ORIGINAL ARTICLE

KARSYS: a pragmatic approach to karst hydrogeological system conceptualisation. Assessment of groundwater reserves and resources in Switzerland

P.-Y. Jeannin · U. Eichenberger · M. Sinreich · J. Vouillamoz · A. Malard · E. Weber

Abstract An approach is presented for the hydrogeological conceptualisation of karst systems. The KARSYS approach helps hydrogeologists working in karst regions to address in a pragmatic and efficient way the three following questions. (1) Where does the water of a karst spring come from? (2) Through which underground routes does it flow? (3) What are the groundwater reserves and where are they? It is based on a three dimensional model of the carbonate aquifer geometry (3D geological model) coupled to a series of simple fundamental principles of karst hydraulics. This provides, within a limited effort, a consistent hydrogeological conceptual model of karst flow systems within any investigation area. The level of detail can be adjusted according to the targeted degree of confidence. Two examples of its application are presented; the approach was first applied with a low level of detail on a national scale in order to assess the groundwater reserves in karst aquifers in Switzerland, suggesting a groundwater volume of 120 km^3. On a regional scale, it was applied with a higher level of detail to some selected karst systems in order to assess their hydropower potential. The KARSYS approach may provide very useful information for water management improvement in karst regions (vulnerability assessment, impact assessment, water supply, flood hazards, landslides, etc.). It leads, in a very cost-effective manner, to a new and highly didactic representation of karst systems as well as to new concepts concerning the delineation of catchment areas in karst regions.

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Introduction

Aim of the paper

Switzerland is discharged by four main rivers belonging to important European river basins, i.e. Rhine river, Rhone river, Inn (Danube basin), and Ticino (Po basin). Let us imagine a fictitious situation in which Switzerland (Fig. 1a) would be completely karstified and, instead of surface runoff, would be discharged underground by four large springs at its borders in Basel (Rhine), Geneva (Rhone), Martina (Inn) and Locarno (Ticino). Let us furthermore imagine that the city of Zürich would like to run a well for drinking water supply, but that a large factory in the city of Chur would be a potential source of pollution. From tracer tests, we would know that Zürich and Chur both belong to the catchment area of the spring at Basel (although, Chur is much closer to the eastern and southern springs). The question is then "Can the well in Zürich be safely used?" The map of the drainage network of Swiss rivers (Fig. 1b) provides a clear answer: yes it is safe, because Zürich is located along a tributary of the Rhine river, while Chur is located along its main stream course.

Many of applied hydrogeological studies in karst aim at answering very similar question such as:

1. Where does the water of a karst spring come from?
2. Through what underground routes does it flow?

Fig. 1 a Assuming a fictitious situation in which Switzerland would be completely karstified and the existing and known surface rivers would flow underground (and would not be known), the cities of Zürich and Chur would both discharge towards a karst spring in Basle. The question would be "Could Zürich be affected by a pollution from Chur?" **b** Once the river network for **a** is known, it is obvious that Zürich is located along a tributary of the Rhine river and, therefore not directly downstream of Chur. There is thus no risk of pollution from Chur in Zürich
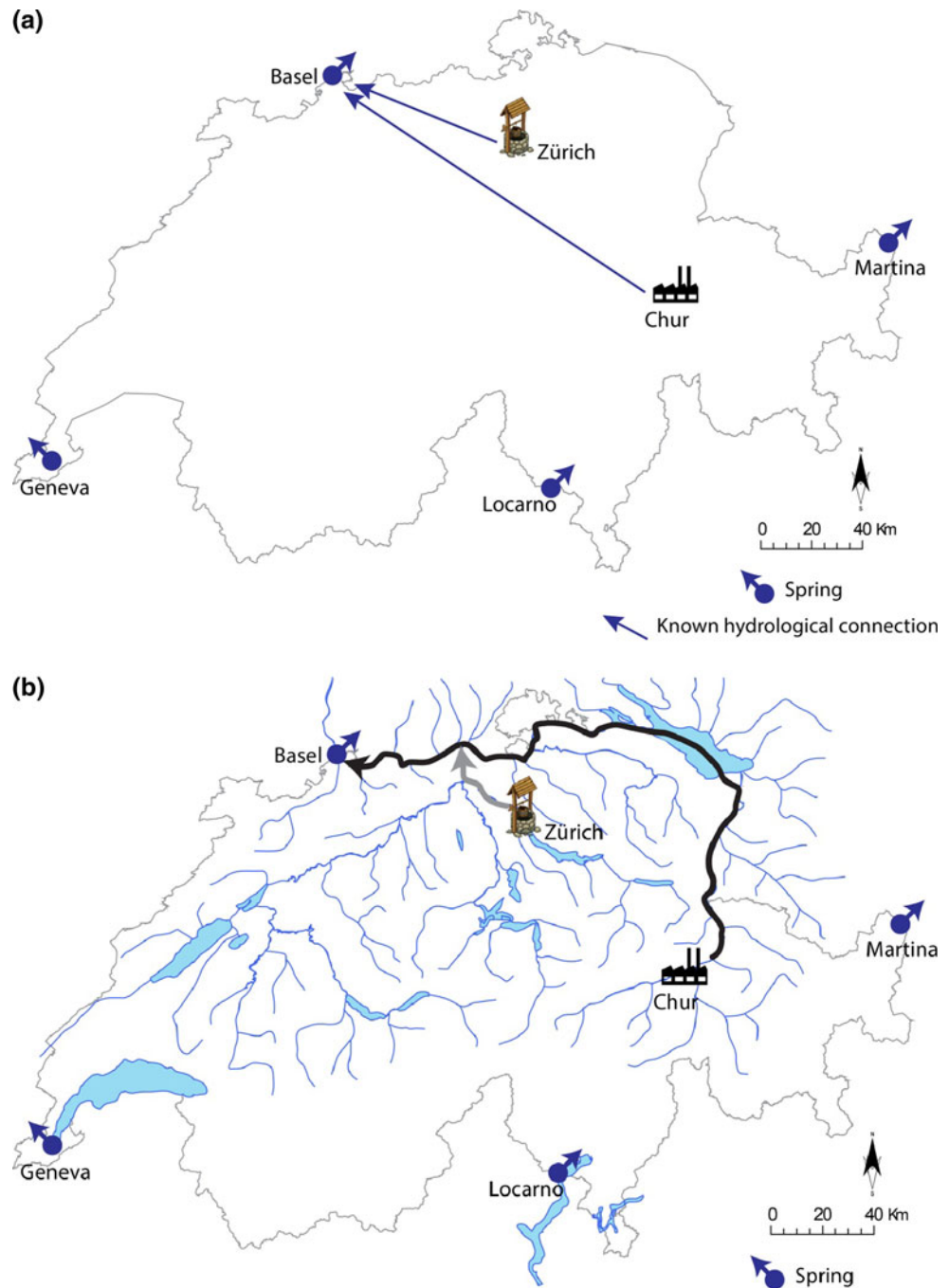
3. What are the groundwater reserves and where are they?

