceptual** and **technical**. Conceptual limitations are inherent to the hypotheses and the principles of the approach and to the workflow while technical limitations are related to the used tools.

10.8.1.2.1. Conceptual limitations

Conceptual limitations are fixed by two criteria: **principles of the approach** and the **application procedures**.

10.8.1.2.1.1 Principles-inherent limitations

As **principles** always results from observation and interpretation of the real-world mechanisms, they may encounter two limits:

(i) **Formulation:** principles may be poorly formulated. In that case, they could not intend to reproduce real-world mechanisms. Regarding KARSYS, principles have been formally described as well as the terms which have been used for the steps description.

(ii) **Simplification:** principles always entail a simplification compared to the real-world mechanisms for the approach to be processed. Depending on the simplification degree, the approach may be more or less generalized. Too simplistic principles may be widely generalized but they cannot provide relevant results as provided by more sophisticated principles (in that case the relevance of the approach may also be questionable). On the opposite, more sophisticated principles may bring relevant information on the mechanisms but they cannot be widely generalized.

Principles of an approach (formulation and simplification) are valid for an application field. Regarding KARSYS, conceptual limitations on the principles are listed Table 10—6.

Principles Description	Limitations
Any exposed soluble rock has to be considered as karstified by meteoric water (epigenic karst). Non-carbonate rocks are considered as impervious.	In reality, the degree between pervious and impervious is not binary; most of the time the transition between these two poles is progressive even if differences are of several orders of magnitude. In some cases, karst conduits may also develop in formations which have been a priori considered as impervious (see in Filipponi et al. [2012], Appendix IV). Observations in the frame of the Swisskarst project show few cases where karst conduits do develop in rocks which were a priori considered as impervious (ex. Goriuda springs in Slovenia, Turk et al. [2014], or Kreuzloch in the Swiss region of Hoch-Ybrig (SZ), etc.).
The organization of the karst conduits is equilibrated with the prevailing base level conditions	Permanent base springs are expected to emerge at the lowest elevation point of the aquifer outcrops. It appears in the literature that some basal springs emerge far above from the lowest aquifer outcrops. This may happen if the regional hydraulic base level recently dropped due to sudden erosion. The approach does not consider the evolutive karstification process. This is a conceptual limit which may be solved by integrating the geomorphological history of the site within the process. However this implies the consideration of more data, which are sometimes difficult to obtain (data limitation). This aspect is however included in the KarstALEA method (Filipponi et al. [2012]). Drainage modalities are not solely a consequence of the actual conditions. They may differ from the expected behavior due to residual structures (conduits) that formed during a former stage. Conceptually it is difficult to assess what is the effect of these residual structures on the actual hydrological functioning. They may offer a preferential flow-path which prevails on the current hydraulic conditions or be almost "ignored" by more recent flowpaths. In case of coastal karst aquifers or when the lowest parts of the aquifer lies under a lake, the main springs may emerge below the free surface of the sea (or the lake) which symbolizes here the hydrological base level.
Due to high hydraulic conductivity, the hydraulic gradient of the supposed phreatic zone upstream from the main karst spring does not exceed 0.1% under low-flow conditions	This is a simplification but not a limitation (see §. 2.2.2.2). If data do contradict the principles on a site, higher hydraulic gradients could be considered in the model.
The karst aquifer volume located below the elevation of the spring is considered as full of water. In the case of under-flowing springs (sub-lakeside or submarine springs), the top of the phreatic zone lies at the level of the free surface water. Closed depressions in the aquifer lower boundary are considered as full of water up to the elevation of the lowest threshold	There is a priori no limitation to this principle.
Above the top of the phreatic zone, the aquifer is considered as unsaturated.	Small perched groundwater bodies do exist in this zone. If no fissures or cracks are present, the seepage water may store in these conduits for a long time, creating a small groundwater body. Extension of these passages (and at least of the groundwater bodies) does not exceed few dozens of meters and do not have implication on the model.
The hydraulic gradient in the unsaturated zone is maximal. Vadose flows are mainly vertical (at least with an inclination up to 45°). In shallow karst - or when the vertical vadose flows reaches the top of the impervious formations before	In reality, flows in the unsaturated zone may diverge from the verticality and may develop along oblique or even sub-horizontal features for several dozens or even hundreds of meters. Local features (faults or other discontinuities) may also divert the basement-controlled flow from the route of maximal hydraulic gradient for several dozens of meters. Depending on the size of the flow-system, such divergences for some dozen of meters are not relevant.

entering in the phreatic zone – water flows along the dip of the formations. Hydraulic gradients are fixed by the topography of the aquifer basement	
In the phreatic zone, the hydraulic gradient is oriented towards the main outlet (i.e. the permanent spring) of the system. Phreatic conduits develop close to the top of the phreatic zone and organize according to the “least hydraulic resistance” route towards the outlets	This is a simplification as it still remains difficult to assess the depth of the karstification in the phreatic zone. It may be seen as a limitation as conduits may develop and be “active” several dozen, even hundreds of meters below the top of the saturated zone. This may be due to older and lower stage of karstification (especially in the basins affected by the Messinian crisis, cf. Audra et al. [2004]) but it may also result from the current karstification processes. In its actual form, KARSYS cannot describe hypogenic karst flow-systems
For high-flows conditions, the hydraulic gradient usually rises within the systems. It may reach several % of inclination upstream of the main perennial spring. This gradient is usually assumed as a monocline plan crossing the overflow springs which are seen as an indicator of the rise of the hydraulic head within the system.	This simplification may be seen as a limitation as the shape of the real gradient is probably more heterogeneous. When no overflow springs do exist, no systematic criteria have been defined to model the shape of the high-flow hydraulic gradient. Only hydraulic-head measurements from boreholes or caves may be used as indications for modelling high-flow hydraulic gradients.

Table 10—6. KARSYS conceptual limitations on the principles

10.8.1.2.1.2 Procedures-inherent limitations

Conceptual limitations may be extended to the workflow which is defined as the succession / combination of **procedures**. Ideally, procedures have to be consistent with the defined principles. Nevertheless it may appear that established procedures fail to respect principles from the conceptual point of view. Regarding KARSYS, limitations on the procedures are described in Table 10—7.

Application procedures	Limitations
1. Data selection and formalization	The density and the accuracy of the geological and hydrological data is the main limitation in this process.
2. Building the 3D geological model	The implementation time is the main limitation. The construction of the 3D geological model represents nearly 80% of the time required for a KARSYS project…
3. Building the 3D aquifer model	No appearing limitations in this process.
4. Building the 3D model of the karst flow-system	No systematic procedure for the delineation of two or more underground flow-systems flowing through the same saturated zone (Figure 10—6).

Table 10—7. KARSYS conceptual limitations on the procedures when applying KARSYS

As mentioned in the table, one of the most limitations concerns the delineation of two or more underground flow-systems emerging from a common saturated zone. In the Figure 10—6, the limit between the flow-systems A. and B. in the phreatic zone is strictly hydraulic. It depends on the respective elevation of A. and B. and on the assumed hydraulic gradient in the phreatic zone for-lows. This limit is also expected to move depending on the hydrological conditions. Without further indications on the fluctuations of the hydraulic gradient in the phreatic zone, the KARSYS procedures may fail in providing the phreatic boundary between A. and B. However, assumptions on the hydraulic gradient may provide indications on where boundaries are more expected to develop.

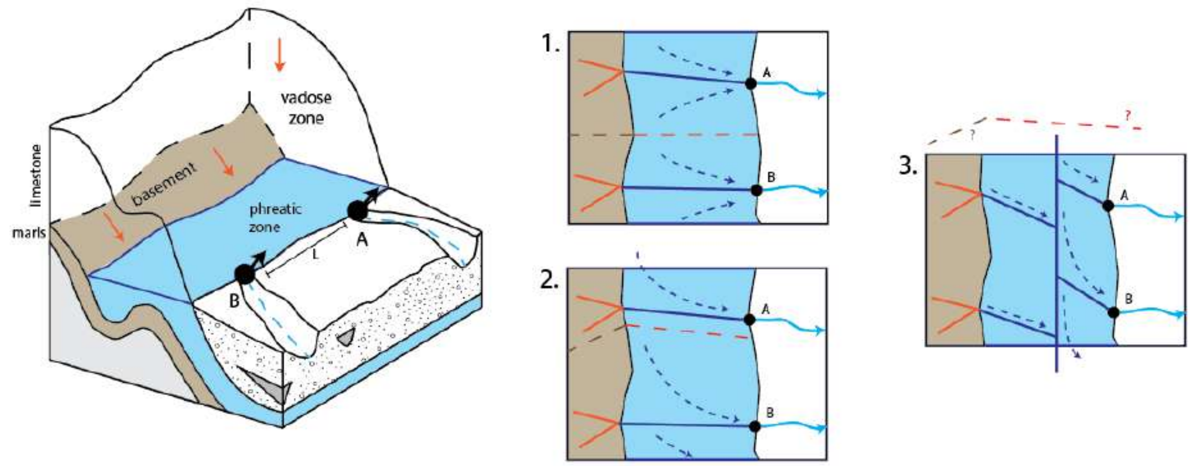

Figure 10—6. The delineation of the flow-systems boundaries in the phreatic zone is difficult to assess in case where the phreatic zone is drained by two or more permanent springs. Such boundaries are controlled by the hydraulic and they are expected to move depending on flow conditions. However, depending on the elevation of springs A. and B. and on the supposed hydraulic gradient in the phreatic zone, it is possible to approximate the location of the boundaries between the two flow-systems even if no further indications are provided. ***1.*** *If A. and B. are at the same elevation, we suppose the phreatic boundary to develop at equal distance from the two springs;* ***2.*** *If elevation A. > elevation B. and if ΔH/L is much lower than the assumed gradient, the phreatic boundary will move upstream, close to the supposed conduit toward A.* ***3.*** *If elevation A. > elevation B. and if ΔH/L is close (or even bigger) than the assumed gradient, the phreatic boundary will move upstream of the phreatic conduit A. In this case, A. and B. are supposed to form an unique flow system as part of the upstream flow may reach B.*

This limitation should be addressed manually case by case. Once the boundaries of the flow systems have been fixed, conduits could be generated according to the conduit generator module (see §. 6.1).

10.8.1.2.2. Technical limitations

10.8.1.2.2.1 Definition

The workflow implies the selection and the use of various tools. The selection of tools depends on a set of criteria. The first criteria refer to the compatibility with the approach but some others are fixed by **external constraints**: price, complexity of implementation, material resources, calculation time, etc. Tools may then present technical limitations which may alter the accuracy of the results. Likewise, an approach is a compromise between **complexity** when implementing principles and applicability; selection of tools is a compromise between **functionality** and external constraints. As the KARSYS approach requires the use of a various set of tools (software), it is subjected to **technical limitations**.

10.8.1.2.2.2 Technical limitations of the KARSYS approach

Technical limitations of the KARSYS are discussed in Table 10—8. KARSYS requires the use of different and complex software (i.e. tools). The combination of these software respects the order of the approach workflow: data (Geographic Information System) → geological 3D model (3D geological modeler) → hydrogeological 3D model (3D modeler) → extension (hydrological and hydraulic simulation models, etc.) → back to GIS.

Processes and software	Limitations
General processes: - Data and results transfer from one software to another	- Loss of information (data form, characteristics, etc.) - Duplication of data - No data traceability - Time consuming
Database	Although they may be displayed, common GIS are not able to properly store and perform calculations on 3D forms. The most usual GIS packages (ArcGIS, Grass, QGIS) are only able to perform calculations on rasters where a single Z is attributed to a couple of XY. Objects entailing multiple points of same XY but various Z cannot be processed. This presents a real limitation as overturned geological structures (folded anticline or thrusts) cannot be displayed in the same object.
Geological modeller	Usual software for 3D geological modelling imply to delineate geological formations with a formal and straightforward boundary. This may be seen as a limitation progressive facies. Resolution of the modelers (especially along the Z axis) requires additional simplification when implementing the geological units. Depending on the resolution, models may reach a limitation in size and complexity. Sometimes, several independent models have to be built and merged afterward. The interpolation mode (which is specific to each modeler) also brings additional interpretations or artefacts that are difficult for the operator to modify… Depending on the resolution of the software, thin hydrostratigraphic layers cannot be considered during the construction process. They often have to be integrated afterward as discrete surfaces instead of a volume. Implementation of discontinuities into most of the 3D geological modelers is still restricted to major faults as too much faults may lead to computing dysfunctions. Faults interpolation in most 3D geological modelers is extremely hard to control as well as their horizontal and vertical extension and their respective movement. Furthermore, consideration of numerous discontinuities which favors the karstification may notably alter the visibility of the geometry.
3D modelers	Even if they are quite polyvalent, 3D modelers are often purely geometric software and do not support interactions with a GIS database. KARSYS processes are then processed apart from the main GIS database and reimported afterward.

Table 10—8. Technical limitations of the KARSYS approach in its actual form

Interface and transfer modalities between the different software remain tricky and despite automatic routines, which have been developed, dealing with the different software remains time-consuming and exposed to numerous errors. Besides, software are complex of use, leading to usual bugs or crashes what may be discouraging. One of the main technical limits may be that as the approach is systematic, pragmatic and integrated, it should be performed within a single dedicated tool instead of being fragmented in various software packages as it is actually the case.

10.9. Appendix 9: Malard et al. 2016 - Praxisorientierter Ansatz zur kartographischen Darstellung vonKarst-Grundwasserressourcen

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Praxisorientierter Ansatz zur kartographischen Darstellung von Karst-Grundwasserressourcen

Erfahrungen aus dem SWISSKARST-Projekt

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Zusammenfassung Trotz ihrer großen Bedeutung als Wasserressource steht für Karst-Grundwasserleiter auch in der Schweiz eine systematische Abgrenzung und quantitative Beschreibung noch aus. Das Fehlen eines integralen Ansatzes zur Charakterisierung von Karstsystemen mag dazu beigetragen haben. Im Rahmen eines Projektes zur Dokumentation der Karst-Grundwasserleiter in der Schweiz (SWISSKARST) war mit der KARSYS-Methode ein pragmatischer Ansatz zur hydraulischen Charakterisierung einzelner Grundwasserleiter und Karstsysteme entwickelt worden. Eine Weiterentwicklung dieses Ansatzes beinhaltet ein Verfahren zur kartographischen 2D-Darstellung des erstellten 3D-Modellkonzepts, welche sowohl auf wissenschaftliche als auch auf Fragestellungen der Praxis ausgerichtet ist. Dazu werden zunächst mehrere thematische Karten mit den wichtigsten Eigenschaften der Karst-Grundwassersysteme erstellt, welche dann zu einer synthetisierten Karte zusammengefasst werden.

Schlüsselwörter Karst-Grundwasserleiter · Karstsystem · Hydrogeologische Karte · Schweiz

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A practical approach for mapping karst groundwater resources

Experience from the SWISSKARST project

Abstract In spite of their abundant water resources, in Switzerland as well as in other countries, the location and extent of karst aquifers have not yet been systematically studied and documented – mainly due to the lack of systematic and dedicated approaches for their characterization. In the framework of a project aiming at documenting the karst aquifers in Switzerland (SWISSKARST Project) the pragmatic KARSYS approach has been developed to systematically assess the main characteristics of karst aquifers and karst systems. One part of this project deals with the development of a practical method for mapping 2D hydrogeological karst systems, which is designed to address both scientific and applied issues. A series of maps based on the approach is proposed to describe the main characteristics of karst groundwater systems resulting in a synthesized map which suitably combines all relevant information.

Keywords Karst aquifer · Karst system · Hydrogeological map · Switzerland

Einführung

Problemstellung und Ziele

Etwa 20 % der Fläche der Schweiz wird durch Karstlandschaften gebildet. Dennoch entfallen mit ca. 120 km^3 bis zu 80 % des gesamten Grundwasservolumens des Landes auf Karst-Grundwasserleiter (Sinreich et al. 2012). Sowohl Klimaänderung als auch die fortschreitende Nutzung des Untergrunds haben Einfluss auf die Verfügbarkeit des Grundwassers. Gleichzeitig steigt der Wasserbedarf für Trinkwasser sowie Brauchwasser für Industrie und landwirtschaftliche Bewässerung weiter an (BAFU 2012). In diesem Kontext wurde in der Schweiz das Nationale Forschungsprojekt zur nachhaltigen Wassernutzung (NFP 61; Forschungsphase von Januar 2010 bis Ende 2013; Schweizerischer Nationalfonds (2013)) gestartet. Das SWISSKART-Projekt, das in einigen Jahren zu einer umfassenden Charakterisierung aller wichtigen Karst-Grundwasserleiter der Schweiz vervollständigt werden soll, ist Teil dieses Programms (Details unter www.swisskarst.ch; SISKA 2013). Es basiert auf der Umsetzung eines pragmatischen Ansatzes (KARSYS), welcher ebenfalls im Rahmen dieses Projektes entwickelt wurde (Jeannin et al. 2013).

Die allgemeinen Eigenschaften von Karst-Grundwasserleitern sind in der gängigen Literatur ausführlich beschrieben (z. B. Ford & Williams 2007, Bakalowicz 2005, Goldscheider & Drew 2007). Zudem sind für viele Systeme Grundlagenkenntnisse vorhanden, jedoch fehlt es häufig an der Umsetzung in brauchbare Arbeitsdokumente für die Wasserbewirtschaftung. Eine fundamentale Fragestellung betrifft die Größe und Abgrenzung von Einzugsgebieten der jeweiligen Karstquellen. Typisch für Karst-Grundwasserleiter sind hier sich überschneidende Einzugsgebiete (Diffluenzbereich) sowie sich mit den hydrologischen Bedingungen ändernde Einzugsgebietsgrenzen, wozu es zahlreiche konkrete Fallbeispiele gibt (z. B. Bonacci 1988, Ravbar et al. 2011). Nur selten werden allerdings die Gründe für diese Phänomene diskutiert und entsprechend fehlt es bisher auch an einem schlüssigen Konzept für die Ausscheidung bzw. Abgrenzung von Einzugsgebieten im Karst. Angaben zu Tiefe und Mächtigkeit von Karst-Grundwasservorkommen sowie Schwankungen von Grundwasserstand und Ausdehnung fehlen häufig völlig.

So auch in der Schweiz, wo eine Lokalisierung und Quantifizierung der Karstsysteme – trotz deren Bedeutung – bis vor wenigen Jahren nicht systematisch angegangen wurden. Zu Projektbeginn verfügte man über einen groben und allgemeinen Überblick der Grundwasservorkommen des Landes sowie über hydrogeologische Karten, welche die Eigenschaften der Karst-Grundwasserleiter partiell beschreiben. Für eine umfassende Grundwasserbewirtschaftung innerhalb eines Karstgebietes sind diese Grundlagen allerdings unzureichend, da sie keine klare Aussage über die Bedeutung und Ausdehnung der Grundwasserressourcen, über die Abgrenzung der Neubildungsbereiche und Einzugsgebiete oder über die Grundwasserfließverhältnisse enthalten. Zum Beispiel kann diesen Karten nicht entnommen werden, wo mit einer erhöhten Wahrscheinlichkeit zu rechnen ist, mit einer Bohrung auf Karstgrundwasser zu stoßen.

