



An integrated approach for catchment delineation and conduit-network modeling in karst aquifers: application to a site in the Swiss tabular Jura

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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 developed in a gently dipping ($<5^\circ$) environment from those located in a steeply dipping ($>5^\circ$) monocline environment. The approach also distinguishes dominantly fractured and bedded media. Even if this approach respects consistent geological and hydraulic assumptions, its application in thrust 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 applicability. 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 geometry 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 developed 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 (relationships 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 process. 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 breakthrough. This approach was very useful for the understanding 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 interpretation 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-conduits 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 numerical 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 supposed to develop. They are based on the relationships linking geometric characteristics of the conduits (orientation, segmentation, connectivity, etc.) with other parameters (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 variables. 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 address 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 outcomes, 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 north-western Switzerland, upstream from the town of Porrentruy (Fig. 1). A detailed geological, geomorphological and hydrogeological description of the site is given by Grétilat (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 m³/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 m³/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 m³/s, but it may exceed 30 m³/s for an extreme event (Grétilat 1996). Upstream from Creugenat, the Creux-des-Prés (CdP) is a second overflow spring which may discharge ~1–4 m³/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 m³/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; Grétilat 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 Grétilat (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, Grétilat (1998) demonstrated a connection with the Dou spring system located in the western part of the area.

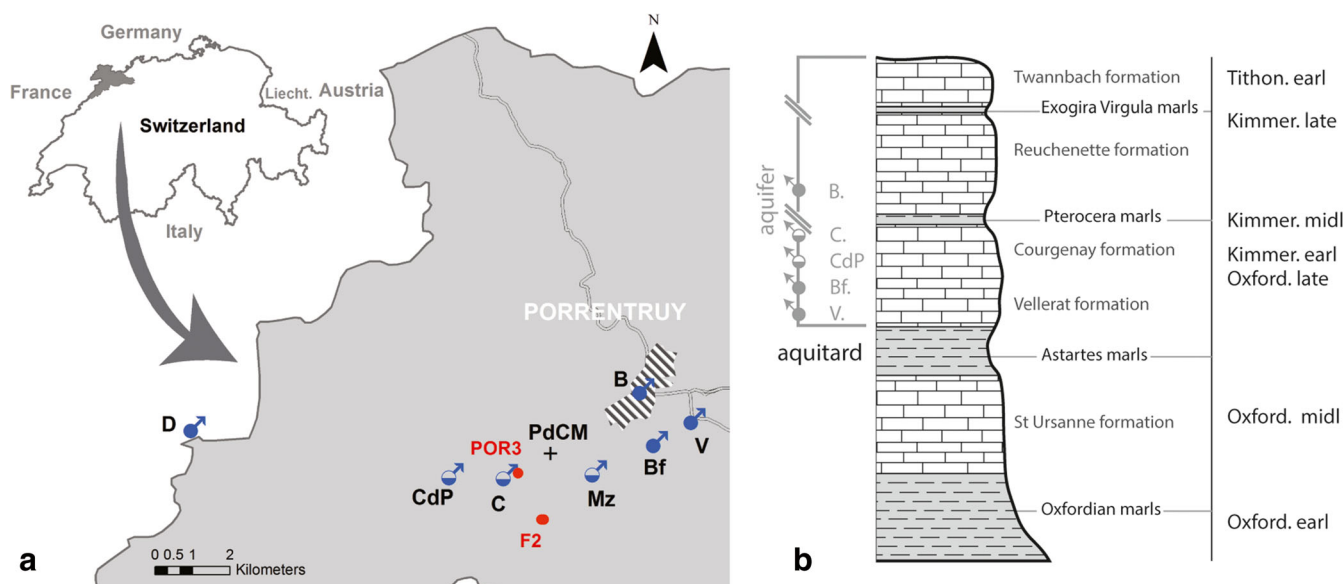


Fig. 1 a Overview of the study site and location of the investigated permanent springs: *B* Beuchire, *V* Voyeboeuf, *Bf* Bonnefontaine, *D* La Doue; temporary springs: *C* Creugenat, *CdP* Creux-des-Près and *Mz* Mavaloz; collapsed cave (*PdCM*), boreholes (*POR3*, *F2*) and b main geological formations 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
Creux des Prés	CdP	Cave/overflow spring	567,500	249,600	Low-water level: 438 Cave entrance: 465 Bottom: 444
Champs Montant	CM	Collapsed cave	570,213	250,253	Low-water level: 444 Cave entrance: 443 Bottom: 436
POR 3	P3	Borehole	569,345	249,730	Low-water level: dry Top: 450 Bottom: 431
Voyeboeuf	V	Base-flow spring	573,950	251,070	Low-water level: dry 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
F2	F2	Borehole (150 m)	570,030	248,492	Low-water level: 443 Top: 512.5 Bottom: 362.5 Low-water level: 450.5