Answers to those questions would be trivial, if the drainage network of a karst system were known. This paper presents an efficient approach for outlining the underground flow system in a karst environment and thus answering the three questions above. The approach presented here has been developed for telogenic (mainly recharged by meteoric waters) mountainous karst.

Adjustments would be necessary in other contexts, especially in hypogenic karst.

Karst hydrogeology

Karst regions are typically characterized by specific hydrologic properties absence of surface water over most of their area, presence of swallow holes, and large springs located in the main valleys with a more or less flashy response to recharge events. These features result from the

specific drainage structure of karst systems, a subsurface network of conduits, somewhat analogous to a river network, which drains a mass of fissured and porous rock, somewhat analogous to groundwater flow in granular aquifers (e.g. Bakalowicz 2005; Ford and Williams 2007; Kiraly 1978). In this paper, we call karst aquifer a volume of rock which is potentially karstified, including the saturated and the unsaturated zones.

The key-factor in karst hydrology is the extreme contrast of hydraulic conductivity between the karst conduits and the surrounding rock matrix (Kiraly 1978). Therefore, the structure and characteristics of the conduit network (mainly the density, position and size of the conduits) almost completely determine the structure and dynamics of the flow system.

Connectivity is almost straight-forward in a telogenic karst system.

Along the last 20 years much effort has been dedicated to improve our knowledge of flow and transport processes in karst aquifers. Many studies have been conducted on surface runoff and water infiltration, flow through the soil, the epikarst, the unsaturated zone as well as within the phreatic zone, the latter including exchanges between the conduit network and the fissured/porous rock mass. These topics involved field observations, field and laboratory experiments and numerical modelling (e.g. Genthon et al. 2005; Hauns et al. 2001; Martin and White 2008). Such detailed academic studies on flow and transport are very meaningful and provide much understanding on karst hydrogeology (e.g. Dogwiler and Wicks 2004; Falcone et al. 2008; Perrin 2003; Perrin et al. 2007; Raeisi et al. 2007; Sundqvist et al. 2007). However, it appears that it is hopeless to introduce this high level of detail into regional models. Experience shows that in most cases models cannot deal with so much information and, if they can (or could), one can never assess the necessary 3D distribution of the aquifer parameters with a sufficient degree of accuracy for feeding such models.

Karst is thus a particular topic located, somewhere between surface hydrology and classical hydrogeology. In surface hydrology (1) the catchment area, (2) the structure of the drainage network as well as, (3) hydraulic heads and (4) discharge are known (at least determinable). In karst hydrogeology, the same parameters are crucial but, in contrast to surface hydrology, none of them are known for most of the time. Effort is thus mainly dedicated to assess characteristics of the drainage network, because it is the structure where more than 90 % of water in the system flows. For instance, this topic (achieving a better knowledge in karst conduit network characteristics) was mentioned as a major challenge for the future in karst hydrogeology at a workshop on "Frontiers of Karst Researches" in 2008 (Martin and White 2008).

Many techniques are applied for studying karst hydrogeology and many of them are summarized in Goldscheider and Drew (2007). Some methods are derived from surface hydrology, others from signal analysis methods, and others from classical hydrogeology. As mentioned, the objective of many karst hydrogeological investigations is to attempt a characterization of the conduit network.

Since the spring is mostly the only point, where karst groundwater can really be observed and measured, many investigations have been developed for the analysis of spring characteristics. The goal of most of these investigations is to infer information about the structure of the drainage system (e.g. Birk et al. 2002; Geyer et al. 2007; Grasso and Jeannin 2002; Grasso et al. 2003; Mangin 1984). Although methods are sometimes quite sophisticated (e.g. Kovács et al. 2005; Labat et al. 2000a, b, 2002; Long and Putnam 2004; Majone et al. 2004; Pinault et al. 2001), interpretations remain very global and equivocal. None of these studies provided clear and proven information addressing the three questions presented in the introduction.

An alternative approach is to generate the conduit network based on fairly sophisticated models of speleogenesis. The number of papers in this direction drastically increased over the past 10 years (e.g. Dreybrodt et al. 2005; Jaquet et al. 2004; Mariethoz and Renard 2011). The main reason for this increasing interest is the failing of karst system flow modelling, if not taking explicitly into account the geometry of karst conduit networks in models; most equivalent continuum modelling approaches showed their limits (Kovács 2003).

However, very few papers (e.g. Ginsberg and Palmer 2002; Palmer 1986; Palmer 1989) deal with a direct assessment of the aquifer geometry and attempt to derive the conduit network geometry from this information. For many authors this aspect (aquifer geometry) is part of the "hydrogeological context" of a karst system, and is therefore too trivial to be explicitly described, and this initial analysis is thus often neglected or conducted in a very simplistic manner.

The approach presented in this paper contributes to the understanding and visualization of the hydrogeological context in karst studies. Basically, it is neither completely new nor revolutionary. However, because many textbooks and scientific papers on karst hydrogeology are dedicated to academic purposes rather than to applied ones, this type of simplified approach is rarely explicitly mentioned. The consequence is that, although it should be the first step in most karst studies, it is often neglected and people start straight away with other investigations (e.g. tracing experiments, hydrograph analyses, hydrochemistry, water isotopes, simulations, etc.) without having first constructed a conceptual model of the karst system they investigate.

In summary, the construction of such an initial model has several advantages, i.e. (1) to restrict substantial costs for possibly superfluous investigations; (2) to define the framework and conditions for conducting complementary investigations; and (3) to improve the interpretability of collected data.

The KARSYS approach is an attempt to standardize the synthesis of available geological and hydrogeological data into a 3D conceptual model assuming some basic hydraulic principles. The model explicitly displays the following features in 3D:

1. System geological boundaries.
2. Infiltration type depicted over the whole catchment area.
3. Geometry of the karst aquifer.
4. Geometry of the karst water body.
5. Sketch of the conduit network or the main hypothesized flow paths.

The resulting 3D conceptual model is thus the hypothesis to be tested (and improved) by any further investigations (i.e. tracing experiments, hydrograph analyses, hydrochemistry, water isotopes, simulations, etc.).

Many applications have been performed at SISKA over the last 10 years. All of them provided a very useful base of information for karst water management such as quality problems, groundwater protection zoning, impact assessment regarding constructions or simply exploitation of karst groundwater at springs or by wells or galleries. Two examples are presented in this paper.

Karst groundwater documentation in Switzerland

About 20 % of Switzerland is covered by karst landscape, mainly in the Jura Mountains, along the northern border of the Alps and in some areas of the Southern Alps. Accordingly, about 18 % of Swiss drinking water supply derives from karst aquifers (Spreafico and Weingartner 2005). The first attempt to give an overview of karst in Switzerland is Wildberger and Preiswerk (1997), a book that is dedicated to a broad audience and not a systematic inventory. However, a large list of references is presented therein and a synthesis is given for some karst systems, giving a first overview.