Entsprechend war es ein Ziel des SWISSKARST-Projektes, den Behörden und betroffenen Interessengruppen eine „pragmatische Dokumentation“ der Karst-Grundwassersysteme der Schweiz zur Verfügung zu stellen. Eine solche Dokumentation soll die Versorgung mit Trink- und Brauchwasser erleichtern, die Bedingungen zur Gewinnung von geothermischer Energie (Erdwärmesonden oder tiefe Geothermie) sowie die Möglichkeiten für den Betrieb von Wasserkraftwerken (Ableitung oder Staudämme) abklären oder auch die Hochwasserproblematik beleuchten. Darüber hinaus kann jede Art von Bauprojekt im Untergrund von Karstgebieten von einer solchen Dokumentation profitieren, sowohl für den Baufortschritt an sich, als auch im Rahmen einer Umweltverträglichkeitsprüfung.

Wie mithilfe des KARSYS-Ansatzes Informationen zur Karsthydrogeologie in einem 3D-Modell zusammengestellt werden können, ist bereits im Detail beschrieben (Jeannin et al. 2013). Ein solches Modell ist zwar hilfreich zum prinzipiellen Verständnis eines Karst-Grundwassersystem, jedoch sind für die Praxis Darstellungen in 2D (Karten und Profile) meist geeigneter. Die Ergebnisse einer Karstgebietscharakterisierung sollten also üblicherweise in Form von hydrogeologischen Karten präsentiert werden können.

Der vorliegende Artikel zeigt, welche thematischen Karten mit den wichtigsten Eigenschaften des Grundwasserleiters aus den mit KARSYS gewonnenen Informationen abgeleitet bzw. aus den 3D-Modellen erzeugt werden können. Zudem wird eine synthetisierte Karte der Karsthydrogeologie vorgeschlagen, und diskutiert, wie bestehendes Kartenmaterial um diese Informationen ergänzt werden kann. Die resultierende Dokumentation ist praxisorientiert und soll zu einer nachhaltigen Wassernutzung der Karstsysteme und ihrer Grundwasserressourcen beitragen.

Bestehende Dokumentation und weiterführender Bedarf

Für die Schweiz liegen hydrogeologische Karten in unterschiedlichen Maßstäben vor (Schürch et al. 2007). So wurde seit den 1970er Jahren eine Reihe von hydrogeologischen Karten im Maßstab 1:100.000 veröffentlicht, welche derzeit etwa die Hälfte der Landesfläche abdecken. Daneben sind hydrogeologische Übersichtskarten der Schweiz im Maßstab 1:500.000 publiziert, welche die *Grundwasservorkommen* des Landes (Bitterli et al. 2004) sowie die *Vulnerabilität der Grundwasservorkommen* abbilden (Philipp et al. 2007).

Hinsichtlich Karstgrundwasser beinhalten die 1:500.000-Karten folgende Basisinformationen (siehe auch Schweizerische Eidgenossenschaft 2014):

- Verbreitung der ausstreichenden verkarstungsfähigen Gesteine
- Lage wichtiger Karstquellen (unsystematisch und ohne dezidierte Schüttungsangaben)
- Bedeutende Versickerungsstellen
- Gewisse Fließverbindungen, die mit Tracerversuchen bestimmt wurden
- Becken und Blindtäler ab etwa 1 km^2
- Abschätzung der Vulnerabilität

Die Karten im Maßstab 1:100.000 (z. B. Pasquier et al. 2006), welche teilweise auch im GIS-Format vorliegen, liefern zusätzlich folgende Informationen zu Grundwasservorkommen im Karst:

- Halbquantitative Angaben zur mittleren Schüttung bedeutender Quellen
- Genauere Angaben zur Verbreitung der verkarstungsfähigen Gesteine
- Genauere Angaben über Verbindungen, die mit Tracerversuchen bestimmt wurden
- Lage ausgewählter Höhlensysteme
- Teilweise Angaben zur Höhe des Grundwasserspiegels und zur Ausdehnung des Grundwasservorkommens
- Angaben zur Lage von Dolinen und Schwinden
- Ausdehnung von Becken ohne oberirdischen Abfluss größer als 1 km^2
- Grobe Angabe zur Bedeckung des Felses durch Deckschichten

Diese großmaßstäblichen Karten stellen vor allem den oberflächennahen Teils des Untergrundes (10–20 m) mit dessen hydrogeologischen Eigenschaften dar. Für Karst-Grundwasserleiter fehlt in diesen Dokumenten zumeist die Gesamtausdehnung, die Mächtigkeit und Tiefe der gesättigten Zone (also das eigentliche Grundwasservorkommen), sowie die Abgrenzung von Fließsystemen. Außerdem sind die Angaben zu Karsterscheinungen und unterirdischen Strukturen, inklusive der Quellaustritte, nicht systematisch und damit teilweise unvollständig erhoben.

Neben diesen Karten, die unter Federführung des Bundes erstellt werden, existieren detailliertere Kartenwerke bei den Kantonen, die aber ebenfalls keinen vollständigen Überblick der Karstwasservorkommen erlauben. Dort sind vor allem die Quellen und Grundwasserschutzzonen verzeichnet. Auch sind sie meist nicht karstspezifisch, mit Ausnahme der Karte von Kiraly (1973), der vermutlich ersten Karte, welche eine tatsächliche Ausdehnung von Karst-Grundwasserleitern – einschließlich der Karsteinzugsgebiete – darstellt (http://sitn.ne.ch, Thema „Hydrogeologie"; République et canton de Neuchâtel 2014). Sie diente als Ausgangspunkt für die Entwicklung des KARSYS-Ansatzes.

Methode: Kurzdarstellung des KARSYS-Ansatzes

Die unterirdischen Karstfließwege werden vor allem von der Geometrie der verkarstungsfähigen Formation sowie von der Lage des Einzugsgebiets und der Entwässerungspunkte (Quellen) kontrolliert. Der darauf aufbauende KARSYS-Ansatz wird hier noch einmal in seinen Grundzügen vorgestellt; Details können den Originalpublikationen (Jeannin et al. 2013 und Malard et al. 2012) entnommen werden.

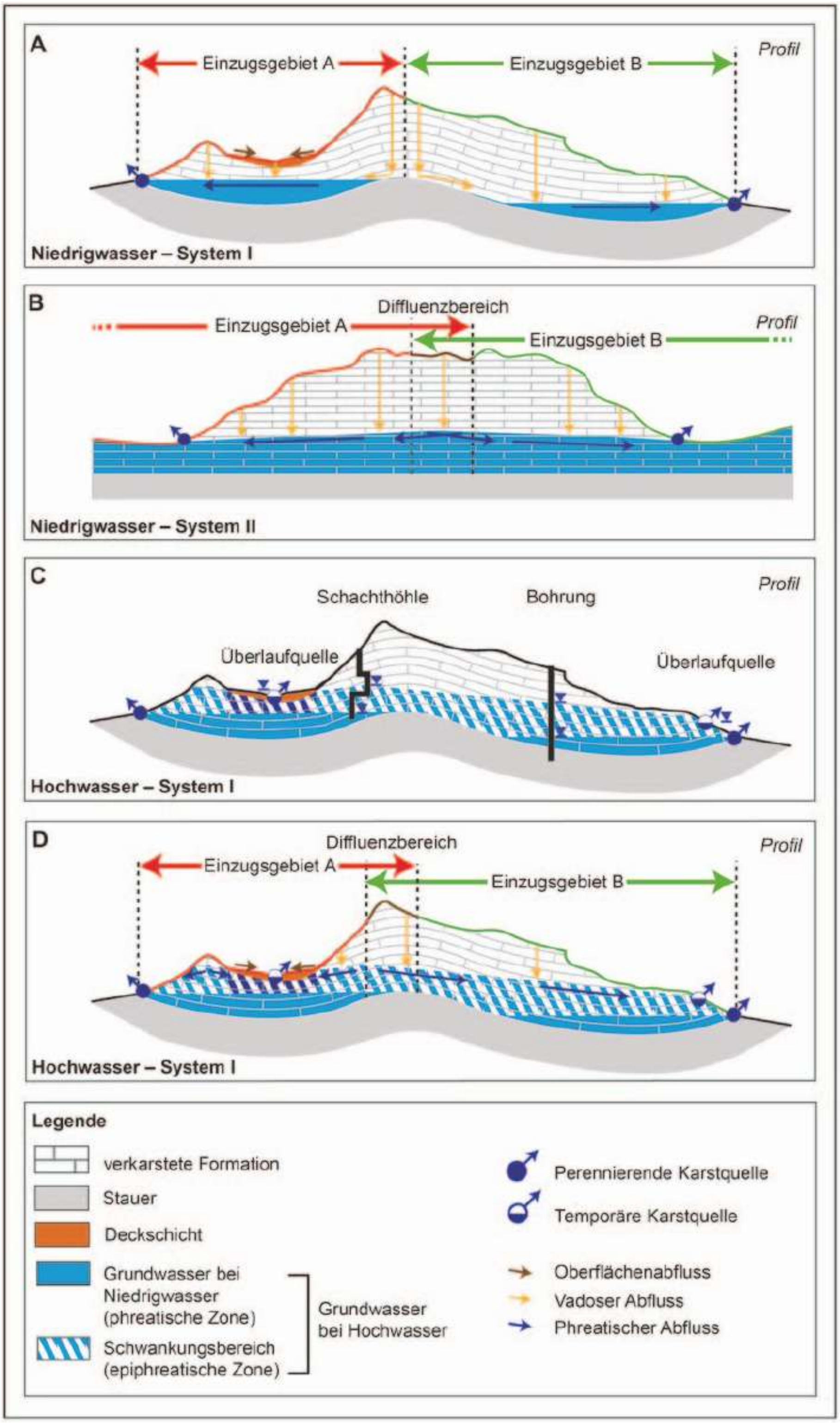
In einer ersten Phase müssen die verkarstungsfähigen (durchlässigen) und nicht verkarstungsfähigen Einheiten identifiziert werden. Bestehende geologische Informationen zur Geometrie dieser Schichten werden dabei in einem 3D-Modell des Karstgebietes zusammengeführt.

Diesem Modell werden dann alle bestehenden hydrologischen Informationen hinzugefügt. Es handelt sich vor allem um Quellen (mit genauer Höhenangabe) sowie sämtliche Informationen zu Grundwasserständen (z. B. aus Höhlen oder Bohrungen). Versickerungsstellen (Schwinden) sind weitere wichtige Elemente. Angaben zur Schüttungsrate von Quellen oder an Schwinden sind elementar. Stehen keine Messungen zur Verfügung, können mittels einer Abschätzung die schüttungsstärksten Objekte identifiziert und halbquantitativ erfasst werden. Sobald diese im geologischen Modell eingegeben sind, kann vereinfacht den folgenden Prinzipien entsprochen werden, um den Karstwasserfluss zu beschreiben:

1. Fließen durch unverkarstete Einheiten (Stauer) wird als vernachlässigbar gering angenommen. Ausnahmen werden in Betracht gezogen, z. B. im Falle von Mergellagen mit weniger als 30 m Mächtigkeit, oder wenn bedeutende Störungsflächen diese Stauerschichten durchziehen.
2. Unterhalb des Niveaus der Basisquelle kann das gesamte Volumen der verkarsteten Formation als wassergesättigt betrachtet werden.
3. Bei Niedrigwasser ist der hydraulische Gradient (im Karströhrensystem) bergwärts der perennierenden Quelle sehr gering (oft < 1 ‰). In der Praxis wird der Gradient Null gesetzt (Standardwert) oder durch direkte Messungen bestimmt.
4. In der ungesättigten Zone sickert das Wasser bis zum Erreichen des Grundwasserspiegels in vertikaler Richtung (bzw. bis maximal 45°).
5. Trifft versickerndes Wasser bereits in der ungesättigten Zone auf den Stauer, so fließt es an der Basis der verkarsteten Formation entlang des Schichtfallens der nicht-verkarstungsfähigen Fläche weiter (= vadoser Abfluss).
6. In der gesättigten Zone fließt das Wasser (= phreatischer Abfluss) entlang der kürzesten hydraulischen Verbindung in Richtung der Quelle(n). Dieser Fließweg kann vertikale Komponenten von mehreren Hundertmetern enthalten.
7. Bei Hochwasser können die Grundwasserstände im Karst-Grundwasserleiter um einige Meter bis zu hunderten Metern ansteigen.

Abbildung 1 fasst diese Prinzipien zusammen. In Bereichen, in denen die Basis des Grundwasserleiters höher als die Karstquellen liegt, wirkt sie bei Niedrigwasser (NW) als Abflussfläche. Die Ausscheidung der Einzugsgebiete geschieht dann ähnlich derer für Oberflächengewässer, allerdings entlang

Abb. 1 Querschnitt durch schematisierte Karstsysteme mit Darstellung der Fließwege und Ausscheidung der Systemgrenzen. Je nach Systemtyp können bereits bei Niedrigwasser Diffluenzbereiche vorliegen (System II) bzw. bei Hochwasser entstehen (System I). Hochwasserverhältnisse und der einhergehende Anstieg des Grundwassers im Karstmassiv können zudem zu einer Verschiebung der Systemgrenzen führen (System I)



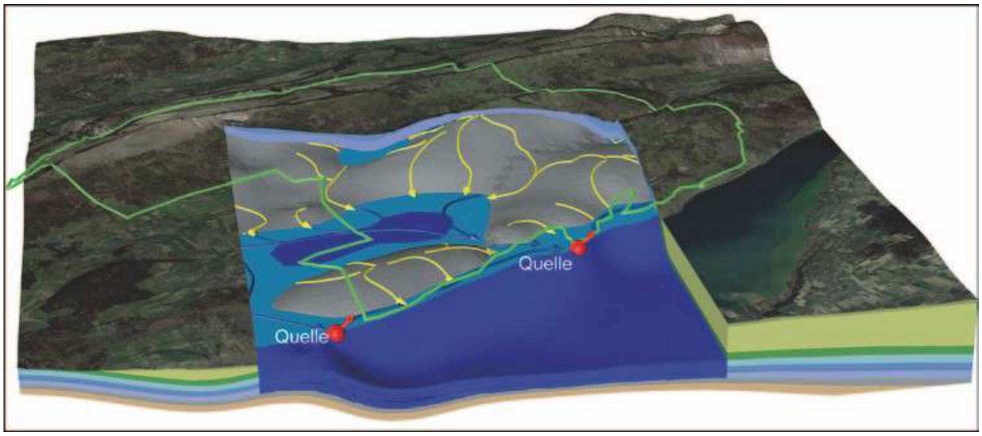


Abb. 2 Konzeptuelles 3D-Modell eines Karstsystems aus der Anwendung des KARSYS-Ansatzes. Mithilfe aller verfügbaren Daten wird zunächst ein geologisches 3D-Modell konstruiert, welches dann um hydrogeologische Objekte und unter Annahme hydraulischer Prinzipien erweitert wird. Damit können die Hauptcharakteristika des Karstsystems visualisiert werden, was das Verständnis für dessen Funktionsweise entscheidend erhöht

der Basis des Grundwasserleiters (Abb. 1A). In Fällen, in denen die Basis des Grundwasserleiters dagegen tiefer als die Karstquellen liegt, ist das Volumen im Grundwasserleiter unterhalb der Quelle(n) wassergesättigt. Die Ausscheidung der entsprechenden Karstwassersysteme ist dann von den hydraulischen Bedingungen innerhalb der gesättigten Zone abhängig (Abb. 1B). An bestimmten Stellen kann das Wasser auch in zwei oder mehrere Richtungen fließen (Diffluenzbereich). Im Allgemeinen ist die Verteilung der hydraulischen Potenziale wenig bekannt. Bei Hochwasser (HW) können die Grundwasserdruckhöhen im Karströhrennetz von verschiedenen Indikatoren abgeleitet werden: Überlaufquellen, die aktiv werden, Pegelmessungen in Bohrungen und in Höhlen (Abb. 1C). Gegebenenfalls können aus solchen Messungen Druckhöhenverluste – d. h. hydraulische Gradienten für Hochwasser – abgeleitet und für unterschiedliche Hochwassersituationen extrapoliert werden. Der Anstieg des Grundwassers im Karstmassiv führt zu einer Vergrößerung des gesättigten Grundwasservorkommens und entsprechend auch einer Verschiebung der Systemgrenzen. Mitunter kommt es zu einer Verbreiterung der bei Niedrigwasser beobachteten Diffluenzbereiche bzw. werden neue geschaffen (Abb. 1D).

Die Anwendung dieser Prinzipien führt zu einem 3D-Modell der Grundwasserverhältnisse, wie in Abbildung 2[1] für das Beispiel der Brunnmühle-Quelle (Berner Jura) gezeigt. Eine solch explizite und ausgereifte 3D-Darstellung ist leider für die Praxis oft nicht sehr hilfreich. Meist bevorzugen Anwender das Arbeiten mit Karten. Im Folgenden wird vor allem beschrieben, wie die Informationen aus dem KARSYS-Ansatz in ein Kartenformat übertragen werden können, sowie die Ergebnisse im Hinblick auf bestehende hydrogeologische Karten diskutiert.

[1] Für diese und die folgenden Abbildungen wurde das Beispiel des Karstsystems der Brunnmühle-Quelle (Berner Jura, Schweiz) verwen- det. Die Charakteristika des Systems wurden für didaktische Zwecke leicht angepasst.

Ergebnisse: Kartographische Darstellungen

Kartensatz zu den karsthydrogeologischen Systemen

Das 3D-Modell sowie die Karten, die aus der Anwendung des KARSYS-Ansatzes resultieren, enthalten zu viele Informationen, um diese auf eine einzige Kartendarstellung reduzieren zu können. Üblicherweise werden die Ergebnisse an Dritte im PDF-Format mit anklickbaren Themen übermittelt oder sind im Internet publiziert (www.swisskarst.ch). An Behörden wird das 2D-Kartenmaterial als GIS-Datei abgegeben. Thematische Auszüge können in Papierform erfolgen (siehe Abb. 3, 4, 5, 6), wobei bei vollständiger Umsetzung des Ansatzes fünf Themendarstellungen dokumentiert sind:

1. Grundwasser bei Niedrigwasser
2. Fließsysteme bei Niedrigwasser
3. Grundwasser bei Hochwasser
4. Fließsysteme bei Hochwasser
5. Oberflächenmerkmale

In Tabelle 1 sind die Charakteristika zusammengefasst, die auf den jeweiligen thematischen Karten dargestellt sind.