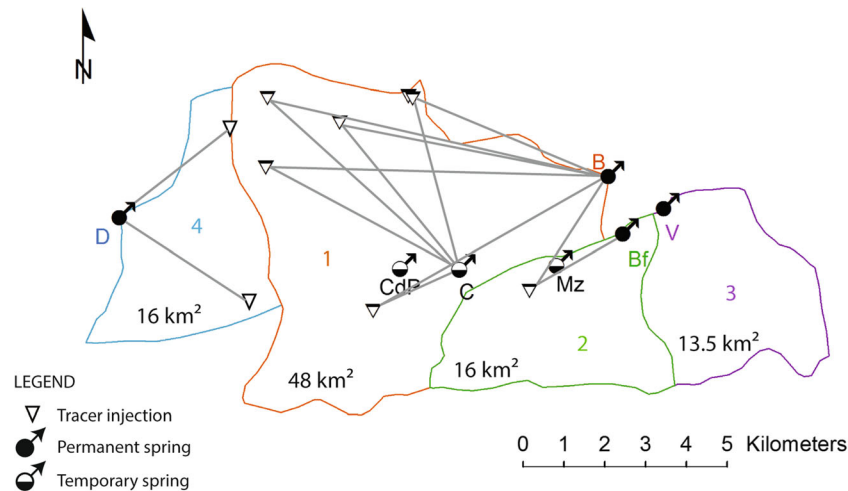


Fig. 2 Existing catchment delineation of the Beuchire-Creugenet (1), the Bonnefontaine (2), the Voyeboeuf (3) and La Dou (4) karst systems proposed by Grétilat (1998). Grétilat considers that Bonnefontaine and Voyeboeuf are two separate systems

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, Filippini 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.).

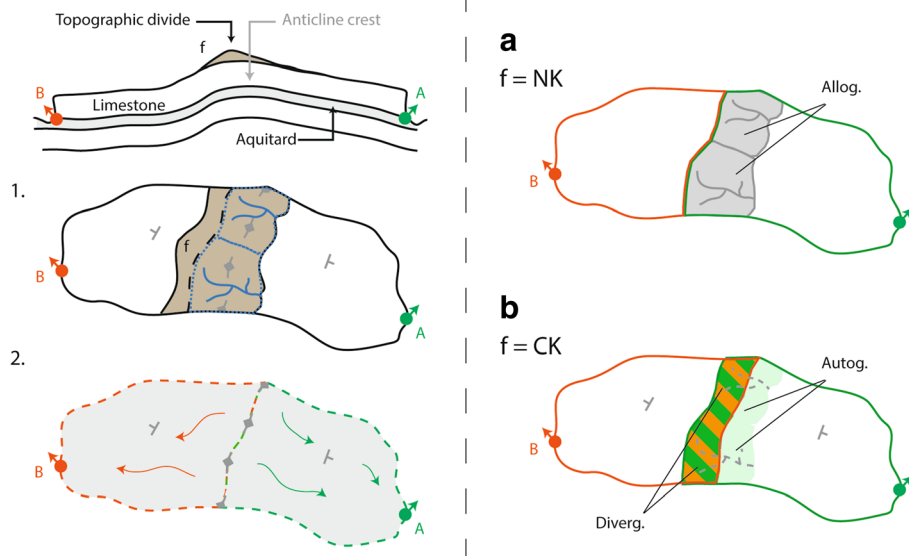


Fig. 3 Principles of spring catchment delineation: Principle (1) springs *A* and *B* emerge on both extremities of the limestone plateau. Stream networks develop on the surficial formation “*f*” and flow toward the *A* spring. Principle (2): the underground flow systems *A* and *B* are separated by the 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 (dolines, 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-