Several types of map have been produced in relation to karst in Switzerland. The first type includes maps describing karst regions in a rather schematic manner, i.e. where karst outcrops or has only a thin cover. Most of them seem to originate from a work made by Wildberger in the early 90s, inferred from the Swiss tectonic, geological and geotechnical maps on a national scale (1:500,000). More recently, the groundwater resources map of Switzerland is based on the same dataset including supplemental hydrogeological features (Bitterli et al. 2004).

Hydrogeological maps of Switzerland on a regional scale (1:100,000), published by the Swiss Geotechnical Commission and the Swiss Federal Office for the Environment, include more precise information (Schürch et al. 2006). However, only a part of Switzerland is covered so far, and new data are continuously acquired making maps quickly outdated. Large-scale hydrogeological maps of various regions in Switzerland, enclosing significant karst areas have been published as well, e.g. by Kiraly (1973) or Grétillat (1992).

Beside maps, water authorities established inventories of water supplies which could be used for groundwater documentation. They include thousands of springs of which, however, only about 1 % are related to significant karst springs. Unfortunately, data on aquifer type and discharge rates is rare, limiting the benefit of those lists to establishing an inventory of the main karst springs of Switzerland.

Both maps and inventories thus include several weaknesses: (1) they provide information in 2D showing the situation at the ground surface, but not underground; (2) the discharge of the springs is not represented (or poorly so), so that large karst springs with catchment areas of more than 100 km^2 may appear exactly with the same signature as small quaternary springs with a discharge rate as low as 1 L/min; (3) in most cases, catchment areas of karst springs are not represented; (4) different karst aquifers (e.g. Cretaceous, Malm and Dogger) are not distinguished leading sometimes to really bizarre representation (e.g. two tracing trajectories crossing each other on the same map, that in reality represent flow routes in two superimposed aquifers).

Because of these weaknesses, most maps are not sufficient for the management of karst groundwater and are poorly understood by environmental managers, administrators and even hydrogeologists. For instance, they are not very useful for tackling problems of applied projects related to the excavation of a tunnel through a karst massif or to determine, where a borehole would have a chance to strike water and at what depth.

The most insightful Swiss map with regard to karst is the one made by Kiraly (1973), where 3D information has been included, and groundwater catchments have been assigned according to the discharge of the springs. This leads to a consistent overview of groundwater circulation in a whole region. The main weakness of this map is its complexity (i.e. low readability) and most people do not take enough time to really understand it or do not possess keys to read information.

The idea that forms the innovation of Kiraly's work was applied with some modifications by various authors

(Aubert et al. 1979; Herold 1997; Perrin et al. 2000; Maillefert and Jeannin 1991; Farine 1997; Jeannin and Beuret 1995; Jeannin 1996; Butscher and Huggenberger 2007). However, none of these works produced an adequate and "easy to understand" concept for karst aquifer mapping. As a consequence, karst aquifers are very poorly documented and understood in many regions.

The KARSYS approach seems to have the potential for making considerable contribution to the field of karst aquifer documentation. Indeed, KARSYS is basically very similar to the procedure initiated by Kiraly (1973) and applied by the authors mentioned above. It is only more general and all principles are described explicitly, which was not the case of Kiraly's work. Another difference is that one can now easily make 3D models of the underground, which was technically almost impossible 40 years ago.

The KARSYS approach

Principles

Flow in karst media is assumed to be predominantly controlled by the hydraulic gradients and the geometry of the aquifer (limestone series for example). The aquifer geometry can be deduced from geological information, mainly geological maps and cross-sections.

Hydraulic gradients can be assessed using the following general rules:

1. Among natural springs, those with a significant discharge (i.e. large catchment area) are generally the outlet of a karst system, unless very special conditions may argue for another hypothesis. The drainage network in karst systems has low head losses, thus a low gradient. In Switzerland springs with a discharge rate larger than 30 L/s are assumed to be mostly karstic with catchment areas larger than 1 or 2 km^2;
2. Due to the high hydraulic conductivity of karst conduits, the hydraulic gradient upstream from the karst springs is very low, at least at low-water stage. It can be assumed to be zero or at least less than 0.1 % (Bögli 1980; Worthington 1991; Worthington and Ford 2009);
3. The aquifer volume located below the spring is therefore considered as water-filled (saturated aquifer volume, SAV);
4. The unsaturated zone above the SAV can be very thick (hundreds of meters or even up to 2,000 m in Switzerland);
5. The hydraulic gradient in the unsaturated zone is assumed larger than 1, i.e. flow is mainly vertical (at least with an inclination higher than 45°);

6. In shallow karst or zone of underground open channel flow (i.e. where the bottom of the karst aquifer is situated higher than the springs) water flows at the bottom of the aquifer and along the dip of the underlying aquiclude. Hydraulic gradients are then determined by the topography of the top of the aquiclude;
7. The hydraulic gradient in the SAV is oriented towards the outlet of the system (often the karst spring or an underground overflow). Indeed flow paths follow the "least hydraulic resistance" route linking inputs into the SAV to the outlet (often the karst spring);

The implementation of those general hydraulic principles in conjunction with the assessment of the aquifer geometry in 3D is a very powerful tool for making an initial conceptual model of flow and addressing the three questions raised in the introduction. Principles 1–3 make it possible to draw the geometry of the SAV (and address question 3). From this geometry, and taking into account principles 4–6, the catchment areas of karst springs can easily be delineated (question 1). Adding principle 5, groundwater flow paths within the unsaturated zone can be assessed (question 2), which is often a strong indication in mountainous karst systems. The application of principle 7 means for instance, that it is occasionally easier for water to travel a ten times longer flow route within karstified rock than passing through aquicludes.

The following sections illustrate how to apply this approach. First, it should be mentioned that the construction of the conceptual model is basically iterative, i.e. that an initial very simple model can be constructed in a few hours' work. It will help to define major uncertainties and to focus the search for further data. Any new information can then be introduced into the model, which is steadily improved during this process. The process will be brought to an end once the precision required for the question to be addressed is reached, and/or the effort (time or money) is considered as too high compared to the expected model improvement. It typically depends on the question to be addressed with the model.