Grundwasser bei Niedrigwasser (phreatische Zone)

Als erstes liefert der KARSYS-Ansatz eine Abgrenzung und Charakterisierung des Grundwasservorkommens unter normalen hydrologischen Bedingungen bzw. bei Niedrigwasser. Mit einem dann als quasi-horizontal angenommenen hydraulischen Gradienten ergibt die Verschneidung von Quellniveau und 3D-Geometrie der Basis der verkarsteten Formation einen Umriss der phreatischen Zone (Grundwasser bei Niedrigwasser). Darauf aufbauend kann das Volumen der wasserführenden Einheit bestimmt werden. Noch wichtiger ist die Möglichkeit, Zonen mit und ohne gesättigte Grundwasserverhältnisse voneinander zu unterscheiden. Auf der entsprechenden Karte (Abb. 3A, B) sind die Bereiche mit ganzjährig vorhandenem Grundwasser in hellblau und die Bereiche ohne

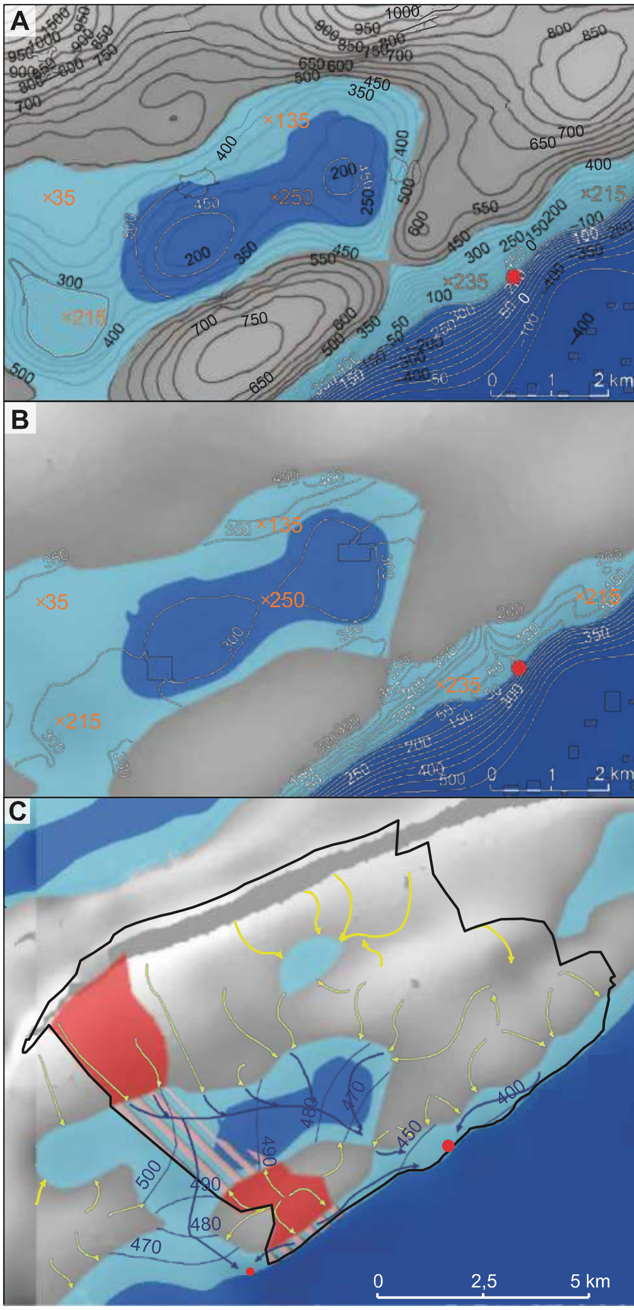


Abb. 3 Kartographische Darstellung der Niedrigwassersituation (Legende s. Abb. 7). **A** Karte der phreatischen Zone inklusive gespanntem Grundwasser mit Isohypsen der unteren (schwarz) und oberen Grenze (weiß) des Grundwasservorkommens (m.ü.M) sowie Mächtigkeitsangabe für die gesättigte Zone; **B** Karte der phreatischen Zone mit Tiefe des Grundwasserspiegels unterhalb Geländeoberfläche; **C** Karte des gesamten Systems mit unterirdischer Begrenzung des Karstsystems bei Niedrigwasser und Höhenlinien des Karstwasserspiegels. Die Dar- stellung der Hauptfließwege veranschaulicht die Diffluenzbereiche in der ungesättigten Zone (rote Flächen) und der phreatischen Zone (ge- streifte Flächen)

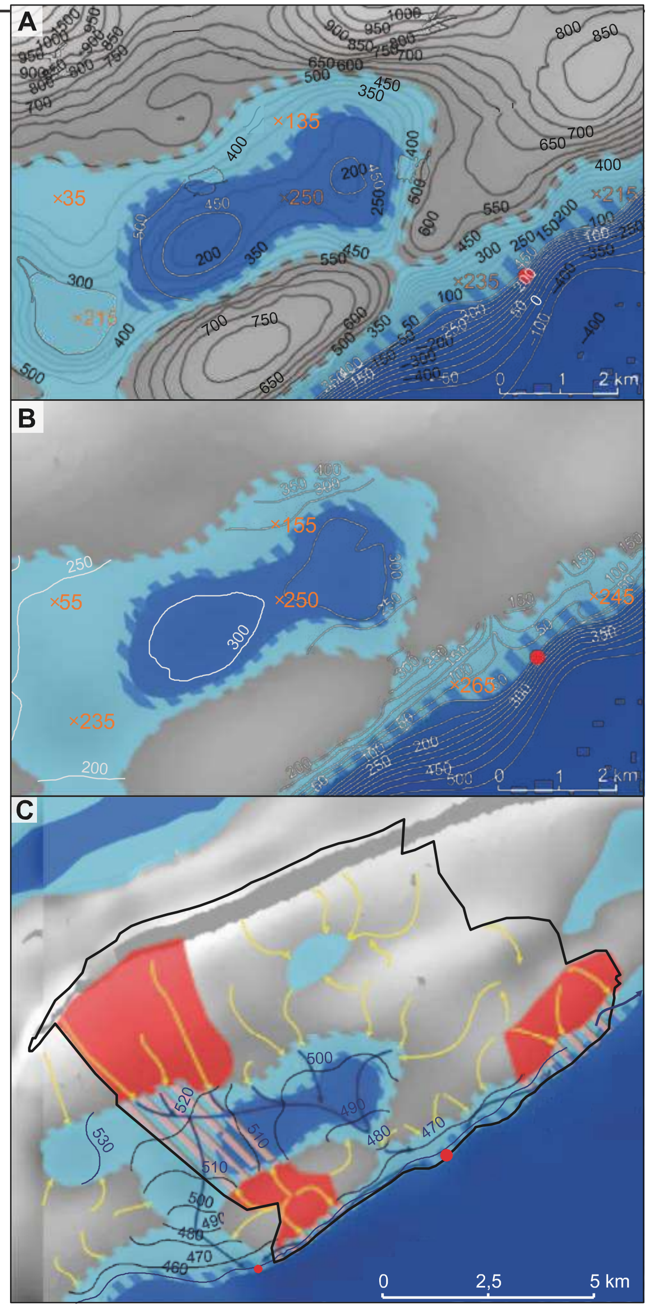


Abb. 4 Kartographische Darstellung der Hochwassersituation (Legende s. Abb. 7). **A** Karte der phreatischen Zone inklusive gespann- tem Grundwasser mit Isohypsen der unteren (schwarz) und oberen Grenze (weiß) des Grundwasservorkommens sowie Mächtigkeitsan- gabe für die gesättigte Zone; **B** Karte der phreatischen Zone mit Tiefe des Grundwasserspiegels unterhalb Geländeoberfläche; **C** Karte des gesamten Systems mit ober- und unterirdischer Begrenzung des Kar- stsystems bei Hochwasser und Höhenlinien des Karstwasserspiegels. Diese Karte verdeutlicht den Anstieg des Karstwasserspiegels gegen- über Niedrigwasserverhältnissen sowie die Ausweitung der Diffluenz- bereiche bei Hochwasser

gesättigte Zone in grau dargestellt. Die Karte erlaubt auch Teilbereiche mit gespannten Grundwasserverhältnissen separat auszuweisen (dunkelblau). Des Weiteren können die Tiefe des Grundwasserspiegels unterhalb der Geländeoberfläche sowie die Mächtigkeit der phreatischen Zone abgeleitet werden. Letztlich kann der Karte die Tiefenlage der unteren

Tab. 1 Charakteristika, die auf den jeweiligen thematischen Karten des KARSYS-Ansatzes dargestellt werden können

Dargestellte Charakteristika/Themen	Grundwasser bei Niedrigwasser (NW)	Fließsystem bei Niedrigwasser	Grundwasser bei Hochwasser (HW)	Fließsystem bei Hochwasser	Oberflächenmerkmale (Infiltration/Exfiltration)	Synthetisierte Darstellung
Ausdehnung des Grundwasservorkommens (phreatische/epiphreatische Zone)	X		X			X
Bereiche mit ausschließlich ungesättigter Zone	X		X			
Grundwasservolumen (phreatische/epiphreatische Zone)	X		X			
Bereiche mit gespanntem Grundwasser	X		X			X
Tiefe des Grundwasserspiegels	X		X			
Grundwassermächtigkeit	X		X			
Höhenlinien der unteren Grenze des Grundwasserleiters	X					
Höhenlinien der oberen Grenze des Grundwasserleiters	X					
Systemaustritte (perennierende Quellen/Überlaufquellen)		X		X	X	X
Abgeleitete piezometrische Wasserscheide		X		X		
Abgeleitete undurchlässige Grenze		X		X		
Abgeleitete Diffluenzbereiche		X		X		X
Abgeleitete Wasserscheide im ungesättigten Bereich		X		X		
Ausscheidung der Einzugsgebietsgrenzen des Systems		X		X		X
Abgeleitete vadose Hauptfließwege		X		X		X
Abgeleitete phreatische Hauptfließwege		X		X		X
Höhenlinien des Grundwasservorkommens (phreatische Zone)		X		X		X
Ergebnisse von Tracerversuchen für NW- und HW-Verhältnisse		X		X		
Wichtigste Schwinden und deren Einzugsgebiete					X	X
Ausscheidung von nacktem Karst					X	X
Ausscheidung von teilweise bedecktem Karst					X	X
Ausscheidung von völlig bedecktem Karst					X	X
Exfiltrationslinie (NW)/Exfiltrationsbereiche (HW)					X	

und – in Bereichen gespannten Grundwassers – der oberen Grenze der verkarsteten Einheit entnommen werden.

Karstfließsysteme bei Niedrigwasser

Aus der Darstellung der phreatischen Zone kann die Abgrenzung der Karstfließsysteme bei Niedrigwasser erfolgen. In Abbildung 3C sind die Fließwege innerhalb eines an eine ganzjährig aktive (perennierende) Karstquelle gebundenen Systems aufgezeigt. Das Fließsystem wird also entweder in der ungesättigten Zone durch die undurchlässige Grenze bzw. Wasserscheide an der Basis der verkarsteten Formation, oder durch die piezometrische Wasserscheide zwischen zwei aktiven Quellen begrenzt (vgl. Abb. 1A, B). Hieraus kann dann auch das Einzugsgebiet des Karstsystems bestimmt werden. Da in Karstsystemen häufig Diffluenzen und nur ungenaue Informationen über hydraulische Gradienten sowie Geometrie der verkarsteten Formationen vorliegen, reicht es nicht aus, diese Abgrenzung des Einzugsgebiets lediglich in Form einer Linie darzustellen. Vielmehr müssen die Randbereiche

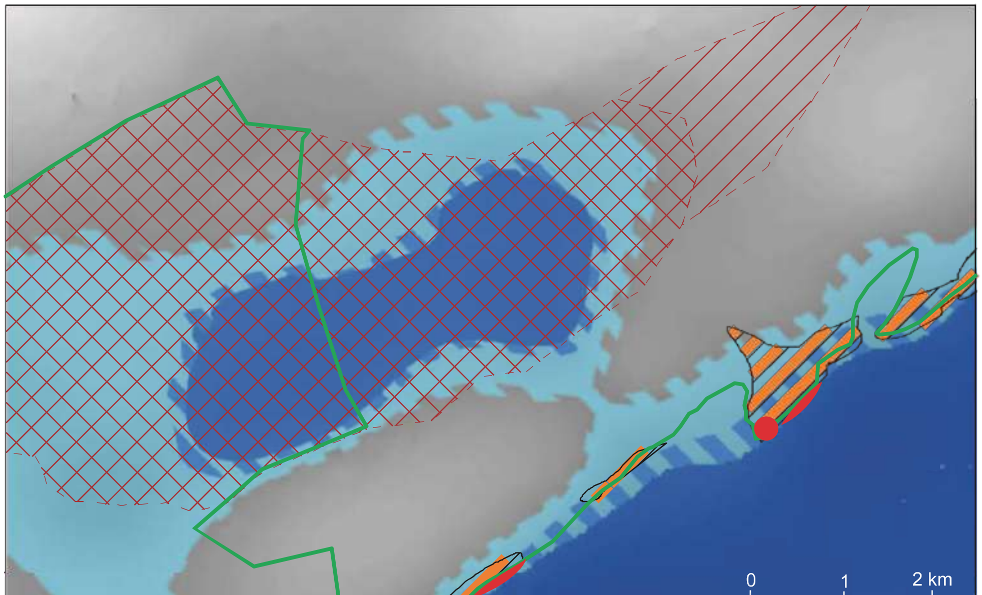


Abb. 5 Darstellung der Oberflächenmerkmale mit Bereichen nackten, teilweise bedeckten und völlig bedeckten Karsts. Bei vollständig bedecktem Karst (Gitterstruktur) kommt es zu keiner direkten Infiltration, sondern zu Oberflächenabfluss mit teilweise allochthoner Grundwasserneubildung und damit mitunter zu einer Abweichung von ober- und unterirdischem Einzugsgebiet. Die schmalen Exfiltrationslinien bei Niedrigwasser können sich bei Hochwasser zu breiteren Exfiltrationsbereichen erweitern (orange) (Legende s. Abb. 7)

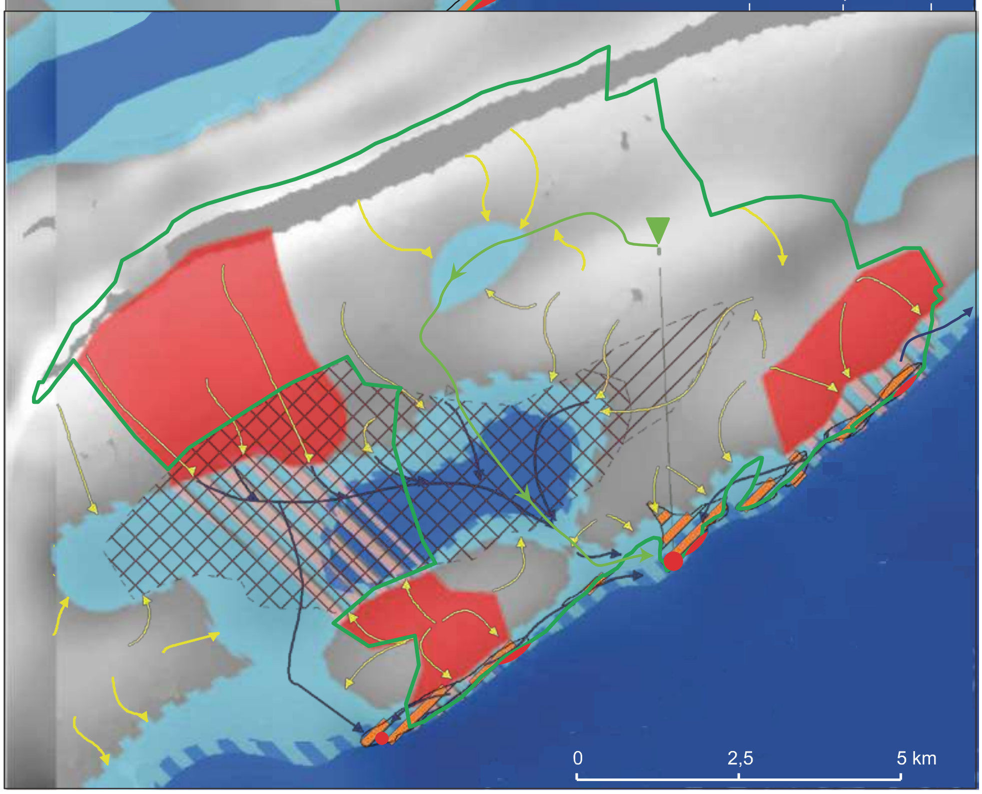
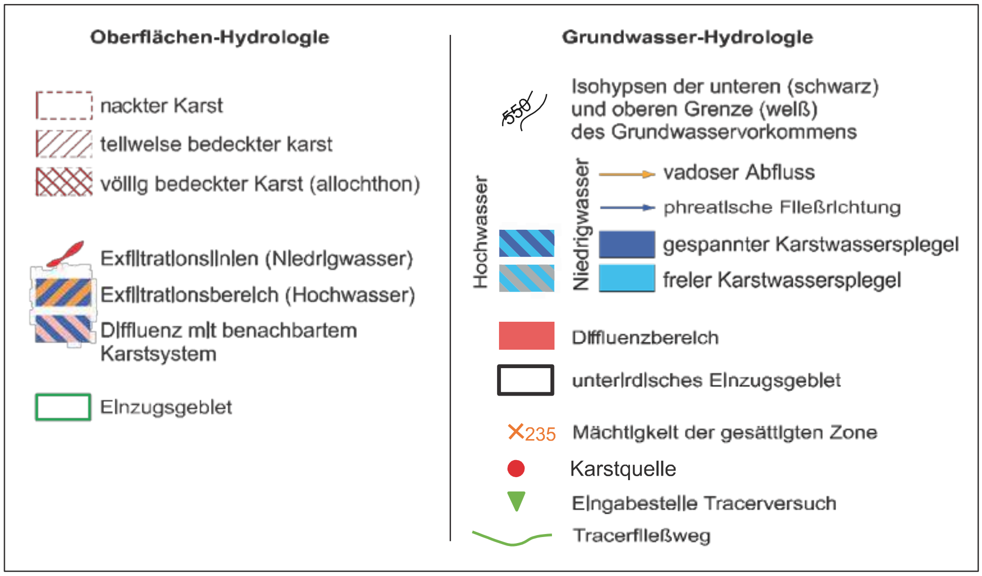


Abb. 6 Synthetisierte Darstellung der hydrogeologischen Situation des Karstsystems. Eine solche Karte kann bereits für Systeme mit relativ wenig verfügbaren Daten erstellt werden. Sie wird als gangbarer Kompromiss zwischen Lesbarkeit und Informationsdichte angesehen. Anhand der damit vorliegenden Informationen kann aus der kartographischen Darstellung z. B. der vermutliche Fließweg eines hypothetischen Tracerversuchs direkt abgeleitet werden (Legende s. Abb. 7)

durch Flächen markiert werden, wobei die Grenzlinie wiederum die maximale Ausbreitung der beitragenden Flächen zur Gesamtschüttung des Systems umschließt. Die Fläche bzw. das entsprechende Volumen beschreiben den Diffluenzbereich, aus dem ein Teil des Wassers auch bei Niedrigwasser in andere Systeme entwässert oder entwässern könnte. Auf diese Art überlappen sich in den meisten Fällen die maximalen Einzugsgebiete benachbarter Karstsysteme.