3D geological model

In this step the aim is to define the geometry of the known or expected aquifer, for example the limestone layer. The bottom of the aquifer is often the top of underlying shales or marls or even the contact with sandstones or other impervious rocks. The top of the aquifer is either defined by the topography or by a less permeable cover. The definition of the bottom and top of the aquifer requires a sufficient knowledge of the geological formations, at least adequate to the scale of the work. Aquifer vertical

Fig. 2 Example of a geological model in northern Switzerland (Ajoie, Jura mountains), built with 3D Geomodeller®
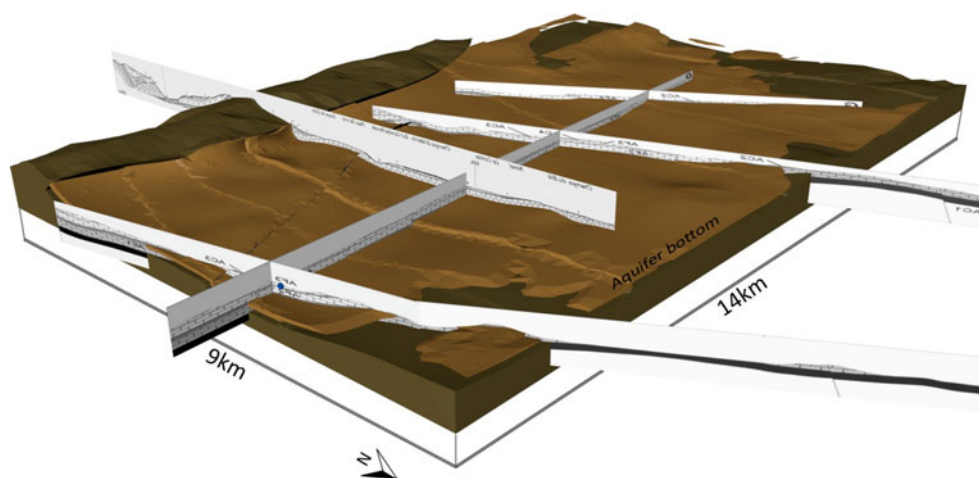
boundaries are sometimes difficult to determine and often require information on the position of springs as well as borehole or outcrop data.

The 3D model construction is mainly based on geological maps and on existing cross-sections. Additionally, data from digital elevation models (DEM) or from aerial or satellite photographs can be very useful, as well as cave data and existing borehole logs. The objective is to construct in 3D the bottom and top surfaces of the aquifer including some major features, such as faults or folds. If only little data are available, one can start with a very approximate model and iteratively improve it in later stages.

Any tool dedicated to 3D modelling can be used. Geological modelling tools (e.g. GoCAD®, Geomodeller®, MOVE®, PETREL®, etc.) are well suited, but tend to be "oversized" and complicated for a simplified approach. Tools for 3D animations (e.g. 3D Studio® or Cinema 4D®) may represent an adequate compromise in being cheaper and more manageable. However, model improvement along the study process is more difficult in those tools. 3D viewers of GIS systems can be used for visualization, but are rather impractical for modelling geological features compared to other 3D-specific software. Figure 2 shows an example of such geological model.

3D hydrogeological conceptual model

Once a first model of the aquifer geometry has been constructed, hydrogeological information and basic principles of hydraulics described above can be introduced in the model. Major karst springs, including overflow springs have to be added too. The identification and selection of springs is often not an easy task, because large karst springs are included in spring inventories enclosing hundreds of very local springs that are not explicitly distinguished.

Quick field recognition is recommended for the identification and evaluation of the major springs.

From the main perennial springs, horizontal planes can be constructed and, as a first approximation, the aquifer volume below those planes can be considered as SAV. This also immediately indicates zones (on maps or in 3D) of confined aquifers (where the top of the aquifer is lower than the level of the spring), of unconfined aquifers (where the top of the aquifer lies above the water table) and zones of underground open channel flow (where the bottom of the aquifer lies above the top of the water table, i.e. shallow karst).

It directly points out all springs discharging from the same SAV, and being therefore potentially hydraulically related. It also shows zones, where perennial or temporary springs are probably located. Depending on their positions and elevation, hypotheses on groundwater divides can be formulated. Since flow in the SAV is mainly horizontal and along the shortest hydraulic flow path to the spring, it can then be sketched in this model.

The thickness of the unsaturated zone can also be measured at any location and flow through the unsaturated zone can be assessed (mainly vertical, but influenced by the orientation of bedding planes and fractures).

Surface streams flowing over unsaturated karst terrains are expected to lose water infiltrating into the karst or to completely disappear at swallow holes. However, this may not be the case during high-water stage, when the water table may rise substantially.

In the zone of underground open channel flow (shallow karst) the main drainage is along the dip of the aquifer bottom. It is then strongly influenced by syncline and anticline structures, as well as by displacements of the aquifer bottom by faults (Butscher and Huggenberger 2007). This makes it possible to sketch the position of expected preferential flow paths.

Fig. 3 Geological model completed with hydrogeological features. The application of simple hydraulics principles makes it possible to determine the saturated aquifer volume (SAV, *blue*), and the catchment area (*red*) including sub-catchments
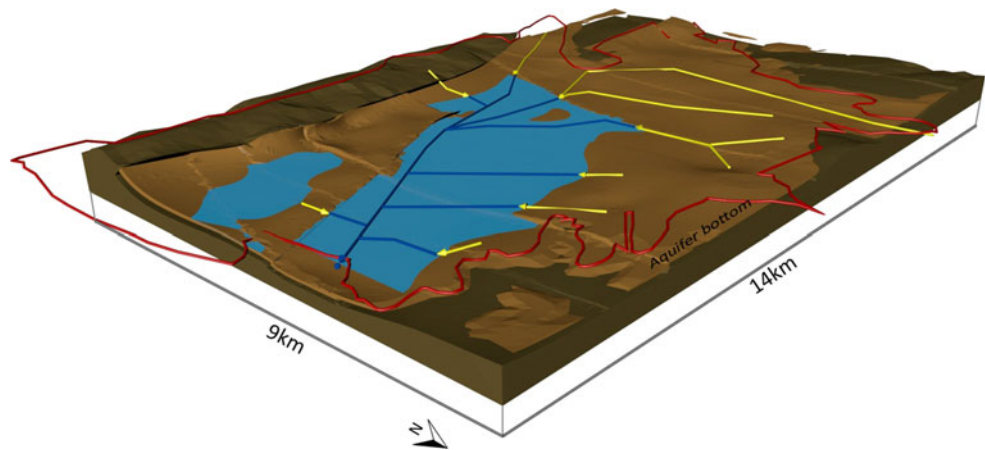
From this image it is also quite easy to deduce the catchment areas of the respective karst springs.

Figure 3 shows the conceptual model resulting from the application of these simple hydraulic principles within the geometry defined by the geological model.

Validation and improvement

Water budget

For validating the initial model, a water budget assessment can be conducted. It implies at least approximate knowledge of the respective spring discharge. If no or very little data are available then a field reconnaissance at medium to low-water stage conditions and for all springs on a given day provides a first approximation of the system's discharge rates. Evaluation of precipitation and recharge (P-ETR) gives an idea of the annual specific discharge (in L/s/km^2). Recharge over the respective catchment areas assessed from the 3D model have to correspond with discharge of the corresponding springs, and have to be in agreement with the annual specific discharge (according to the hydrological conditions during the field recognition).

Ideally this comparison should be conducted at a regional scale, including all neighbouring karst systems. Even with very approximate discharge data (± 100 %) the consistency with the respective aquifers is already quite a strong constraint.

This analysis often results in the hydrogeological model, and even sometimes the geological model, to be reconsidered and adjusted accordingly.

Tracing experiments

In many regions a large number of tracing experiments have already been conducted. The KARSYS conceptual model has to be consistent with this existing data. Locations of tracer injection can be introduced into the model

and the expected flow path the tracer took to reach the spring (s) can be visualized in 3D (Fig. 4). Tracing results can directly be compared with the first hydrogeological model, and both can be criticized. Sometimes the model can be improved directly; otherwise, areas with a higher uncertainty can be identified. New geological investigations and/or supplemental tracing experiments can thus be designed in a targeted manner.

However, it must be pointed out here that tracing experiments results have to be critically dealt with (Jozja et al. 2011). Besides purely analytical uncertainties, one should never forget to consider that diffluent areas are widespread in karst, that catchment boundaries may vary between low and high-water conditions and that tracing results are often dominated by the kind and location of injection (often into swallow holes, often at high water). Even analytically correct results may therefore not represent standard conditions.

Hydrochemistry

Spring water chemistry is the consequence of all processes occurring within the karst system or within the recharge area (e.g. in the case of allogenic recharge). The presence and quantity of a specific ion, isotope or pollutant at a karst spring may provide pragmatic information about water flow paths and/or their origin from a particular part of the catchment.

However, because the concentration of all these natural tracers usually strongly varies with time, a hydrochemical approach can only be applied to water samples taken after a long period of stable conditions, typically low-water stage or for a high number of samples taken during variable conditions.

Conditions and interpretive models for this type of data are beyond the scope of the present paper. It can just be stated that in contrast to the two previous methods (water budget and tracing experiments), which afford more or less
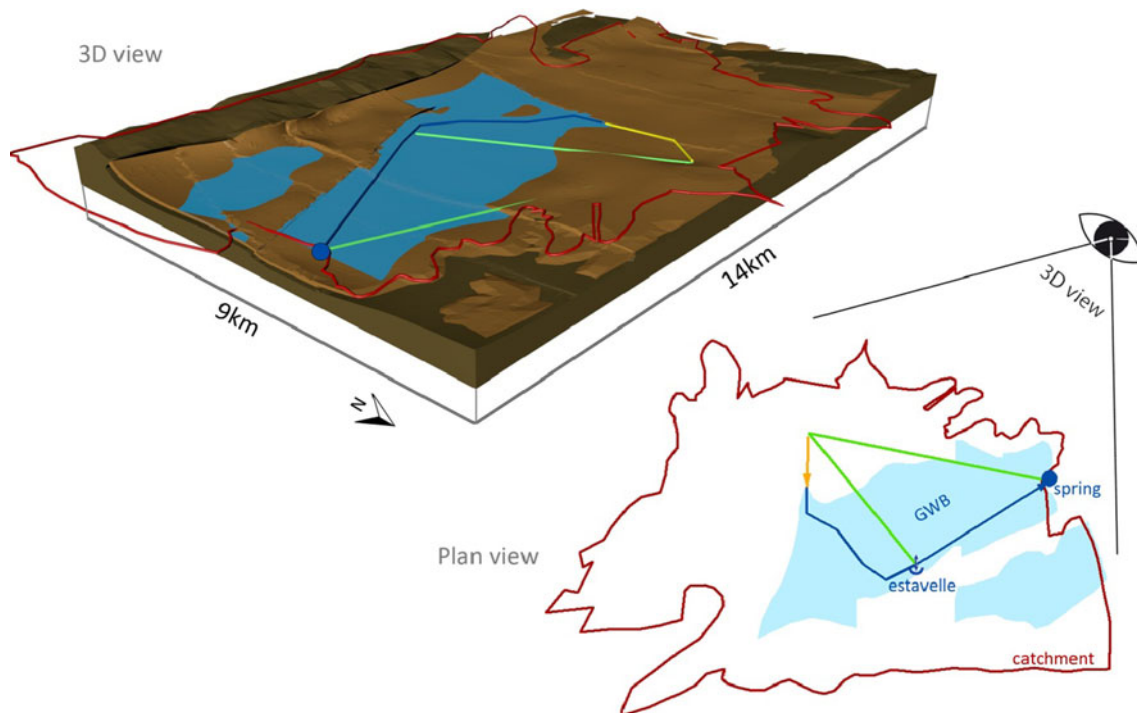
Fig. 4 Example of tracer flowpath visualization using the KARSYS conceptual model. *Green line* classical tracer visualization, *yellow line*: vadose flow path based on principle 6, *blue line* phreatic flow

path based on principle 7 (see text). In 3D view, it is obvious that the tracer cannot travel as a crow-fly towards the spring, because it should flow through the aquiclude as shown by the *green line*

"hard facts", these methods have an interpretation range and thus uncertainty that is much larger.

Other methods

As mentioned in the introduction, the so-called "global approach" is based on the interpretation of time series from karst springs (e.g. Criss et al. 2007; Hunkeler and Mudry 2007; Jakucs 1959). The basic idea is that variations of water discharge, chemistry, isotopic composition, etc., reflect characteristics of the flow system. Very interesting interpretative models have been and are still being developed for this purpose (e.g. Kuniansky 2011; Ravbar et al. 2011). However, this approach requires at least 1 year of high resolution hydrographic data plus at least three floods covered by chemical or isotopic (or any other) measurements. It is thus in most cases not cost-effective, at least not for a first conceptual overview of karst hydrogeology of a given system.

Anyway, the establishment of the KARSYS conceptual model should be conducted prior to applying any other global approach, because it helps to better design which outlets (springs) should be monitored and how. It also contributes to select a reasonable interpretative model, which somehow fits the conceptual model. Global approaches can then provide a real improvement to the conceptual model.

Besides global approaches all local scale methods such as geophysics, drilling and well tests can be applied to refine the model at some location or for any targeted purpose.

Once considered as sufficient (which depends on particular project requirements), the KARSYS conceptual model can be used as a basis for application of further assessment methods, e.g. for groundwater protection areas (vulnerability assessment) or karst hazards assessment (e.g. KarstALEA method by Filipponi et al. 2011).

Applications

The KARSYS approach can be applied with a large range in the level of details depending on the aim of a study. Two examples are presented, hereafter with contrasting levels of detail and expenses.

Example 1: karst groundwater reserve assessment in Switzerland

Procedure

In 2008, the Swiss Federal Office for the Environment (FOEN) conducted an assessment of the groundwater resources in the different aquifer types of the country. This

comprised a rough estimation of the reserves enclosed in karst aquifers on the national scale. The idea was to provide an order of magnitude for the karst groundwater volume within 10 days work. All potentially karstified rocks (mainly carbonate rocks in Switzerland) have been considered as karst aquifer for this study.

This required to proceed in a very pragmatic way in order to give a realistic result within such restriction (ISSKA 2008). For example, it was impossible to clearly identify and separately consider each single karst system, because no complete national inventory of karst springs exists.

The first simplifying assumption made was that the volume of carbonate rocks located below the level of the main valleys is fully saturated. Together with the second assumption of known aquifer geometry and porosity, a water reserve volume could be assessed. In summary, three parameters were considered: (1) the carbonate aquifer porosity; (2) the elevation of the main valleys; and (3) the carbonate aquifer geometry. A fourth parameter had to be assumed for thick and/or deep aquifers, i.e. the maximum depth to which a reserve should be considered. It has been decided that the value of 1,000 m below the surface was the maximum depth to be taken into account, due to potential exploration and water quality restraints.