Wie in Abbildung 1 skizziert, können dieser Darstellung die wichtigsten (vermuteten) Fließwege des Karstsystems hinzugefügt werden (Abb. 3C). Für die ungesättigte Zone wird angenommen, dass das Wasser vertikal versickert, bis es entweder die Basis der verkarsteten Formation oder das Grundwasser (phreatische Zone) erreicht. Trifft das Wasser zunächst auf die undurchlässige Basis, folgt es dieser Fläche in Richtung des Schichtfallens (ähnlich dem Oberflächenabfluss). In

Abb. 7 Legende zu den Abbildungen 3 bis 6



der phreatischen Zone gilt dann das Prinzip, dass das Wasser auf der kürzesten hydraulischen Verbindung in Richtung der Quelle fließt. Weitere Quellen, die hydraulisch direkt mit der ganzjährig aktiven Quelle in Verbindung stehen, können identifiziert werden. Eine solche Quellgruppe umfasst alle wichtigen Austrittspunkte des Karstsystems. Falls piezometrische Daten des Niedrigwasser-Karstwasserspiegels existieren (am ehesten Beobachtungen in Höhlen oder Bohrlochmessungen), können die entsprechenden Gradienten abgeschätzt werden. Eine piezometrische Karte kann die Systemdokumentation ergänzen. Dabei ist allerdings zu beachten, dass Pegelstände in Bohrungen deutlich (mehr als 20 m) vom Karstgrundwasserspiegel abweichen können (Jeannin 1995); Karstgrundwasserspiegel können nur durch hydraulische Tests bestimmt werden. Zusätzlich können auf diesen Karten die Ergebnisse von Tracerversuchen dargestellt werden, welche bei Niedrigwasserverhältnissen durchgeführt wurden.

Grundwasser bei Hochwasser (phreatische + epiphreatische Zone)

Bei Hochwasser, d. h. zu Zeiten erhöhter Quellschüttungen, steigen die Fließgeschwindigkeiten in den Karströhren entsprechend der Druckhöhen an. Beobachtungen und Messungen in Höhlen zeigen, dass je nach System Schwankungsbereiche (epiphreatische Zone) bis zu 500 Höhenmetern vorkommen (Abb. 1C). In topographisch eher flachen Karstgebieten bewegen sich die Schwankungen im Bereich von 5–50 Metern (z. B. Milandre in der Schweiz (Jeannin 1996)), manchmal sogar darunter (z. B. Mammoth Cave in den USA (Quinlan et al. 1983)). In gebirgigen Karstsystemen mit ihren mächtigen Kalkformationen und starken Niederschlägen (sowie Beiträgen aus Schnee- und Gletscherschmelze) – wie dies in den Schweizer Alpen häufig der Fall ist – können Schwankungen größer 350 m erreicht werden (z. B. Hölloch (Jeannin 2001) oder Luire (Morel et al. 2006)); üblichere Werte liegen zwischen 50 und 200 Metern (z. B. Bärenschacht (Häuselmann et al. 2003) oder Areuse (Schürch et al. 2006)). Diese Schwankungen führen in der Regel zu einer signifikanten Vergrößerung der Mächtigkeit der gesättigten Zone bei Hochwasser.

Die Bestimmung der Hochwassersituation ist nicht eindeutig, da die Schwankungshöhe von Quellschüttung und Druckhöhe von der Intensität der meteorologischen Ereignisse abhängt. Je nach Fragestellung betrachtet man eine übliche (jährliche) oder eine extreme (30- oder 100-jährliche) Hochwassersituation. Die Bestimmung der Hochwasserverhältnisse erfolgt durch Beobachtung der Grundwasserstände während des Ereignisses meist an Überlaufquellen sowie in Höhlen und Bohrungen. Sollten keine solchen Daten zur Verfügung stehen, muss auf die Darstellung der epiphreatischen Zone verzichtet werden. Kann diese allerdings bestimmt werden, so ist auch eine Abschätzung des Wasservolumens möglich, welches in der epiphreatischen Zone gespeichert ist. Auf der entsprechenden Karte (Abb. 4A, B) sind die epiphreatischen Bereiche in hellblauen Streifen dargestellt. Bereiche mit bei Hochwasser gespannten Grundwasserverhältnissen sind mit dunkelblauen Streifen gekennzeichnet. Sind ausreichende Datenreihen vorhanden, können zudem Karten für Hochwassersituationen unterschiedlicher Wiederkehrperiode produziert werden.

Karstfließsysteme bei Hochwasser

Üblicherweise variieren die Fließgrenzen und hydraulischen Bedingungen in den Karstsystemen je nach Wasserstand (Abb. 1D). Sehr häufig führt das Ansteigen des Grundwassers zu einer Art „unterirdischem Überlauf", welcher entweder zu einem Wasserverlust oder zu einer Wasseranreicherung im System führt. Somit ist für die Hochwassersituation – neben den Niedrigwasserverhältnissen – eine weitere Analyse der Abgrenzung der Grundwassersysteme und deren Einzugsgebiete notwendig; in gewissen Systemen sollten sogar Zwischenstände berücksichtigt werden. Neue Abgrenzungslinien und -bereiche müssen skizziert werden, ebenso wie neue Diffluenzbereiche – diesmal für Hochwasserverhältnisse – bestimmt werden müssen.

Analog zur Niedrigwassersituation können die wichtigsten (vermuteten) Fließwege des Karstsystems eingezeichnet werden (Abb. 4C). In vielen Fällen verändert die Aktivierung von Überlaufquellen die Systemaustrittspunkte sowie die Fließwege relativ stark. Falls piezometrische Daten des Karstwasserspiegels für Hochwasser vorliegen (aus Höhlen, Überlaufquellen oder Bohrungen), können die Hochwassergradienten abgeschätzt werden. In der Regel steigen diese in Karstsystemen nicht gleichmäßig, sondern eher stufenweise (z. B. Wildberger & Ziegler 1992). Eine piezometrische Karte für Hochwasserverhältnisse kann die Dokumentation des Systems ergänzen. Gebiete, in denen der Karstwasserspiegel die Geländeoberfläche erreicht (oder sich ihr annähert), sind als überflutungsgefährdete Bereiche zu betrachten. Entsprechend kann die Tiefe des Grundwasserspiegels bei Hochwasser unterhalb der Geländeoberfläche – für eine gegebene Wiederkehrperiode – auf der Karte dargestellt werden. Auf diesen Karten können analog die Ergebnisse der Tracerversuche, die bei Hochwasser durchgeführt wurden, vermekt werden.

Darstellung der Oberflächenmerkmale

Die berücksichtigten Oberflächenmerkmale umfassen die Darstellung von Infiltrations- und Exfiltrationsbedingungen (Abb. 5).

Bezüglich Infiltration wird die Fläche des gesamten Einzugsgebiets gleichsam für Niedrigwasser und Hochwasser in drei Kategorien unterteilt: (i) nackter Karst, (ii) teilweise bedeckter Karst und (iii) völlig bedeckter Karst. Nackter Karst entspricht Bereichen, in denen die Bedeckung nur mäßig mächtig ist (0 bis ca. 2 m), und wo angenommen werden kann, dass der Hauptteil des Nettoabflusses unterirdisch in den Karst erfolgt. Wenn sich dagegen bei starkem Niederschlag Oberflächenabfluss bilden kann und/oder im Fall bedeutender Deckschichten, wird eine Region als teilweise bedeckt kartiert. Diese Unterscheidung kann meist bereits aus dem digitalen Höhenmodell und den Bodenkarten getroffen werden. Wenn der Hauptteil des Niederschlags an der Oberfläche abfließt, wo also ein Bach oder Fluss an der Oberfläche existiert, ist das Gebiet als bedeckter („allochthoner") Karst kartiert, vorausgesetzt dass dieser Oberflächenabfluss zumindest teilweise in den Karst entwässert.

Bei den Exfiltrationsphänomenen handelt es sich um ganzjährig aktive Quellen, temporäre Überlaufquellen sowie Exfiltrationslinien bzw. -bereiche für Niedrigwasser und Hochwasser. Bereiche, die nur bei Hochwasser zum Exfiltrationsbereich werden, sind in der Regel bei Niedrigwasser Infiltrationsbereiche.

Synthetisierte Darstellung

Da mehrere Karten notwendig sind, um sämtliche beschriebene Informationen zu visualisieren, wird eine synthetisierte Darstellung der KARSYS-Ergebnisse vorgeschlagen (Abb. 6). Eine solche zeigt die Quellen, die Ausdehnung des Grundwasservorkommens bei Niedrigwasser (bei Bedarf zusätzlich bei Hochwasser), die Hauptfließwege des Systems bei Niedrigwasser, das gesamte Einzugsgebiet, die Diffluenzbereiche sowie die drei unterschiedenen Infiltrationsszenarien (nackter, teilweise bedeckter und völlig bedeckter Karst). Üblicherweise bleiben Kartendarstellungen mit diesem Umfang an Angaben noch lesbar. Die Karte wird in der Regel durch ein hydrogeologisches Vertikalprofil ergänzt.

Dokumentation für unterschiedliche Aspekte des Wassermanagements

Zwischen 2010 und 2013 wurde der KARSYS-Ansatz auf mehr als 100 Karstsysteme vor allem in der Schweiz (von hochalpinen Systemen bis Jura-Plateaus), aber auch in Slowenien und Spanien angewendet (Turk et al. 2013, Ballesteros et al. 2013). Diese Dokumentationen wurden im Hinblick auf eine breite Palette von Nutzern erstellt. Tabelle 2 führt die Anwendungsbereiche, für welche Karten des KARSYS-Ansatzes geeignet erscheinen, auf.

In etwa der Hälfte der Anwendungen waren Fragen zur Wasserversorgung Auslöser der durchgeführten Arbeiten (z. B. Berner Jura (Malard et al. 2012)). Die gelieferten Karten konnten aufzeigen, wie viel Wasser im Karst-Grundwasserleiter gespeichert ist und wo die Erstellung einer Fassung günstig oder ungünstig wäre. Einzugsgebiete wurden neu ausgeschieden, und viele bis dahin unverstandene Beobachtungen früherer Untersuchungen konnten nun eingeordnet werden. Die 3D-Modelle spielten stets eine wichtige Rolle in der Kommunikation der Ergebnisse. So halfen die anschaulichen Darstellungen den Wassermanagern, ihre Karstsysteme konkret zu verstehen, und konnten in Bezug auf die Abschätzung der Wasserverfügbarkeit eine gewisse Plausibilität vermitteln.

In einem Fall wurde der KARSYS-Ansatz herangezogen, um die Ursache von Verschmutzungen eines Pumpbrunnens im Schweizer Jura (Poljé von La Brévine, Kanton Neuchâtel) zu eruieren. Bisher wurde dort ein lokal begrenztes Einzugsgebiet von 0,5 km^2 angenommen. Das 3D-KARSYS-Modell und die Karte des Grundwasservorkommens haben jedoch ein solch begrenztes Einzugsgebiet nicht bestätigt; vielmehr ergaben sich zahlreiche Anzeichen für ein um ein Vielfaches größeres Einzugsgebiet. Dies wurde schließlich auch durch einen Tracerversuch belegt. Die Infiltrationsbereiche dieses Gebietes, die aus dem 3D-Modell abgeleitet und auf den syn- thetisierten Karten dargestellt wurden, können dann genutzt werden, um angepasste Schutzzonen zu bemessen.

Der Kanton Waadt interessierte sich für eine Abschätzung des Energiepotenzials der Karst-Grundwasserleiter und ließ dafür seine 50 Karstsysteme mehr oder weniger detailliert mit dem KARSYS-Ansatz dokumentieren (Jeannin et al. 2010). Analog zu Abbildung 4C konnten diejenigen Systeme kartographisch dargestellt werden, in denen ein unterirdischer Bach deutlich oberhalb des Vorfluters verläuft und somit unterirdische Wasserkraftwerke installiert werden könnten. Die Einzugsgebiete dieser potenziellen Fassungsstellen wurden bestimmt und die Abflussmengen abgeschätzt. Eine daraus resultierende Stromproduktion von insgesamt 20 MW wäre zwar bescheiden, aber nicht unbedeutend. Drei Projekte erscheinen rentabel und werden weiterverfolgt. Gleichzeitig wurde das Potenzial für Wärmegewinnung aus Karstgrundwasser untersucht. Das Potenzial ist vorhanden, aber nicht immer am günstigen Ort, d. h. zu weit entfernt von den entsprechenden Nutzern. Trotzdem gibt es bereits einige solcher Anlagen in Karstgebieten der Schweiz.

Ein weiteres Anwendungsbeispiel ergibt sich im Rahmen der Beurteilung von Hochwassergefahren. In Karstgebieten gibt es Bereiche, die zwar so gut wie nie einen Oberflächenabfluss aufweisen, jedoch manchmal von aufsteigendem Karstwasser geflutet werden. In der Ajoie in der Nordschweiz (Kanton Jura) ist dies der Fall und die Ingenieure hatten sehr wenig Kenntnis und Informationen, um die Wahrscheinlichkeit und das Ausmaß einer solchen Überflutung abzuschätzen. Der KARSYS-Ansatz wurde benutzt, um Karten des Grundwassersystems bei Niedrig- und Hochwasserverhältnissen zu erstellen (entsprechend Karten der Abb. 4 und 5). Bereiche, in denen das Grundwasser die Geländeoberfläche erreichen kann, wurden mitsamt ihrer Einzugsgebiete ausgeschieden (Vouillamoz et al. 2013). Mit einfachen hydraulischen Modellen konnten die Wassermengen und Wiederkehrperioden von Ereignissen bestimmt werden. Zwar wird eine echte Validierung der Ergebnisse erst mit dem Eintritt entsprechender – aber seltener – Ereignisse stattfinden können, jedoch wurde das Modell bei normalen Hochwassern schon sehr gut bestätigt, nicht zuletzt dank des Einbaus zusätzlicher Messgeräte im Untergrund. Erdwärmesonden sind nicht nur in der Schweiz mittlerweile sehr verbreitet. Die Bewilligung dafür erfolgt über die Kantonsbehörden, jedoch ist die Beurteilung solcher Bohrungen in Karstgebieten nicht immer evident. In einigen Kantonen sind Erdwärmesonden im Karst generell Bauwesen Impaktstudie auf das Grundwasser verboten, in anderen Kantonen teilweise oder kaum regle-mentiert. Im Kanton St. Gallen wurde der KARSYS-Ansatz herangezogen, um ein Konzept für die Reglementierung des Erstellens von Erdwärmesonden zu entwickeln. Dafür wurden die Karstsysteme des Kantons vollständig mit KARSYS dokumentiert. Für jedes System wurden Karten im Stil der Abbildung 3 erstellt, woraus als Endprodukt eine kantonsweite Karte für die Erteilung von Bewilligungen für Erdwärmesonden in Karstgebieten hervorgehen soll.

Der KARSYS-Ansatz und entsprechendes Kartenmaterial kamen auch bereits für die Beurteilung der Auswirkungen von Projekten oder bestehenden Bauten (Deponien, Anlagen, Tunnelbauten) zum Einsatz. Eine konkrete Erweiterung des Ansatzes wurde für die Prognose von karstspezifischen Gefahren im Untertagebau vorgenommen (KarstALEA, Filipponi et al. 2012).

Einige der mit KARSYS dokumentierten Systeme wurden zusätzlich hydrologisch modelliert, um das heutige Fließregime besser zu charakterisieren, oder auch um die Auswirkung zukünftiger Klimaänderungen abzuschätzen. Dies hat gezeigt, dass hydrologische oder hydrogeologische Modelle relativ leicht aus der KARSYS-Dokumentation entwickelt werden können.

Diskussion und Schlussfolgerungen

Im Vergleich zur klassischen kartographischen Darstellung erlauben die mit KARSYS erstellten Karten eine deutlich umfangreichere Charakterisierung der Karst-Grundwasserleiter und Fließsysteme. Dieses Material ist praxisorientiert und wurde im Hinblick auf die Anforderungen der potenziellen Anwender entwickelt (siehe Tab. 2).

Der Vorteil einer expliziten 3D-Darstellung – ergänzt durch Karten – liegt vor allem in der Tatsache, dass alle Projektbeteiligten trotz unterschiedlicher Fachkenntnis das gleiche Bild vom Funktionieren des betrachteten Karstsystems vor Augen haben. Dies hilft Missverständnisse zu vermeiden, konträre Vorstellungen zu diskutieren und damit das Modellverständnis insgesamt zu verbessern. Die Anwendungen haben gezeigt, dass die KARSYS-Dokumentation für viele Aspekte der Bewirtschaftung eines Karstgebietes von Nutzen sein kann. Ein solches Verständ-

Tab. 2 Auswahl von bisher bearbeiteten Anwendungsbereichen fürKarten des KARSYS-Ansatzes

Anwendungsbereich	Beispiele
Wasserversorgung	Ressourcenerkundung und -exploration; Bemessung von Schutzzonen
Wasserkraft	Abschätzung des hydroelektrischen Potenzials
Geothermie	Grundlagen für die Reglementierung und Dimensionierung von Erdwärmesonden
Naturgefahren	Abschätzung Hochwasserpotenzial; Einsturzgefahr
Altlasten	Impaktstudie auf das Grundwasser
Gebietsentwässerung	Abschätzung des Potenzials; Impaktstudie auf das Grundwasser

nis stellt auch die notwendige Grundlage für quantitative Ansätze bezüglich Wasserbilanz, hydrologische Modelle sowie unterirdische Fließ- und Transportmodellierungen dar.

Zwar ist das 3D-Modell des Untergrundes, aus dem die thematischen Karten abgeleitet werden, sehr konkret und scheint die Realität abzubilden. Der Nutzer muss sich aber bewusst sein, dass es sich um eine vereinfachte Darstellung der natürlichen Verhältnisse handelt, welche stets komplexer als das Modell sind. Wie groß die Unterschiede zwischen Modell und Realität letztlich sind, hängt einerseits von Verfügbarkeit und Qualität der Daten ab, anderseits vom Vereinfachungsgrad, der im Ansatz angenommen wird. So bleiben z. B. Entwässerungsbahnen durch Stauerformationen in der Regel außerhalb von Verwerfungszonen unberücksichtigt.

Trotz der Funktionalität des Ansatzes gibt es noch Verbesserungsmöglichkeiten. So ist die Darstellung der jeweiligen Informationen in 3D und in den thematischen Karten noch nicht endgültig definiert. Hierzu sind Rück- und Bedarfsmeldungen explizit erwünscht, insbesondere ob die hier gewählten thematischen Darstellungen sinnvoll erscheinen, wie die Karten für geometrisch komplexe Systeme aussehen könnten oder ob die synthetisierte Karte wirklich die für die Anwender wichtigsten Informationen enthält.