Concerning porosity, it was simply assumed to be 2 % for all formations which is a reasonable value for karst aquifers in Switzerland (Kiraly 1973).

Regarding the elevation of the main valleys, the carbonate outcrops were processed in terms of identifying which valleys entrenches the limestone aquifers the deepest. For each aquifer the elevation of the deepest valley was considered as a base level and assumed to be the top of the saturated zone.

The most difficult point was the assessment of the geometry of the carbonate aquifers. Seven tectonic units were distinguished (Fig. 5): Jura Mountains, Prealps, Helvetic nappes, Penninic nappes, Austroalpine, Southern Alps, and Molasse basin. In each tectonic unit carbonate aquifers were identified and as many geological profiles as possible were collected (within the limited time frame available). This provided an idea of the aquifer geometry.

As presented in Fig. 6, the top of the saturated zone (according to valley levels) was drawn on each geological profile and the SAV below this line was highlighted, either down to the aquifer bottom or down to 1,000 m depth. Subsequently, the coloured surface areas were measured. Because aquifer geometry could not be constructed in 3D within the available time frame, the extrapolation between the profiles had to be conducted in a very approximate manner, taking into account the breadth of the tectonic unit (i.e. length of the geological profiles) as well as changes of assessed groundwater volumes between the respective profiles. A simple validation of this interpolation was performed by means of areas, where 3D models already exist, mainly in the Jura Mountains (unpublished material).

Fig. 5 Geological sketch of Switzerland (Swisstopo) with the main geological units. Added lines indicate profiles considered for the national scale groundwater reserve assessment (ISSKA Eichenberger 2008)
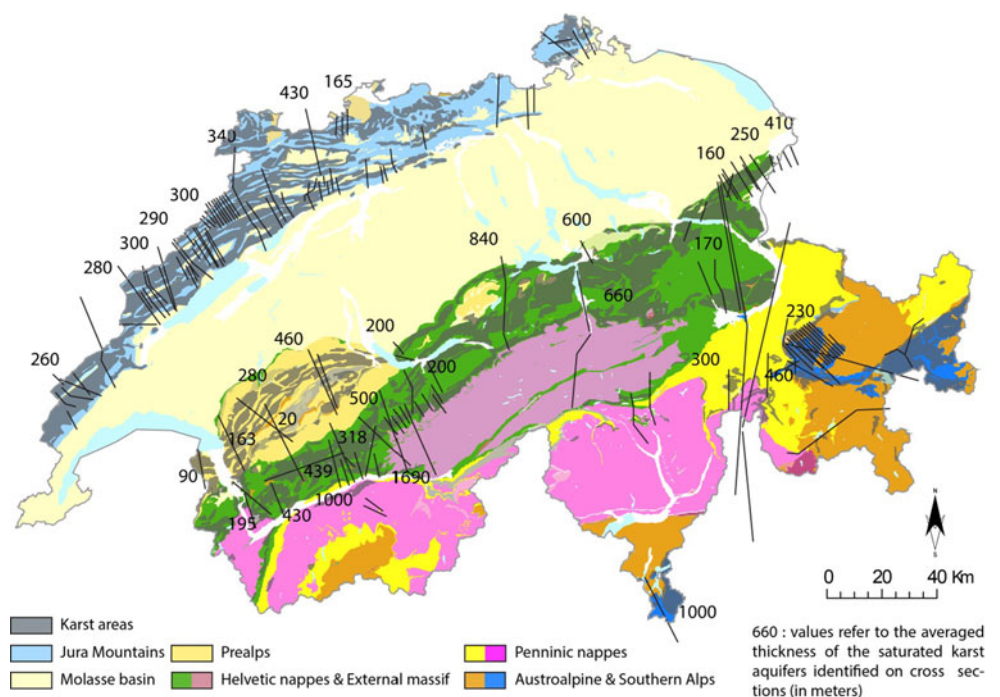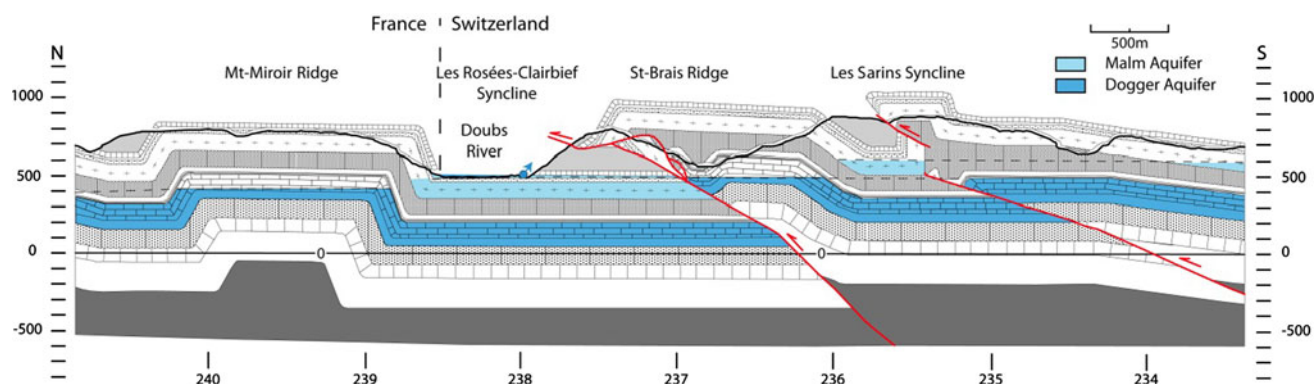
Fig. 6 Typical geological profile. Parts of limestone aquifers located below the spring level (*blue* and *green* colours) are assumed to be water-filled. Groundwater volumes has been assessed by measuring the length of aquifer colours in *blue* (Malm limestone aquifer) and *green* (Dogger limestone aquifer) multiplied by the aquifers' thickness and by an assessed lateral extension. This volume has been multiplied by a porosity of 2 %

Among the 175 geological profiles found for the respective tectonic units (displayed in Fig. 5), 40 profiles were selected to be really worked out.

Results

Table 1 shows the results for the seven tectonic regions considered. In total, the groundwater volume for Swiss karst aquifers is estimated 120 km^3.

The concept behind this assessment is equal to that of the KARSYS approach; however, implemented in a very quick and approximate manner. This procedure was sufficient to provide the karst groundwater volume, i.e. the reserve in such aquifers in Switzerland with the requested precision (a factor of ±3). Validation tests using existing 3D models (Malard et al. 2012) and the map of Kiraly (1973) showed the results being notably close to "reality".

Besides the assumption on the porosity (2 %), the main source of uncertainty in the test regions was not the quick way used to assess the volumes, but the uncertainty inherent to the geological profiles available (i.e. tectonic interpretation), which may lead to changes in aquifer volumes as large as ±100 %.