Die Bearbeitung der Daten von den Grundlagen in Papierform bis zum Endresultat (3D-Modell und Karten) benötigt den Einsatz etwa zehn unterschiedlicher Software-Programme und eigener Skriptsprachen. Gewisse Teilbereiche müssen noch aufwändig von Hand bearbeitet werden. Für die Ersterstellung einer Systemdokumentation ist eine solch halbautomatisierte Vorgehensweise ein gangbarer Weg. Eine standardisierte Aktualisierung durch neue Dokumente (z. B. eine neu abgeteufte Bohrung) ist damit aber nicht machbar und somit derzeit noch nicht realisiert.

Ein weiteres Problem liegt in der Darstellung der Rohdaten und der Verdeutlichung von Unsicherheitsgraden. Im GIS-Projekt sind alle Ausgangsdaten zugänglich, jedoch ist ihre Darstellung in den publizierten Dokumenten nicht umgesetzt. In den Fällen, in denen die Anwender das vollständige GIS-Projekt erhalten, können diese Daten jedoch eigenständig eingesehen werden. Die Berücksichtigung der Modellunschärfe ist im Moment noch nicht gegeben. Derzeit ist es für den Anwender schwierig, ein System mit vielen und genauen Daten von einem mit wenigen und grob abgeschätzten Daten zu unterscheiden. Hier gibt es noch Verbesserungsbedarf.

Auch ist die Darstellung von mehrstöckigen verkarstungsfähigen Einheiten nicht gelöst. Zwar können solche Wechsellagerungen aus Karst-Grundwasserleitern und Stauerschichten mit dem 3D-Modell relativ gut nachvollzogen und visualisiert werden, jedoch ist es schwierig, dies auch kartographisch darzustellen. Dies geschieht bislang auf getrennten Karten, wobei für die Beispiele in der Schweiz bisher ohnehin hauptsächlich der oberste Grundwasserleiter betrachtet wurde.

Die systematische Anwendung des KARSYS-Ansatzes hat dessen Effizienz, aber auch das Optimierungs- und Erweiterungspotenzial aufgezeigt. Mit relativ bescheidenem Arbeitsaufwand kann ein konkretes Modellkonzept eines Karstsystems entwickelt werden. Die hier vorgestellten Ergebnisse mit den thematischen Karten – inklusive der synthetisierten Darstellung – haben die Praxistauglichkeit und Nützlichkeit des Verfahrens an einem breiten Spektrum von Themen und Fragestellungen unter Beweis gestellt. Sie sollen einen Beitrag zur Diskussion hin zu einer besseren Berücksichtigung karstspezifischer Phänomene bei der Erstellung hydrogeologischer Karten leisten.

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10.10. Appendix 10: Malard et al. 2014 - Assessing Karst Aquifers in Switzerland: The 2010/2013 Swisskarst Project

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Assessing Karst Aquifers in Switzerland: The 2010/2013 Swisskarst Project

Arnauld Malard, Pierre-Yves Jeannin, Eric Weber, and Jonathan Vouillamoz

Abstract
As karst groundwater represents a significant part of the Swiss water reserve (120 km^3) and resource (6.6 to 9.1 km^3), the Swisskarst project (01/2010−12/2013) was included as a component of the National Research Program 61 dedicated to the sustainable management of water. Karst aquifers are sensitive to contamination and they may be disturbed by land management or civil construction. Furthermore their evolution according to climate changes strongly depends on contexts (low-land or alpine karts). In order to improve the management of karst aquifers, the project focused on two aspects: (i) the documentation of karst aquifers through a dedicated and systematic approach, maps and 3D models and (ii), the comparison and selection of applicable hydrological simulation tools, including karst recharge and karst hydraulics, which can adequately address pragmatic topics in karst such as flood hazards, low-flow recessions, etc., as well as mid-term behavior (climate changes, glaciers melting,…). Between 2010 and 2013 it was possible to document about one third of karst areas in Switzerland, including nearly one hundred karst systems. Water authorities at federal, cantonal and community levels were directly involved. This documentation clearly improved the understanding of karst aquifers and the way to manage them. Results of the project are available on www.swisskarst.ch. The work will continue along the coming years. Only results concerning the characterization of karst aquifers and systems, as well as some mapping procedures are discussed here.

Keywords
Karst aquifer • Reserve • Resource • Documentation • Switzerland

Introduction

The Swiss territory—41,000 km^2—encloses 7,500 km^2 of exposed karst (mainly Jura, Prealps and Helvetic Alps). Most aquifers are formed by Jurassic and Cretaceous limestones but also some in Triassic. Groundwater reserves in karst aquifers were estimated to 120 km^3 and annual resources between 6.6 and 9.1 km^3/year (Sinreich et al. 2012, ISSKA 2013). As these systems were poorly known, the management of these significant groundwater resources was not always adequate. In addition, engineering projects, land-management or civil-construction are often designed without considering the karst functioning or in underestimating its significance and effects. In the frame of a sustainable management of water reserves and resources at the country scale, the National Research Program 61 (www.nrp61.ch) included one project on karst groundwater. Aims were: (1) to develop a dedicated, applicable, systematic and efficient approach to document (i.e. understand) flow through karst hydrogeological systems, (2) to apply it ideally on all karst systems, (3) to identify the best way to simulate recharge and flow through karst systems.

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The present paper is focused on the first aim and includes new concepts for the hydrogeological mapping of karst systems, which resulted from the application of this approach.

A Consistent Approach to Characterize Karst Aquifers and Systems

An new approach, named KARSYS (Jeannin et al. 2013) was developed at the beginning of the Swisskarst project. Numerous improvements have been introduced in the formulation and the application of this approach along the course of the project. Successive application of the approach in the cantons of Vaud, Bern, St Gall, Schwyz, Fribourg… provided a concrete overview of aquifers and groundwater circulations in these regions (Malard et al. 2012, www.http://www.swisskarst.ch/). Nearly one hundred systems were docu- mented in these cantons and locally in other ones. For each system the following elements could be characterized:

- the 3D geometry of the impervious layers surrounding the aquifer;
- the position and regime of the system’s outlets (perennial and temporary ones);
- the delineation of the phreatic zone(s) of the aquifer and the presence of a superimposed aquifer level (if any). Depending on the tectonic context, the phreatic zones (or groundwater bodies) may be local to regional, shallow or deep. Alpine systems tend to have deeper but local groundwater bodies and systems in the Jura Moutains are more regional but shallower, with several exceptions;
- the position of the main supposed underground flow-paths which are referred as “drainage axis”. Flow may take place in the unsaturated part (i.e. vadose flows) or in the saturated part of the aquifer (i.e. phreatic);
- the delineation of the overall catchment area (under low-flow conditions), as well as sub-catchment units which contributes to each main drainage axis. The combination of these catchment units provides the real boundaries of the systems catchment at low-flows;
- for high-flow conditions, the approach makes it possible to assess the hydraulic gradient based on the position of overflow springs and further information when existing. System’s boundaries often considerably change and some sub-catchment units may overflow towards or away from/to neighboring systems. As a result, some sub-catchment units may be strictly related to one single karst system or may be common to several systems. In other words, two adjacent systems may share a common part of their catchment (divergent part). In some cases flow is always diverted to the two systems in various proportions or, in other cases, flow is only diverted at high flow. The explicit identification of diffluent sub-catchment units is really relevant in the documentation process of karst systems.

Results of the documentation are summarized on a map and a fact−sheet for each system (cf. Fig. 114.1).

Consequences for Hydrogeological Mapping

Hydrogeological maps in a karst environment often do not meet the requirements of users. Although formal and international guidelines have been proposed and accepted for hydrogeological maps (Struckmeier and Margat 1995), their

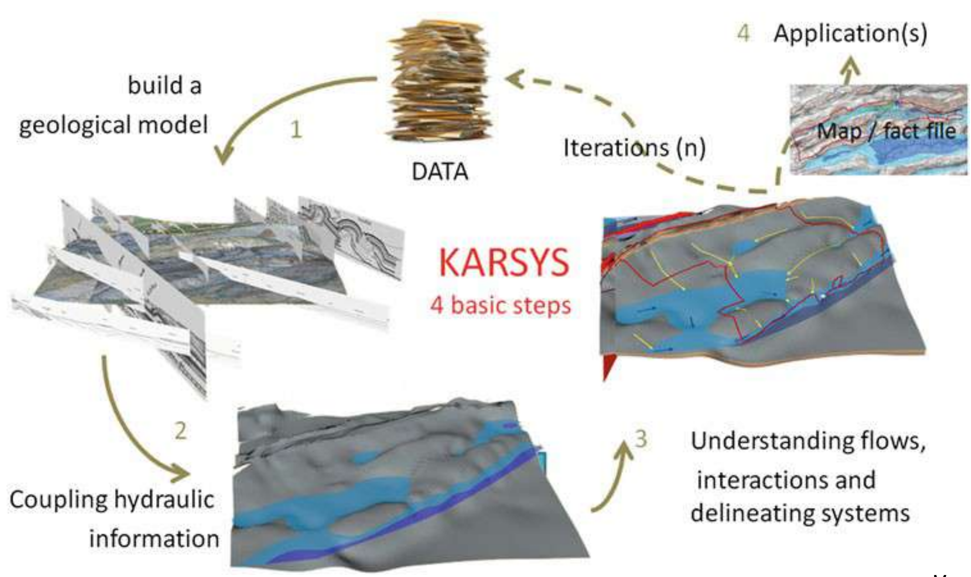

Fig. 114.1 The workflow of the KARSYS approach includes 4 basic steps which can be iteratively processed. The approach was applied systematically over nearly a third of the Swiss karst territory. Outputs of the documentation may be consulted on www.swisskarst.ch

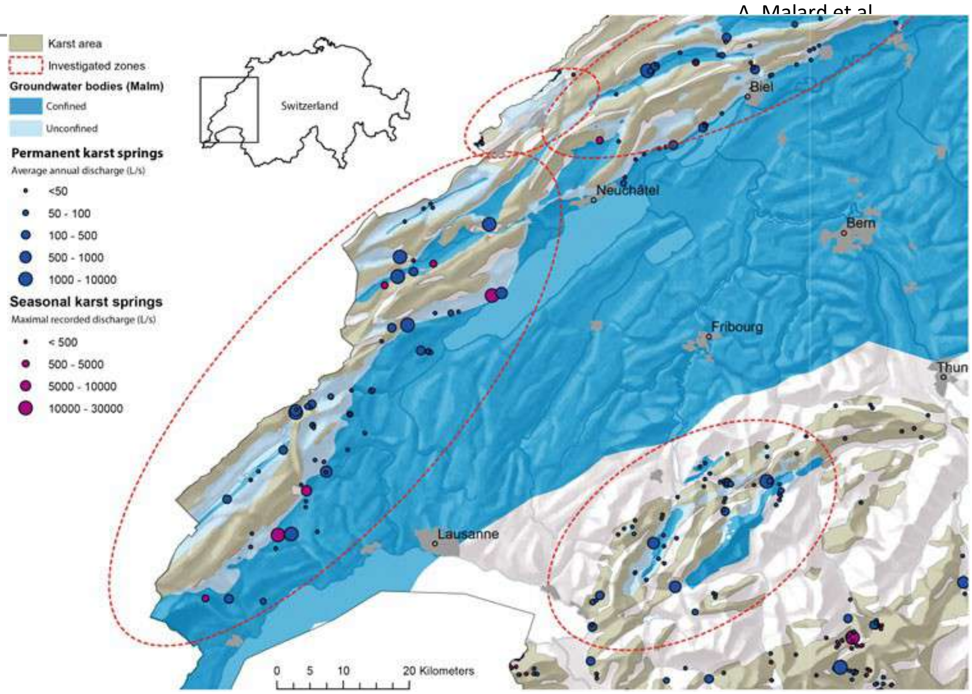

Fig. 114.2 Overview of the 1/500,000 karst hydrogeological map of the Malm aquifer (*Upper* Jurassic) in western Switzerland

application in karst show some limitations due to its specific hydraulic functioning.

One of the ways to encourage the consideration of karst aquifers and systems in the field of groundwater exploitation remains to establish pragmatic and unambiguous hydrogeological maps. Efforts have been applied within the project to develop a new concept for mapping karst aquifers and systems at small scale (1/500,000), regional scale (1/100,000) and a local scale (1/25,000 or more).

At small scale, the map is mainly seen as a groundwater reserves map rather than as a resources map. Groundwater bodies are delineated and distinguished between confined/unconfined and indirectly or directly recharged (example Fig. 114.2). Perennial and temporary springs are displayed according to their average/maximal discharge rates respectively. Regional hydrogeological maps do already exist in Switzerland (Schürch et al. 2007) but do not consider integrally the characteristics of karst aquifers. The example

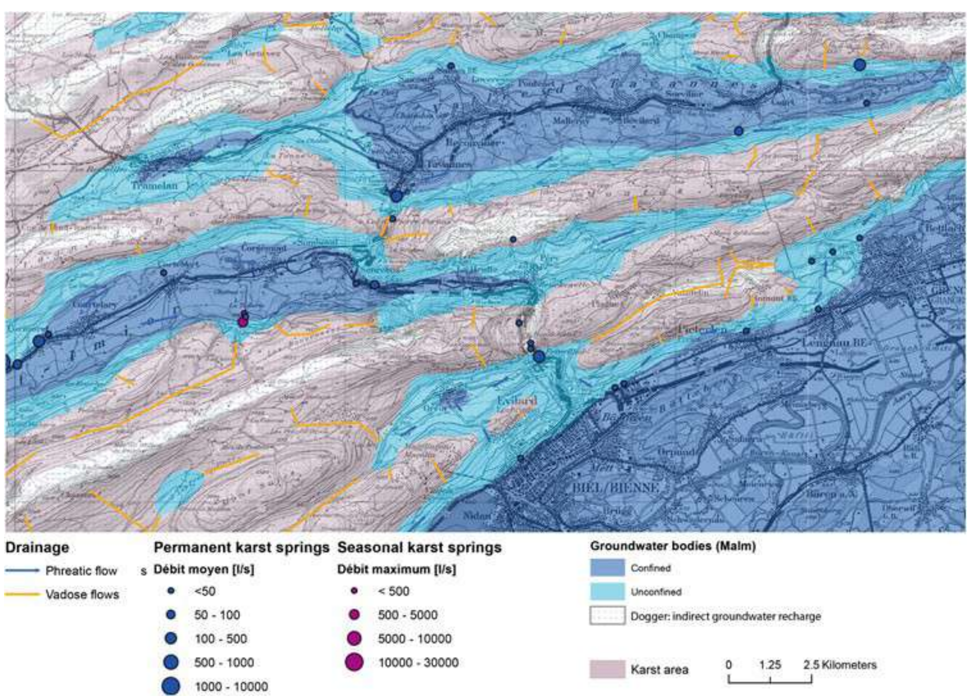

Fig. 114.3 Overview of the 1/100,000 karst hydrogeological map of the Malm aquifer in the Bernese Jura (region Biel). The shape of the aquifer *bottom* and the main drainage axes are represented on the map. This map may be considered as a map of the "aquifer functioning"

presented in Fig. 114.3 is now being proposed. It includes the following information:

• the delineation of karst groundwater bodies (i.e. the phreatic zones) the direction of flows;

• the geometry (hill-shaded topography) of the aquiclude;

• the main drainage axes (conduit network) discharging most of the groundwater flows;

At a local scale, maps are focused on one single karst flow-system with a group of hydraulically related springs. All previously described information are displayed as well as, in addition, the respective catchment and sub-catchment areas. High-flow situations may be incorporated on that map if they were assessed (see on www.swisskarst.ch).

Conclusion

The Swisskarst project was the opportunity to initiate the documentation of karst aquifers in Switzerland in a systematic and pragmatic way to offer a consistent information and material to actors (institution, communities, private companies, etc.) who frequently interact with these environments and their resources. About 35 % of the Swiss territory was investigated in this way for a large variety of purposes, demonstrating the feasibility and usefulness of the approach. The project's frame allowed the development and the improvement of a dedicated approach—KARSYS—as well as a series of simulation tools to approach the hydro- logical and hydraulic behavior of the karst systems. As of today, the project material represents by far the most docu- mented database on karst aquifers in Switzerland. The pro- ject also provided a series of dedicated approaches and tools to assess main issues in any karst environment in Switzer- land and abroad: water supply, flood hazards prediction, assessment of hydroelectric potential or geothermal implantation.

A new set of karst hydrogeological maps have been proposed to the Swiss water authorities in order to integrate the main characteristics of karst aquifers into the official set of hydrogeological maps (1/500,000, 1/100,000), as well as for more local and specific maps (1/25,000, 1/10,000).

We hope that thanks to the Swisskarst project, karst aquifers and their specificities will be better included in the management schemes leading to a sustainable management of water resources and of the environment.

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10.11. Appendix 11: Efficiency criteria for models calibration and validation

Although relevant model calibration should be first **visually estimated**, different statistical or graphical criteria do exist to **objectively evaluate** the efficiency of the model calibration. Different authors proposed guidelines for the objective evaluation of the calibration; Madsen et al. [2002]; Moriasi et al. [2007] Biondi et al. [2012]; . Most of these criteria are presented and discussed in Biondi et al. [2012] who also provide general guidelines for a validation protocol.

The first criteria to check are the **volume conservation coefficient (VCC)** and the **discharge balance coefficient (β)**. VCC compares the volume of water generated by the model with the observed one over the simulation period (Equation 10—1). β is a similar indicator. It reflects the ratio between the mean simulated outflows and the mean observed ones. These two coefficients bring global information on the outflows quantity from the model; they should be supplemented by additional criteria providing indications on the dynamics at time t (respect of peak-flows amplitudes, respect of recession phases, etc.)

A. $VCC = \sum_{t=1}^{n} \frac{Q_{s,t}}{Q_{o,t}}$

B. $\beta = {}^{\mu_s}/_{\mu_o}$

Equation 10—1. A. Expression of the volume conservation coefficient (VCC), n is the number of time step, $Q_{s,t}$ is the simulated value (here discharge rate) at time t while $Q_{o,t}$ is the observed one. B. Expression of the discharge balance coefficient; μ_s is the mean of the simulated values while μ_o is the mean of the observed values

The **mean squared error** ("MSE", see Equation 10—2) is the simplest calibration coefficient. It depends on the units of the simulated variable. Ideally MSE tends to zero.

$$MSE = \frac{1}{n} * \sum_{t=1}^{n} (Q_{s,t} - Q_{o,t})^2$$

Equation 10—2. Expression of the Mean squared error MSE; n is the number of time step, $Q_{s,t}$ is the simulated value (here discharge rate) at time t while $Q_{o,t}$ is the observed one

The **variance** ("Var", see Equation 10—3) of the residual series (simulated values minus observed one) may also be used as an indicator of the calibration. The smaller the variance, the more the model accurate is.

$$Var = \frac{1}{n} * \sum_{t=1}^{n} (Q_{diff,t} - \mu_{diff})^2$$

With $Q_{diff,t} = Q_{s,t} - Q_{o,t}$

Equation 10—3. Expression of the Variance; n is the number of time step, $Q_{s,t}$ is the simulated value (here discharge rate) at time t while $Q_{o,t}$ is the observed one and μ_{diff} is the mean of the residual series Q_{diff}.