Example 2: regional karst groundwater hydropower potential assessment

Perched underground flow paths in karst may have a significant discharge and can be situated tens to hundreds of meters above the regional base level. This situation may be of interest for the production of electricity. The position and extension of karst phreatic zones can also be of interest for artificial water storage. Following a request by the energy authority of the Swiss canton of Vaud, this type of water

Table 1 Karst groundwater volumes (reserves) for seven tectonical units in Switzerland

Swiss tectonic regions (count of related cross-sections)	Average thickness of the saturated karst aquifer (m)[a]	Extension of karstified formation (km^2)	Volume of saturated aquifer (km^3)	Estimated groundwater volume (km^3)[b]
Jura mountains (14)	300	4,000	1,200	24
Prealps (5)	200	1,900	380	8
Helvetic nappes (14)	500	7,600	3,800	46
Penninic nappes (2)	500	400	200	3
Austroalpine (4)	300	800	240	5
Southern alps (1)	800	160	128	1
Southern jura foothill until a depth of 1,000 m underneath the molasse surface	500	3,300	1,650	33
Total		18,160	7,598	120

[a] Refers to the values measured on cross-sections (see Fig. 5)

[b] Until a depth of 1,000 m underneath the level of the main springs and assuming an effective porosity of 2 % of the saturated rock volume
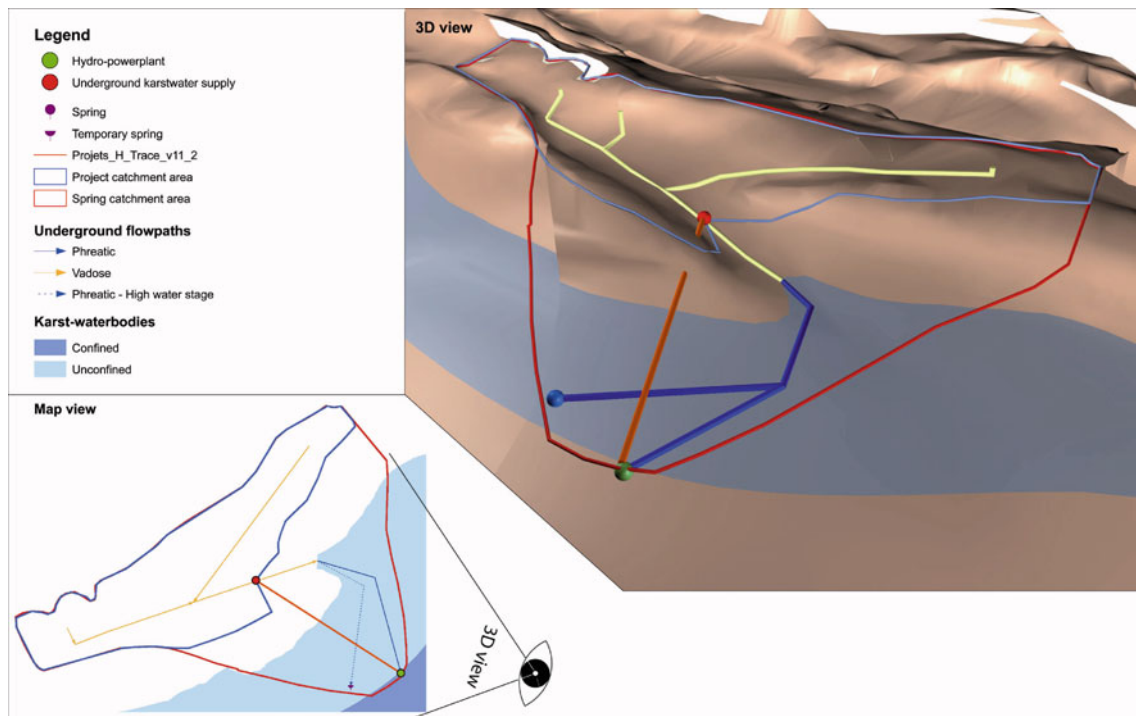
Characteristics of the project	
Catchment area, surface and aquifer	Raisse, 46.9 [km^2], Malm and Cretaceous.
Project catchment area	24 [km^2]
Hydrology : Q_{100}, Q_{180}, Q_{347}	818 [L/s], 440 [L/s], 116 [L/s]
δ elevation	260 [m]
Production	
Electrical production	6.3 [GWh/yr]
Electrical power	1.85 [MW]

Fig. 7 Case example from the hydropower production project (Raisse karst system, Jeannin et al. 2010b)

resources was assessed in 2010 for about 80 karst systems in order to assess the hydropower potential in its territory using the KARSYS approach (Jeannin et al. 2010a).

As outlined, KARSYS provides a conceptual model of the main underground flow paths. This includes an estimate of the position of karst sub-systems or branches of the conduit network and their respective sub-catchment areas. This enables a prediction of the discharge of the respective branches as well as their elevation. Concerning storage, KARSYS provides an idea of the size and position of karst phreatic zones for low- and high-water conditions. Storage volumes and potential drainage points can therefore be assessed.

KARSYS was applied to the whole territory of Vaud canton in order to assess the potential electricity production. From the initial set of 80 karst systems, 39 with average discharge larger than 30 L/s were identified. A geological model was constructed for each of them and hydraulics principles of the KARSYS approach were applied in order to depict a conceptual model for each ones. On this basis, perched flow paths and perched phreatic zones have been looked for and quantified with respect to discharge and elevation (i.e. hydropower potential). Figure 7 gives an example of the model obtained for one of these systems.

As a result a series of seven projects have been recognized as economically feasible within the short term. A further five projects are more risky and would require more investigation. They might become of interest economically in the future, depending on changes in technology and electricity prices.

Even though this study was dedicated to the evaluation of hydropower potential, the same model could have been used for drinking water or irrigation water supply purposes.

Discussion

Overview and limitations

KARSYS is rather an approach than a completely defined methodology, because it can be applied at a large range of precision levels. The volume estimation of Swiss karst groundwater was a very approximate and quick assessment. This level of detail can (and should) be applied as a first step of any investigation of a karst aquifer. This affords a first sketch of the underground flow systems (conceptual model). However, the construction of a simple (somehow schematic) 3D model on computer is nowadays possible within a few work days. This strongly improves the model compared to 2D representations or to an approximate 3D representation in the hydrogeologist's mind. However, it must never be forgotten that the reliability of a "nice 3D model" is related to data used for building it, and not to its fancy and clear aspect.

The first benefit (or advantage) of the proposed approach is that the 3D geological model may point out inconsistencies between the existing geological documents (typically geological maps and cross-sections). The construction of the geological model often requires that we reconsider existing geological data and interpretations. It also often requires that some verification be undertaken at specific locations in the field.

Another advantage is that hydrogeological relationships (observed or interpreted) can be directly viewed in 3D within the derived hydrogeological model. For instance, springs can be visualized both at their location in the field (DEM) and in the aquifer (geological 3D model). The karst phreatic zone (i.e. SAV) can be constructed within a few seconds throughout the presumed aquifer. Accordingly, various scenarios can quickly be tested (e.g. diverse hydraulic gradients). The low-water catchment area of the system can be deduced with a distinction between "gravity divides" in the unsaturated zone and "hydraulic divides" in the saturated zone. The position of major flow paths within the catchment area can often be hypothesized, making it possible to suggest sub-catchment areas inside the main catchment. Zones of expected diffluence can be identified and later on tested by tracing experiments. Finally, proved connections can be represented not as straight lines between tracer injection and detection points, but as assumed realistic flow paths through the unsaturated and saturated zones.

Once a low-water phreatic zone has been tentatively identified, various hydraulic gradients for medium to high-water phreatic zones can be tested. This usually indicates changing interactions with nearby systems and may clarify questionable results of tracing tests. The position of potentially flooded zones at very high-water stage can also be identified.

Thus, depending on the question to be addressed, the model can be refined and improved in order to reach an acceptable level of uncertainty. Certainly, a simple 3D KARSYS conceptual model is already much better than no model. The main reason for this statement is that an explicit representation of an expected reality is a strong mean of synthesizing different visions of a same system. (Hydro)geologist with a discordant vision will immediately react, if the model does not correspond to their views and data. The model can thus be improved according to all visions. After two or three iterations, the model becomes a real synthesis of the various representations existing in the mind of the people involved. However, it should always be clearly stated that the resulting images are models and are not reality.

The KARSYS approach should thus be viewed as an iterative process, provoking reactions and thus improvements.

Regarding the three questions raised in the introduction, KARSYS addresses the following points:

Concerning question 1 It provides a delineation of the catchment area, as well as interactions with neighbouring karst systems. This includes not only the situation at low water, but may also sketch other situations (medium/high water). Zones of contact between superimposed aquifers can be clearly identified and the expected exchanges can be assessed accordingly.

Question 2 (flow paths) is also fairly well addressed by showing the position of the main drainage axes of the system and their hypothesized nature (open channel flow/phreatic, perennial/intermittent) as well as their approximate discharge. However, the position of the conduits in the phreatic zone remains quite uncertain.

Question 3 (groundwater reserves) is in fact the first question be answered in the KARSYS procedure. As long as geological information is available and somehow liable, this question can be addressed (assuming a liable value for porosity), and resources as well as reserves can be estimated separately. In case of several springs emerging from the same aquifer, the proportion of the reserve feeding each spring remains difficult to be determined.

Further limitations in the application of KARSYS can occur at least in the following situations: unclear aquiclude layer limiting the main aquifer (on top or bottom) or lateral changes in aquifer/aquiclude characteristics, presence of significant fractures with little displacement (potential link with another aquifer, although the aquiclude seems continuous). If the karstified rock is very thick and its bottom is located far below the base level, the approach can be applied but should probably be completed by some further information (geomorphology, hydrography, speleogenesis,

etc.). Otherwise, the application of KARSYS in a karst system with a hypogenic component would require some modifications and should be developed further.

Perspectives

There are many perspectives in improving (or expanding) the KARSYS approach for common water management issues.

Probably the next question concerns the simulation of the system response to recharge events (Birk et al. 2006; Peterson and Wicks 2006; Wu et al. 2008). Once sub-catchment areas have been determined in terms of their diverse characteristics (diffluence, cover thickness, soil type, elevation, exposition, etc.) storm response models can be better parametrized (Weber et al. 2011).

This type of grey-box model will hardly provide information on head distribution and flow velocities. Only adequate karst groundwater flow models can achieve this and they should at least respect the hydraulic principles exposed in the "Introduction". Several authors suggested that the conduit network has to be explicitly integrated in those models to provide reliable results (e.g. Kovács 2003). Dozens of "karst conduit generators" have been published over the last 15 years (e.g. Borghi et al. 2011; Dreybrodt et al. 2005; Jaquet et al. 2004; Mariethoz and Renard 2011) for addressing this question. Although some results are promising, flow modelling in karst is still far from being completely solved, especially considering the simulation of flow in the epiphreatic and vadose zones, as well as in the epikarst and soil.

The conditioning of conduit generators is also a challenge for which general speleogenetical principles have to be considered. The KarstALEA method (Filipponi et al. 2011) delivers an applicable way in identifying the main parameters controlling the position of karst conduits (i.e. mainly inception horizons and paleo-phreatic zones).

KARSYS represents a basis on which those methods and tools can (and are being) be coupled and integrated.

A further topic is to link methods developed for the definition of protection areas (or perimeters) of drinking water supplies. Several vulnerability assessment methods dedicated to karst landscapes (e.g. EPIK, PI, PAPRIKA, etc.) have been developed in the last decade, but they are mostly based on a strongly simplified conceptual model of karst flow systems. A coupling of those approaches to KARSYS would probably improve the proposed zoning and related restrictions.

Conclusion

KARSYS represents an approach based on a series of well-known and basic principles controlling groundwater flow in karst media. The approach consists of a well-defined work-flow and of an empirical weighting of these principles, as well as in an explicit 3D representation of a conceptual model of a karst flow system. The model can be iteratively improved once new information becomes available. The approach is pragmatic and leads to a synthetic model that represents a karst system in 3D. It is believed that the proposed approach is a valuable contribution for improving water management in karst areas. It can also be used as a base for the application of further methods or simulation.

Considering the fact that in Switzerland many karst systems are used for various purposes and that no hydro-geological conceptual model has been constructed (at least not explicitly), it has been decided to apply KARSYS to all major karst systems of the country. This is currently done in the framework of the Swisskarst project, which is part of a national priority research on "sustainable water management" (NRP61 supported by the Swiss National Science Foundation) on the request of the government. Results are presented on a web site (http://www.swisskarst.ch) where this information can be found. Beside a 3D view of the respective systems, an "identity card" summarizing the major characteristics of the system on one page, as well as map views and profiles are available. Furthermore, a literature list is provided for each system. By the end of 2011 a series of examples were already available on the Internet, and the project will last until 2013. This web site provides a first level of documentation, which is expected to be useful, among others, for the following purposes:

- Karst groundwater protection (protection zones)
- Evaluation and exploration of karst water resources (contribution to stream base-flow, drinking water supply, irrigation, hydropower)
- Evaluation of the implementation of geothermal heat pumps in karst regions
- Impact of civil engineering projects on groundwater
- Hydraulic boundary conditions for neighbouring aquifers or aquicludes (e.g. in relation to nuclear waste deposits)
- Identification and prevention of natural hazards in karst environment

KARSYS has been applied so far to a reasonable number of case studies, although limited to situations found in Switzerland. Applications to a larger number of cases, as well as to cases with direct and systematic field verifications (e.g. tunnels, boreholes, tracing experiments) will help to really assess the advantage and limitations of this approach. Applications in setting and situations clearly differing from those found in Switzerland will also help in suggesting limitations and improvements to this approach. Two applications are currently being carried out in Slovenia and further ones are expected in other countries as well.

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