Nash and Sutcliffe [1970] introduces a specific coefficient (**"NASH"**) based on the MSE divided by the variance of the observations (Equation 10—4). This coefficient is widely used for calibration of hydrological model and often integrated as the main (or even "unique") indicator in most commercial software.

$$NASH = 1 - \frac{\sum_{t=1}^{n}(Q_{s,t} - Q_{o,t})^2}{\sum_{t=1}^{n}(Q_{s,t} - \mu_o)^2} = 1 - \frac{MSE}{\sigma_o^2}$$

Equation 10—4. Expression of the NASH coefficient; n is the number of time step, $Q_{s,t}$ is the simulated value at time t (here discharge rate) while $Q_{o,t}$ is the observed one, μ_o and σ_o are respectively the mean and the standard deviation of the observations

The NASH coefficient ranges from -∝ to 1 (1 being the ideal value). For NASH < 0, the mean of the observed values is a better indicator than the calibrated model. For NASH = 0, the results provided by the model are as accurate as the mean of the observed values. Usually, the model may be considered as reliable once NASH > 0.8.

Several authors discussed the reliability of the NASH coefficient: Krause et al. [2005], Gupta et al. [2009]; , etc. As explained by Gupta et al. [2009], the expression of the coefficient is decomposed in three components which could be interpreted one after the other as (i) the mean, (ii) the deviation (or bias) and (iii) as the ability of the model to "*reproduce timing and shape as measured by the correlation coefficient"* (= measure of variability) in order to test each member independently.

In its actual form, the NASH coefficient provides a better score to models that underestimate the variability of the outputs. As most of the models are automatically calibrated by regressing simulated again observed values, Gupta et al. [2009] noticed that if the NASH coefficient is used to calibrate the model's parameters, high values (i.e. peak-flows) will be slightly underestimated while low values (low-flows) tend to be overestimated.

The authors then introduced a revised form of coefficient (**"KGE"** for Kling-Gupta Efficiency) based on the computation of the Euclidian distance of the three components from the position of an ideal point. The revised equation may be expressed in the following form (Equation 10—5):

$$KGE = 1 - \sqrt{(r-1)^2 + (\propto -1)^2 + (\beta - 1)^2}$$

$$\text{with} \quad r = {}^{Cov_s}/_{\sigma_s \, . \, \sigma_o}$$

$$\text{and} \quad \beta = {}^{\mu_s}/_{\mu_o}$$

$$\text{and} \quad \propto = {}^{\sigma_s}/_{\sigma_o}$$

Equation 10—5. The alternative KGE coefficient; r refers to the linear correlation coefficient between simulated and observed values, Cov refers to the covariance of simulated data, μ refers to mean values (μ_s for simulated and μ_o for observed values) and σ refers to deviation (σ_s for simulated and σ_s for observed values).

Compared to the NASH coefficient, the use to the KGE coefficient avoids the above-related problems (overestimation of the base-flows, respectively underestimation of the peak-flows and minimization of the variability). As for the NASH coefficient, KGE ranges from 0 to 1 (1 being the ideal value).

10.12. Appendix 12: RS3.0 Simulation test

10.12.1. Design of the recharge simulation model

The model is based on the extension of the low-flow catchment areas of the BC and BV systems which are both divided in sub-catchments of autogenic or allogenic source (the reader is asked to refer to Malard et al. [2015a] for additional information on the low-flow catchments of the systems). Autogenic sub-catchments are usually square of 500 m by 500 m while allogenic ones may be of various sizes as they do not directly infiltrate. Each sub-catchment is tagged with an unique ID and each autogenic sub-catchment refers to an unique karst conduit (of vadose or phreatic type).

237 sub-catchments have been defined for the BC flow-system and 76 for BV. All of these are introduced into RS3.0. Permanent and overflow springs of BC and BV (B, C, Bf and V) are considered as two unique and virtual outlets (Figure 10—7) in order to compare the recharge simulation with the systems regime. When records overlap, discharge rates of the B and C springs have been summed over the period 27/08/2001 to 01/01/2013 at an hourly time step. Discharge rates of the Bonnefontaine and Voyeboeuf springs have been summed over the period 01/01/2001 to 01/01/2013 at an hourly time step. Simulated discharge rates of the BC and BV karst systems will be compared with the observed ones at the systems outlets thanks to the BV and BC comparator. CdP and Mz are implicitly included in the simulation as respective outlets of BC and BV flow-systems.

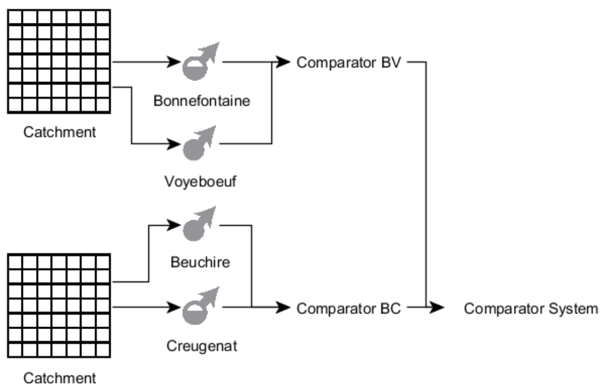


Figure 10—7. Schematic overview of the recharge model and the comparator in RS3.0 for BC and BV. Computed recharge at BV is compared to the summed discharge rate of Bf + V while the computed recharge at BC is compared to the summed discharge rate of B + C

Depending on their respective range of elevation, sub-catchments may be refined in elevation bands for a better discretization of the precipitation vs. elevation, making the model structure quite complex.

10.12.2. Calibration

As displayed in the §. 6.3.2.1, hydrological measurements of the 4 springs may only be compared over the periods 2002-2004 and eventually 2009 as measurements of Beuchire are missing for the other periods. The calibration is performed over the period from **Dec. 2001 to Dec. 2004** (i.e. 3 years) at hourly time step, using hourly rainfall / temperature values from the three meteorological stations FAH, THE and BRE and using daily ETP at FAHY. The RS Calibrator makes it possible to adjust the different parameters of the calibration (see details in e-dric [2012]).

The accuracy of the calibration is discussed first, with respect of the baseflow signal, then with the coefficient of Volume conservation (VCC), third with the respect of the ETR order and at last with the NASH criteria (KGE is not computed in RS3.0). It should be kept in mind that the NASH criteria is considered as a non-so relevant criteria as it overestimates the relative significance of the peaks matching compared to the authors criteria (especially the low-flow signal, the flanks profile, etc.). Calibration curves for BC and BV are displayed in Figure 10—8.

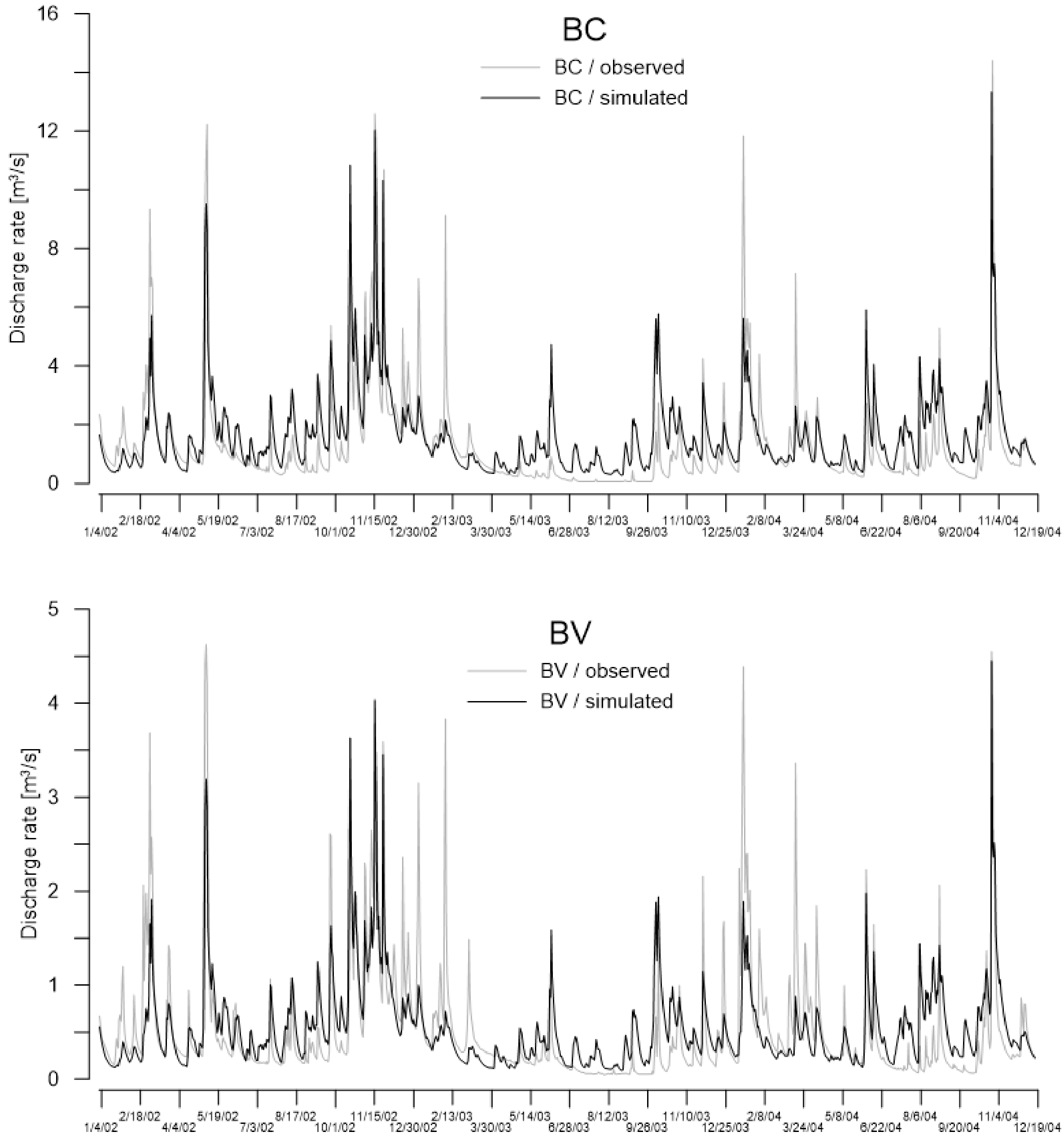


Figure 10—8. Calibration of the RS3.0 recharge model over the period 2002-2004 for BC and BV compared to the cumulated discharge rates of their respective springs: Beuchire + Creugenat for BC and Bonnefontaine + Voyeboeuf for BV

The best calibration provides a VCC comprised between 0.96 for BV and 1.10 for BC and a NASH criteria close to 0.6. These criteria show that the calibration is far from being satisfactory.

The slopes of the recession and the shapes of the peak flanks for the simulated curve are consistent with the measurements. In detail the calibration curve slightly underestimates the baseflow signal in winter and conversely the baseflow signal for the summer time is overestimated. This underestimation could be observed systematically between December and April (-50%). The overestimation concerns the period from May to November (+50%).

Peaks of flood events are systematically underestimated in winter (January to February) while in summer (August to November) the model significantly overestimates the flood peaks. Nevertheless, flood events are well reproduced for the autumn period (October to December). These contrasted reaction of the system compared to the modelled regimes have been already mentioned by Monbaron and Bouvier [1999]. The authors already observed that the intensity of winter floods are larger than expected and are not consistent with the intensity of the rainfall.

When zooming, peak floods appear to be more or less delayed compared to the measurements. The graph show that simulated winter peak floods are concomitant with the observed ones while simulated summer peak floods show a sensitive delay compared to the records.

Results of the calibration with RS3.0 should be nuanced depending on the seasons… These seasonal misfits are assumed to be a consequence of the RET computation. The annual RET reaches here 225 mm, i.e. 20 % of the annual mean precipitation over the 3 years (~1'050 mm). Such a value is too low compared to values assessed by Jeannin and Grasso [1995a] who assess RET between 430 and 530 mm for an adjacent karst system of lower elevation, i.e. 40 to 50% of the raw precipitation. Thus we expected that the global RET of the BC and BV system may be about 200 m higher than the simulated value... In spite of the efforts which have been made to constrain the upper GR3 reservoir, the model did not really improve the computation of the RET. First, the Turc formula used for computation may be questionable; although it provides monthly values, it reveals awkward to discretize such values to daily or hourly values. In a second time, it may be supposed that a part of the RET comes from the interception reservoir which is computed upstream of the GR3. Nevertheless, the interception sub-model is too simplest to discretize land-uses and to compute seasonal variations of the RET due to the vegetation development.

This observation suggests that RS3.0 is then more adapted to alpine catchments where vegetation is scarce and where the recharge mainly depends on the snow and the glaciers melt processes. In low-land areas, RS3.0 is not appropriate as recharge depends on the computation of RET which is mainly controlled by land-uses (soils and vegetation) and seasons.

10.12.3. **Simulation 2007**

Simulations have been operated over the first 13 days of August 2007 at hourly time step in order to assess the groundwater recharge responsible for the flood event of the 9th of August. Results are displayed on the Figure 10—9. It is recalled that no measurements do exist for the Beuchire spring over this period, only those for the Creugenat overflow spring. Consequently the simulated regime for the BC system cannot be compared one-to-one to the measurements. For BV, the relevance of the simulated regime may be compared to the measurements as both Voyeboeuf and Bonnefontaine springs were measured at that time.

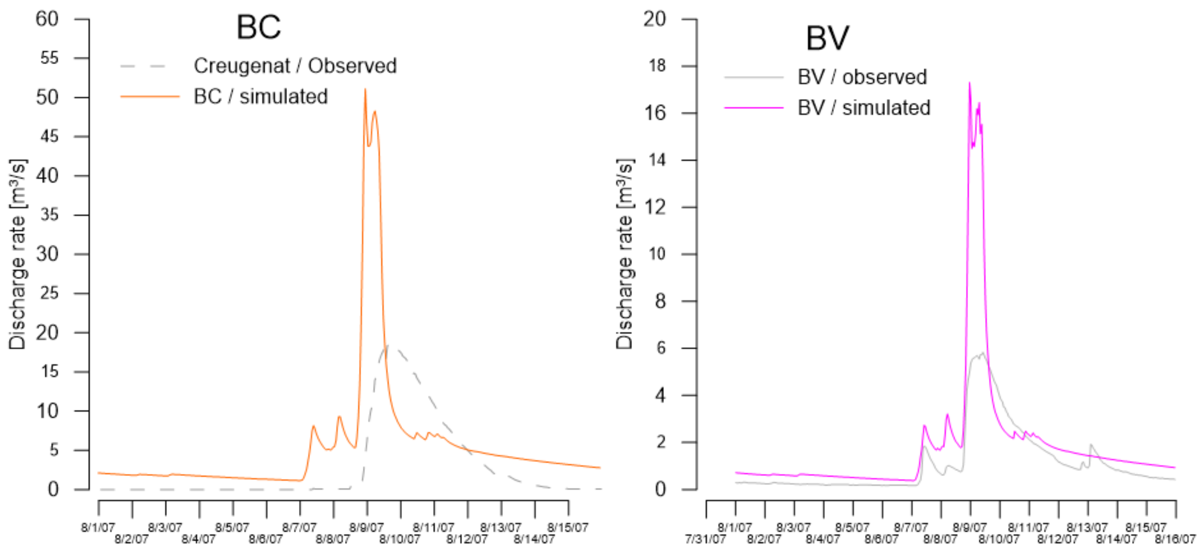


Figure 10—9. Results of recharge simulations for the flood event of August 2007 using RS3.0. Simulations could only be compared with measurements at BV as the Beuchire spring (BC) was not measured over this period.

For BC, the comparison between simulated and observed is difficult because measurements of the Beuchire spring are missing. The baseflow cannot be compared. However, the peak for the flood event of August 2007 is clearly overestimated by the model. Altogether, the cumulated discharge rates of Beuchire, Creugenat and Creux-des-Près was supposed to be about 24 m^3/s for the peak of the flood while the model predicts more than 50 m^3/s, i.e. a difference of about 26 m^3/s! At that stage, it is possible to argue that the model is wrong for this period.

For BV, the baseflow regimes are well reproduced by the model even if they are still slightly underestimated in winter and slightly overestimated in summer. Floods are also underestimated in winter (January to April) and underestimated in summer (May to October). As for BC, simulated floods fit the observed measurements between November and January. Regarding the flood event of August 2007, the model also overestimates the peak of the flood (17 m^3/s instead of 6-7 m^3/s recorded, both including Mz). Here also the model is not reliable for the simulations.

As for the calibration, simulations results for August 2007 confirm that simulated recharge for summer floods are overestimated by about a factor 2. These simulation results could not be considered as reliable and <u>will not be further used</u>.

10.13. Appendix 13: Selection of appropriate meteorological stations in Ajoie (JU) for being used in the recharge models

Climate in Ajoie (JU) is mostly dominated by meteorological disturbances coming from the West. A recurrent lag may exist between measurements depending on the longitude of the stations. Six meteorological stations Fahy (FAH), Montenol (MTO), Mormont (MMO), Vacherie-Mouillard (VAC), Theodoncourt (THE) and Bressaucourt (BRE) do exist in the vicinity of the BC and BV karst flow-systems (locations and characteristics of the stations are respectively displayed in §. 6.3.3.2.2). As they display a few deviation in measurements, a **cross-correlation analysis** between the regime of BC system (daily values) and rainfall measurements for each meteorological station (daily values) over a few months in 2002 has been realized in order to select the most appropriate stations for the simulations (Figure 10—10).

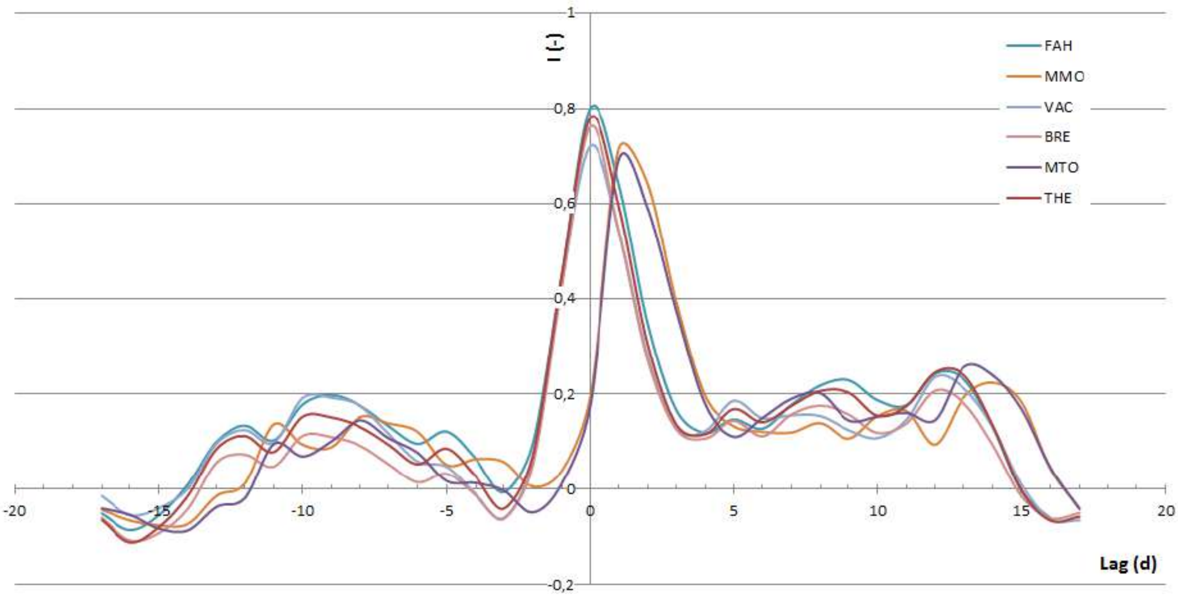


Figure 10—10. Cross-correlation plots between the BC system's regime and the measured precipitations at meteorological stations FAH, MMO, VAC, BRE, THE, MTO (daily time step)

It appears that recorded values at FAH provide the best correlation with the system's regime in intensity (0.8) and in time. Stations THE and BRE show a good correlation in intensity (close to 0.8) and in time; no significant lags may be observed with the system's regime. These last two stations being located within the catchment, which explains the good correlation in time. VAC shows a good correlation in time but correlation in intensity is low (~0.72); the station is quite elevated (810 m a.s.l.) and lies outside of the catchment area. MTO and MMO show both a lower correlation in time and intensity (~0.7). Based on these observations, only FAH, THE and BRE will be considered.

The comparison of the daily precipitation values P_1, P_2, P_3 at the stations FAH, THE and BRE makes it possible to point out periods for which significant dispersions between measurements are observed. Over the period from Dec. 2001 to Dec. 2004, these dispersions have been computed with the following Equation 10—6. The normalized daily dispersion between the three station is plotted Figure 10—11.

$$E = \frac{std(P_1 + P_2 + P_3)}{Md(P_1; P_2; P_3)}$$

Equation 10—6. Normalized dispersion E of the gauged precipitation rates between the three meteorological stations (Std = standard deviation, Md = median)

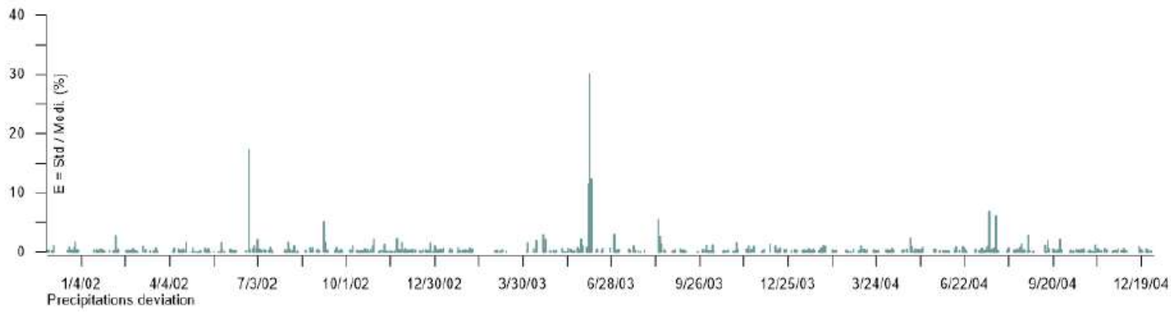


Figure 10—11. Normalized daily dispersion of gauged precipitation rates for the three meteorological stations FAH, BRE and THE; over the period, the global uncertainty in precipitation measurements is about 1% but for specific events, especially for higher rates of precipitation, dispersion may reach up to 30%...

Regarding the graphic, the average deviation between recorded values all along the period from Dec. 2001 to Dec. 2004 is about 1%. For rainy periods, misfits are still negligible as they reach 2 to 5%. They reflect as well **disparities of the precipitation** over the catchment as the **device deficiencies**. However, significant misfits (E > 5%) do appear at six occasions in summer (24/06/2002, 08/09/2002, 06/06/2003, 15/08/2003, 17/07/2004 and 24/07/2004). These are attributed to local storms that occur on a small part of the catchment. Consequently, computed values of equivalent precipitation for these episodes cannot be considered as representative for the whole catchment.

10.14. Appendix 14: Simplified hydraulic model

A simplified SWMM hydraulic model of the BC/BV karst systems has been built in parallel to the establishment of the detailed SWMM model (§. 6.3.4). The objective was to test various scenarios on the simplified model as it runs faster than the detailed one. This model will use recharge time-series provided by KRM_1.

10.14.1. Model design

10.14.1.1. Conduits geometry

The catchment area of the BC flow-system has been divided into **9 sub-catchments** while the catchment area of BV has been divided into **2 sub-catchments**. The BC conduit network is reduced to one main conduit with nine tributaries (resp. sub-catchments J3, J5, J6, J16, J17, J18, J19, J20 and J21) and BV entails one main conduits with two tributaries (resp. sub-catchments J13 and J14). Conduits diameter has been adjusted as follow (Figure 10—12). The narrow conduits linking the Creugenat to the POR3 borehole does not exceed **0.8 m of diameter** while the diameter of the **by-pass conduit is about 1.3 m**. As evidenced by the KARSYS model, two bypass conduits have been implemented, respectively at 450 m and 470 m a.s.l. These conduits are supposed to transfer groundwater from BV to BC for high-flow conditions. In this model, minor springs (Chaumont, etc.) are here not considered.

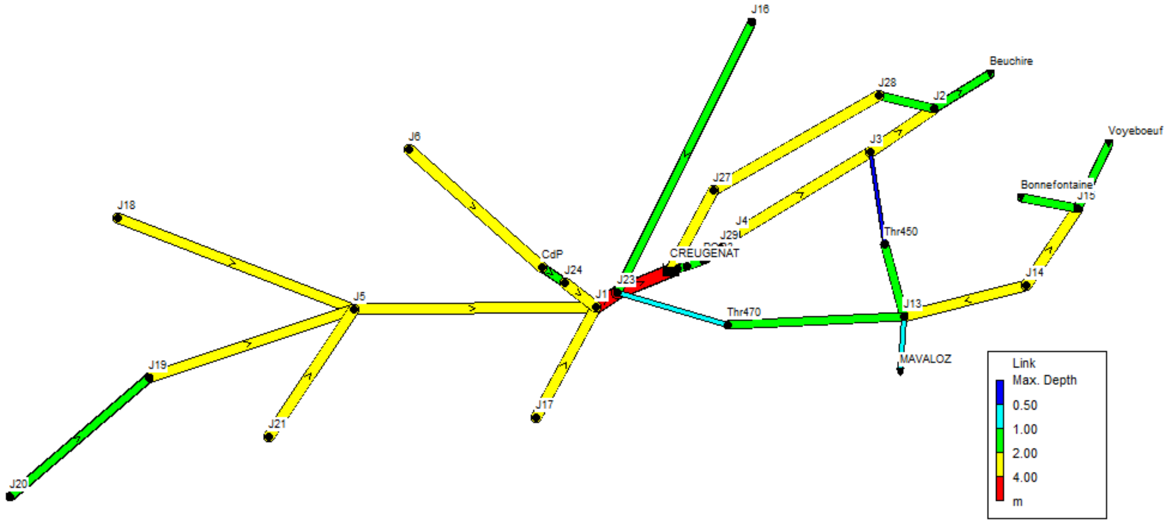


Figure 10—12. Overview of the simplified SWMM hydraulic model of the BC/BV karst systems; colors refer to the diameter of the conduits. “Thr450” and “Thr470” refer to the supposed bypass conduits between BC and BV.

Details of the 11 sub-catchments and of their land-uses are listed in the Table 10—9.

Sub-catchments	Surface (km^2)	FOREST (km^2)	MEADOWS (km^2)	URBAN (km^2)	DENUDATED KARST (km^2)
j3	3.5	1.165	2.188	0.112	0.035
j16	6.0	1.998	3.7500	0.192	0.060
j6	13.0	4.329	8.125	0.416	0.130
j18	5.0	1.665	3.125	0.160	0.05
j5	7.0	2.331	4.375	0.224	0.070
j19	4.5	1.499	2.812	0.144	0.045000
j20	7.0	2.331	4.375	0.224	0.070
j21	5.4	1.798	3.375	0.173	0.054
j17	7.0	2.331	4.375	0.224	0.070
j13	9.4	3.130	5.875	0.301	0.094
j14	9.5	3.164	5.937	0.304	0.095

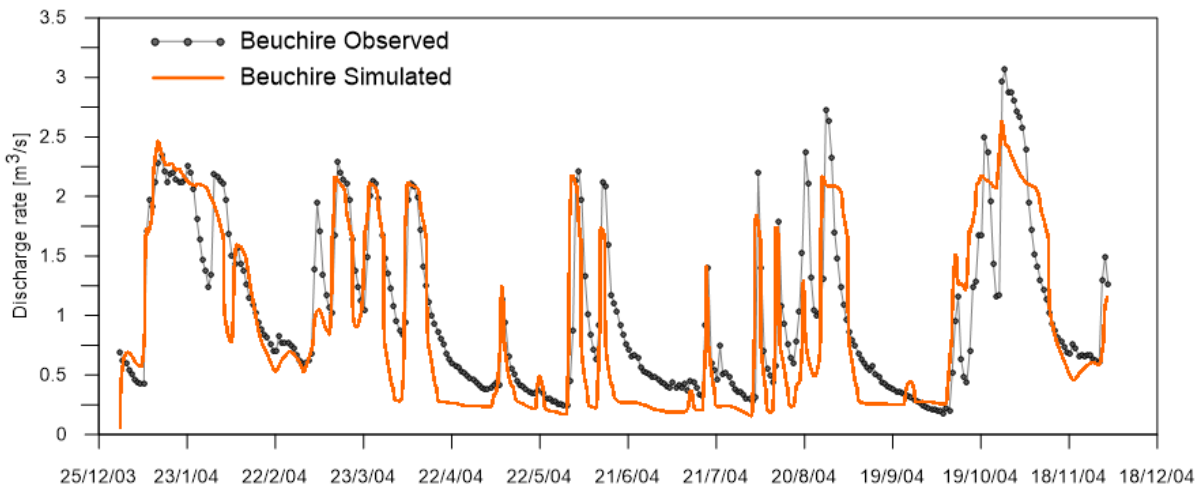
Table 10—9. Characteristics of the 11 sub-catchments of the simplified recharge model (KRM_1)

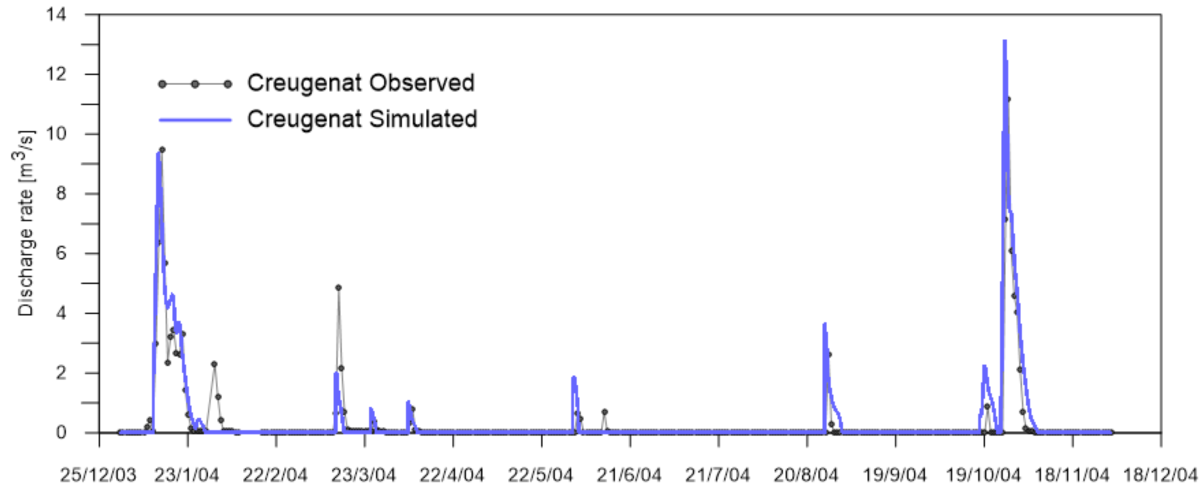
10.14.1.2. Input recharge files

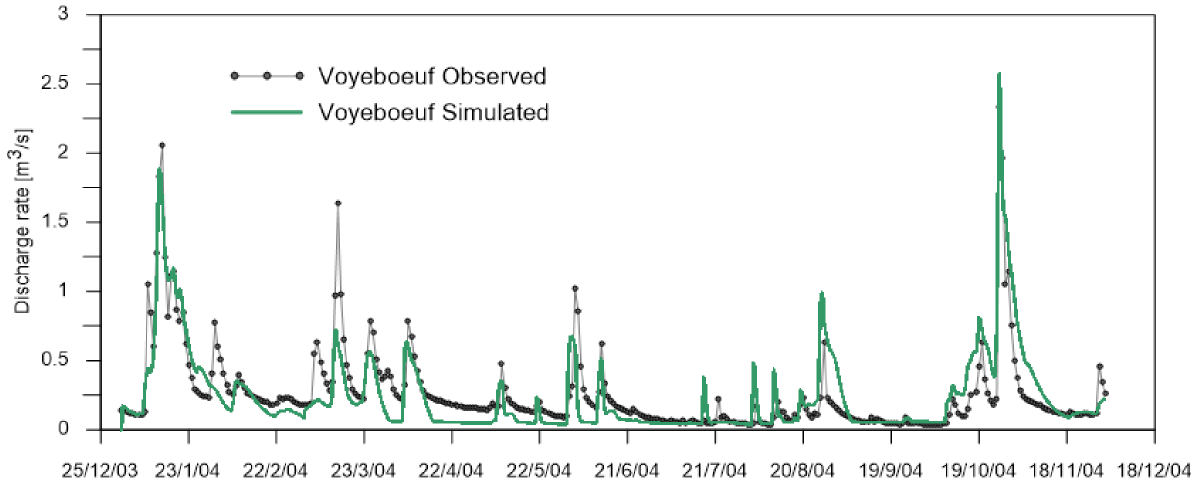
For each sub-catchment, the associated recharge has been computed for the period **from Jan. 2004 to Dec. 2004** by applying KRM_1 (similar as for §. 11). Recharge is computed at hourly time step by using distributed P_{eq} obtained from the three meteorological stations FAH, THE and BRE. A second recharge time-series has been computed for August 2007 by using the distributed P_{eq} based on hourly FAH measurements.

10.14.2. Calibration and validation

Computed recharge files are implemented in SWMM as inputs of the conduits model. The calibration of the conduit model is performed over the whole period from **Jan. to Dec. 2004**. Results of the calibration for springs discharge rates (B, C, Bf, V) and for hydraulic heads (POR3 borehole and Mz) are displayed Figure 10—13 and compared to existing measurements. The hydraulic relation between the simulated discharge rate at the Beuchire spring and the simulated water level in the Creugenat is plotted Figure 10—14.




Creugenat Observed
Creugenat Simulated
Discharge rate [m3/s]
0
2
4
6
8
10
12
14
25/12/03
23/1/04
22/2/04
23/3/04
22/4/04
22/5/04
21/6/04
21/7/04
20/8/04
19/9/04
19/10/04
18/11/04
18/12/04


Voyeboeuf Observed
Voyeboeuf Simulated
Discharge rate [m3/s]
0
0.5
1
1.5
2
2.5
3
25/12/03
23/1/04
22/2/04
23/3/04
22/4/04
22/5/04
21/6/04
21/7/04
20/8/04
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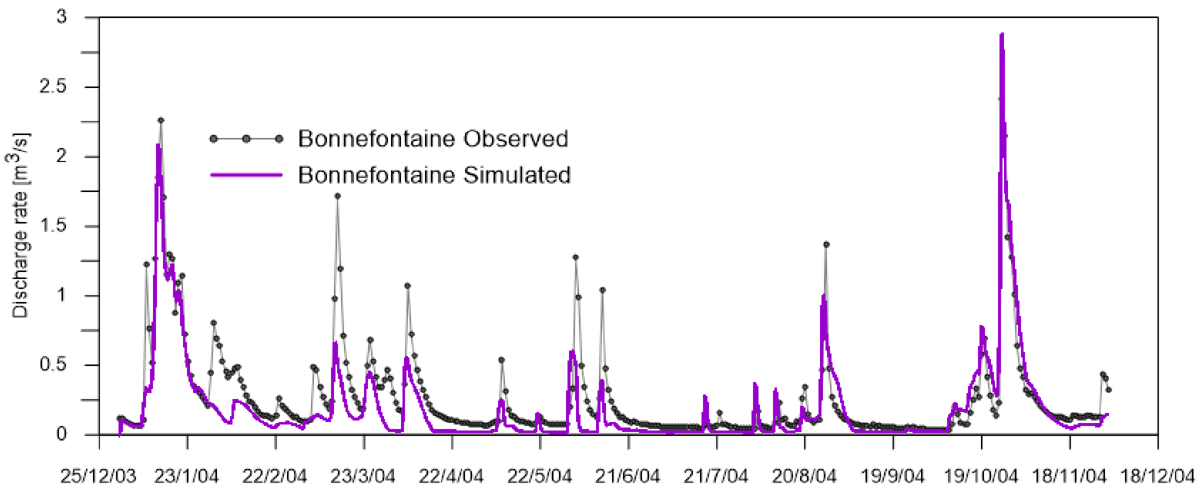
19/10/04
18/11/04
18/12/04


Bonnefontaine Observed
Bonnefontaine Simulated
Discharge rate [m3/s]
0
0.5
1
1.5
2
2.5
3
25/12/03
23/1/04
22/2/04
23/3/04
22/4/04
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18/11/04
18/12/04

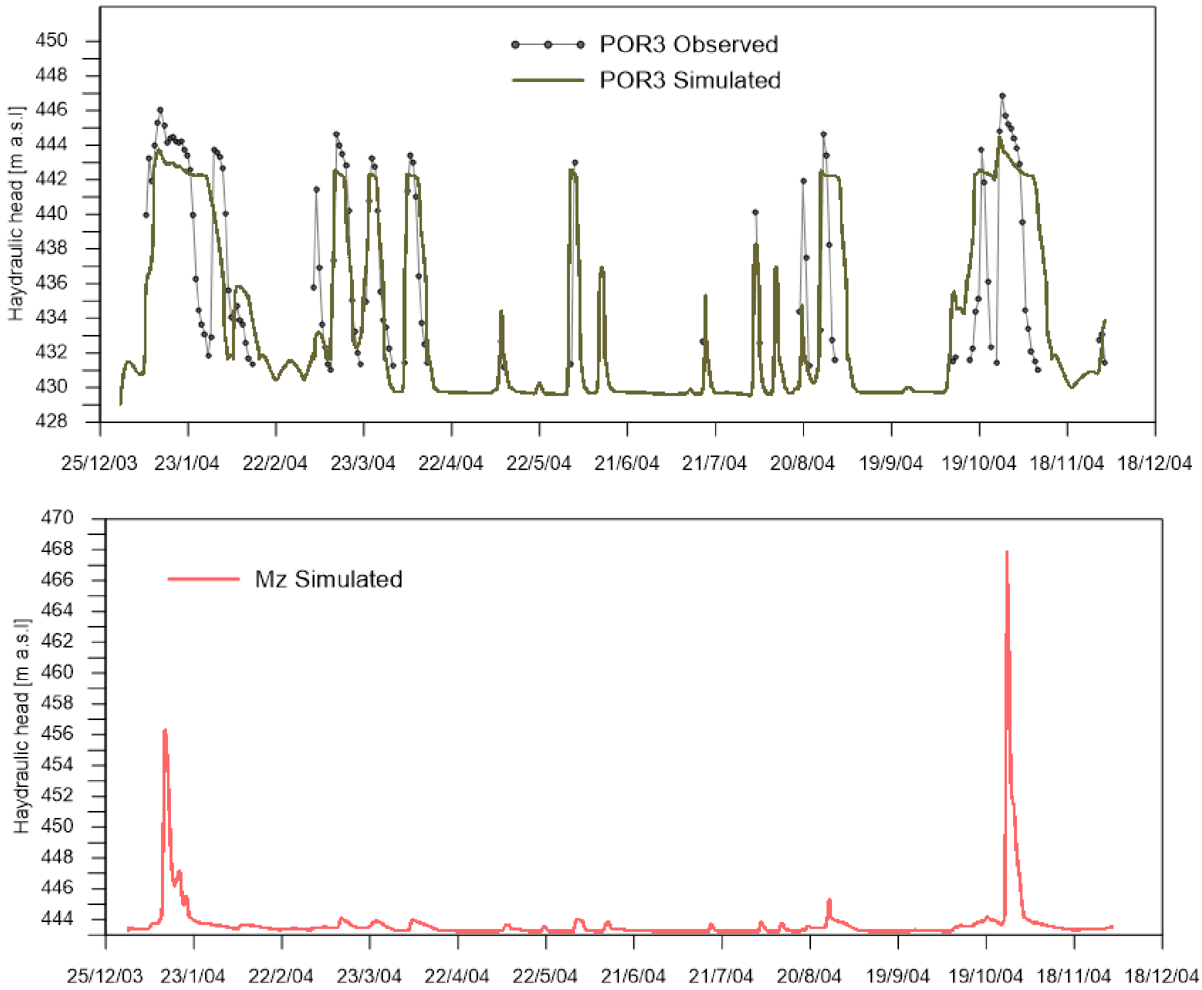


Figure 10—13. Calibration results for the discharge rates at Beuchire (B), Creugenat (C), Voyeboeuf (V) and Bonnefontaine (Bf) springs and for hydraulic heads at POR3 (borehole) and Mz (cave).

Globally the calibration shows a **good fit** between observed and simulated values. Amplitudes of simulated regimes are the same order of magnitude than the observations. For all springs, **frequencies of floods are fairly well reproduced**. Intensities of the floods are better simulated for autumn and winter time while they are a bit underestimated for summer time. This is independent of the hydraulic model; it mainly depends on the recharge time-series. Recession and low-flow regimes for permanent springs are **underestimated** (Beuchire, Voyeboeuf and Bonnefontaine). Simulated regimes sharply decrease after the floods compared to the observed dynamic. This probably reflects the release of the groundwater stored in the soils/epikarst and in the low permeability volumes of the aquifer, especially for the summer time… Smoothed recessions cannot be solved within the hydraulic model.

Calibration results for **POR3** do well match with the measurements. Variations of the hydraulic head in the borehole are consistent in frequency with the observations (frequencies and intensities). However, fluctuations of observed floods and recessions are faster than simulated ones. For this case, hydraulic heads in the aquifer fluctuate faster than in the model which is a bit contradictory with the dynamics of the recessions we observed at the springs. In **Mz cave**, two peaks could be observed on the simulated curve. As the cave opens at 471 m, simulations show that the cave does not overflow in 2004 even if the water was close to the ground surface in late October (~468 m). This is consistent with the hydrological regime of this cave which may flood one or two time(s) per year.

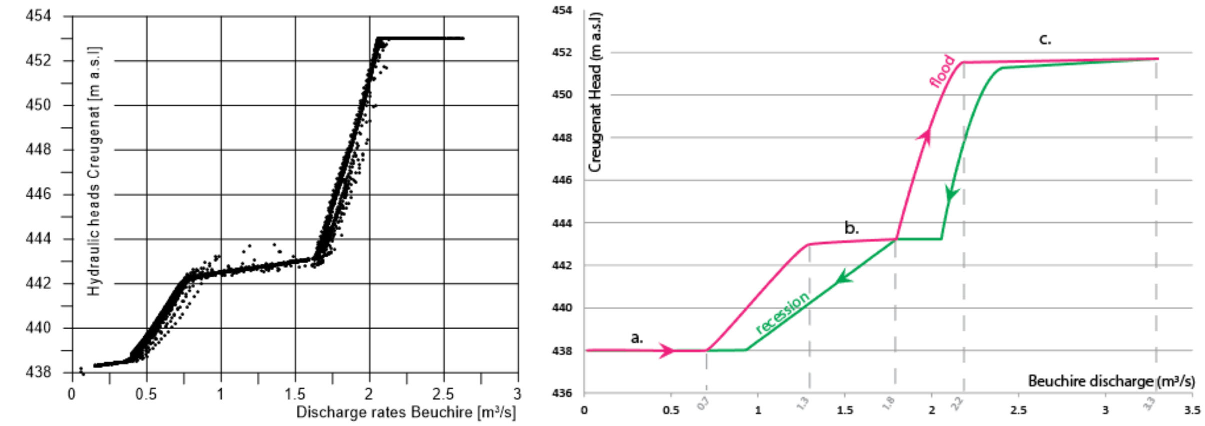


Figure 10—14. Hydraulic relationship between the discharge rate at the Beuchire spring and the evolution of the hydraulic head in the Creugenat (left: simulated, right: observed)

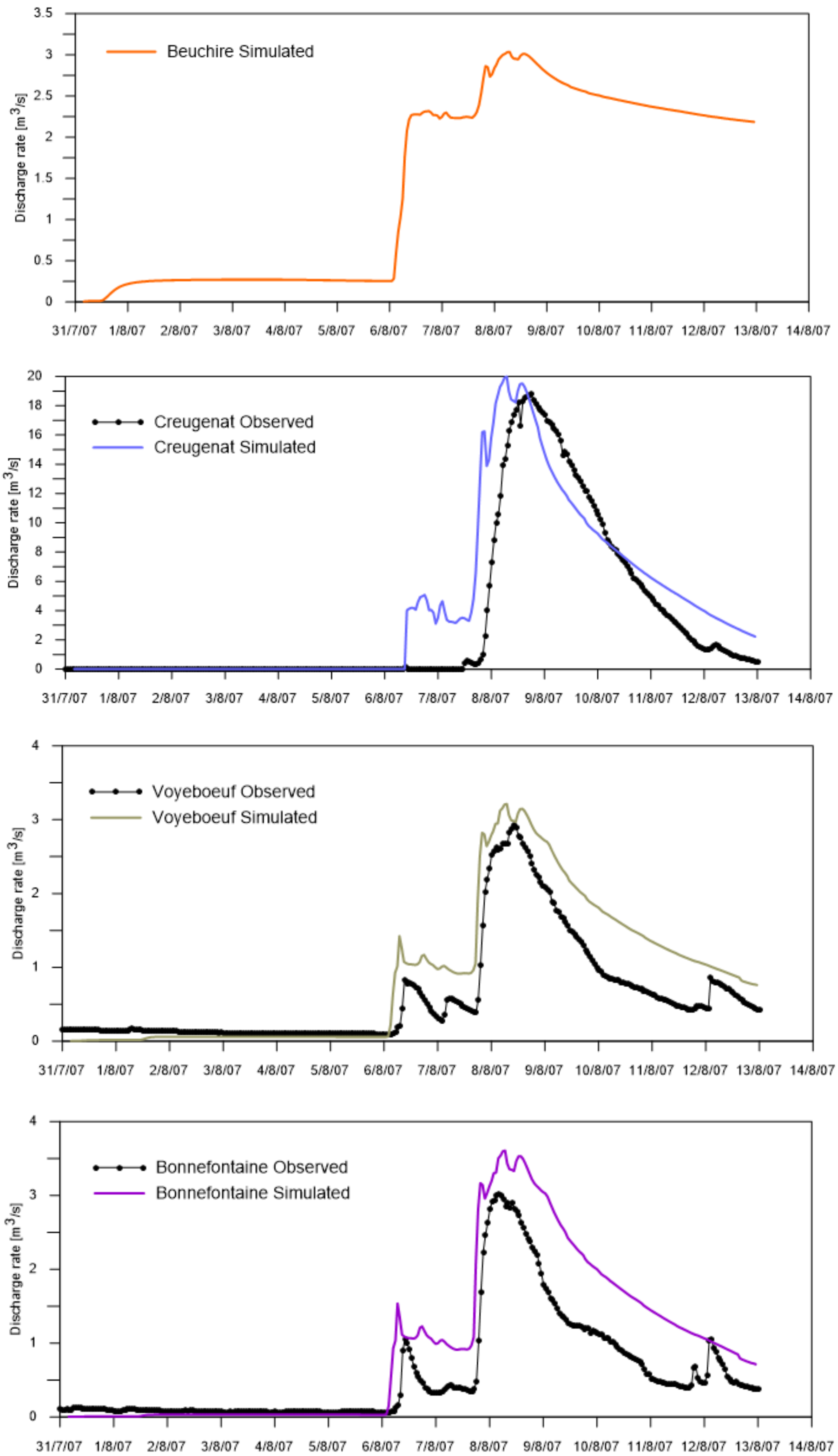
The simulated relationship between the discharge rate at the Beuchire spring and the evolution of the hydraulic head in the Creugenat is close to the observed curve. The three stages a., b, and c. are well reproduced; they confirm the activation of the by-pass conduits at 443 m. In detail, the model reacts a bit faster compared to the observations: the hydraulic heads at Creugenat starts rising above 438 m when the discharge rate exceeds 0.5 m^3/s (instead of 0.7 m^3/s), the plateau at 443 m a.s.l is reached for a discharge of 0.75 m^3/s (instead of 1.3 m^3/s). For both curves, the hydraulic heads rise again above the plateau when the discharge exceeds 1.8 m^3/s and finally the Creugenat starts overflowing once the discharge rate exceeds 2.2 m^3/s. The model does react a bit fast at the beginning of the floods compared to the real dynamic, but once the plateau has been reached, deviations between simulations and observations are significantly reduced. The hydraulic functioning between these two stations is fairly well reproduced and it is locally validated by the simulated hydraulic heads in POR3.

Regarding water exchanges between BC and BV (via the bypass conduits at 450 and 470 m a.s.l.), the simulation shows that max. 0.5 m^3/s may be transferred from BV to BC once the hydraulic head in the upstream part of BV reaches / exceeds 470 m. Such exchanges may be controlled by recorded fluctuations at Mz. As we know that Mz may overflow one or two time(s) per year, it gives an indirect indication on the discharge capacity of the conduits at 450 and 470 m. The equivalent diameter of these two conduits is respectively of 0.2 and 0.5 m.

10.14.3. **Simulation of the flood event from August 2007**

The flood event of August 2007 is described in §. 6.3.3.4.2. Measurements show that the flood progressively rise until August 9th. The **peak flood is about 25 m^3/s**. Unfortunately, as the Beuchire spring was not monitored over this period, the whole computed recharge cannot be compared one to one with measurements. Existing measurements for the period show that: the Creugenat spring exceeded 18 m^3/s, V and Bf springs respectively 3 and 3 m^3/s. The supposed discharge rate of the Beuchire spring for this event was about 3.5 m^3/s (+minor springs up to 400-500 L/s). CdP may have discharged up to 2 m^3/s and Mz was also active for sure (max. 500 L/s). Globally, the sum of the discharge rates of all the springs altogether reached **30 m^3/s**.

Dynamics of this extreme event has been reproduced by using the simplified SWMM model. Computed recharge time-series for the 11 catchments are introduced as inputs of the simplified SWMM model. The model is computed at hourly time step between 1st and 15th of August. Results of the simulation are displayed Figure 10—15 and compared to measurements when they exist (hourly time step).



Beuchire Simulated
Creugenat Observed
Creugenat Simulated
Voyeboeuf Observed
Voyeboeuf Simulated
Bonnefontaine Observed
Bonnefontaine Simulated
Discharge rate [m3/s]
31/7/07 1/8/07 2/8/07 3/8/07 4/8/07 5/8/07 6/8/07 7/8/07 8/8/07 9/8/07 10/8/07 11/8/07 12/8/07 13/8/07 14/8/07

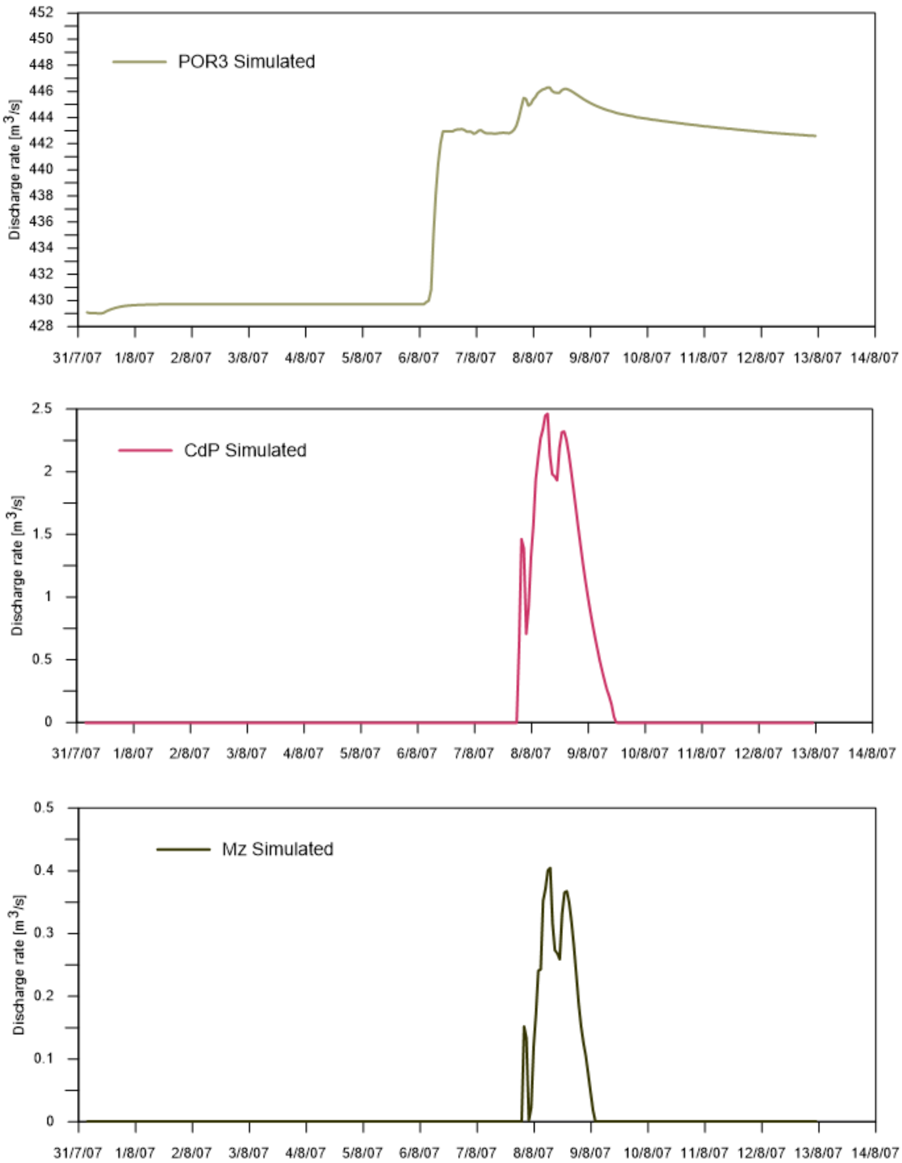


Figure 10—15. Simulation results of the simplified hydraulic model for the flood event of August 2007. Over this period, no measurements do exist for B, POR3, CdP and Mz.

Although a few measurements are available for some of the springs, simulation results show that the hydraulic model does well reproduce the expected discharge rates and hydraulic head at the different observed stations. Compared to the previous calibration over the year 2004, the simulation of this extreme event makes it possible to verify the activation of overflow springs that usually do not overflow. Here, activation time-laps and discharge rates of the Creux-des-Prés (CdP) and Mavaloz (Mz) are consistent with observations on the field (respectively 2 m^3/s and 0.5 m^3/s). As CdP usually activates one time in the decade, results show that this hydraulic model may be well suited to simulate flood events with a return-period of ~10 years. The simulation shows that exchanged groundwater from BV to BC via the conduits at 450 and 470 m a.s.l. was about 1 m^3/s during the flood peak.

10.14.4. **Conclusion**

Although the here-proposed conduits model is a strong simplification of the supposed BC and BV conduit network which certainly entail more tributaries and more complexities regarding conduits geometries in reality, calibration results for the year 2004 show relative good fits with the existing measurements or observations regarding the evolution of both discharge rates and hydraulic heads in the conduit network. Calibration results of this simplified hydraulic model should be compared to the calibration results previously computed by the detailed hydraulic model. This comparison shows that while the complexity of the model significantly increases, the quality of the calibration does not reach a much better precision when compared to existing measurements or observations. Moreover, detailed (syn. complex) models are more difficult and longer to calibrate and routing errors significantly increase.

Results of this simplified hydraulic model and of previous applications: Flims (Jeannin et al. [2007]), Brunnmühle (Jeannin et al. [2015a]) or Aubonne-Toleure (e-dric et al. [2016]) show that the hydraulic functioning of complex karst flow-systems; i.e. systems entailing multiple basal and overflow outlets, hydraulic thresholds and/or by-passes conduits may be reproduced by modeling a minimal conduit network as a starting point and by progressively adding hydraulic features as they are identified by measurements or through the analysis of hydraulic relationships (discharge rates vs. hydraulic heads, hydraulic head vs. hydraulic heads or discharge rates vs. discharge rates) between different stations of the same karst flow-system. This already supposes that a few measurements exist on the site, at least one time-series of discharge rate at the spring and one time-series of hydraulic head fluctuations (in a cave, a borehole, etc.)