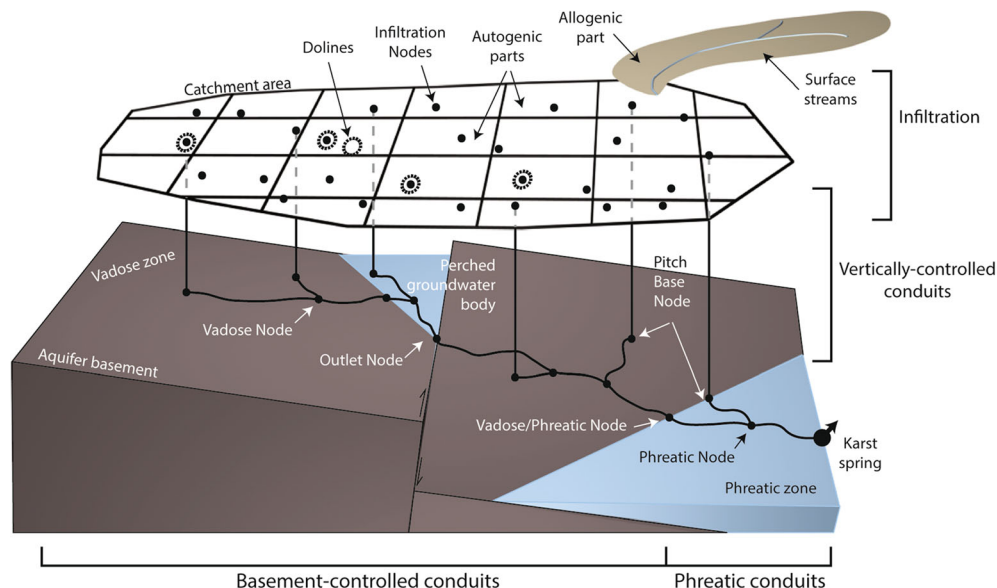


Fig. 4 Principles of the karst conduit network generator. The model is divided into four parts: the infiltration sub-model, the vertically controlled conduits sub-model, the basement-controlled conduits sub-model, and the phreatic conduits sub-model. Depending on the issue and the system, additional sub-models may be integrated to complete the network: epikarst, inception, and speleogenetic

controlled vadose conduits 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.

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 Hydrogeology Journal (2015) 23: 1341–1357

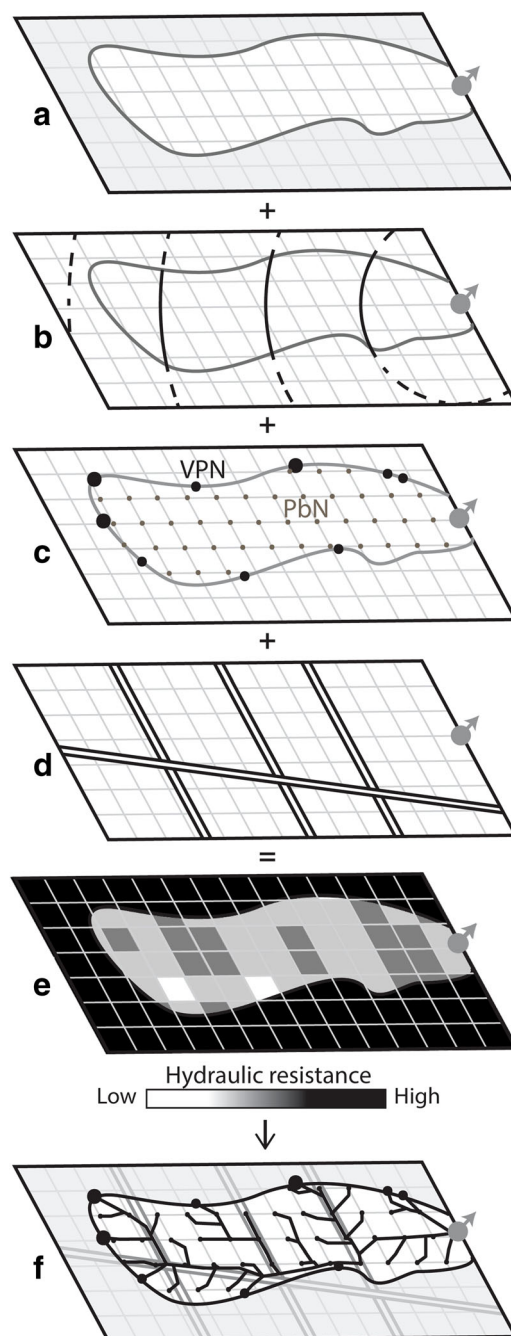


Fig. 5 Parameters controlling the development of phreatic conduits: **a** extension of the phreatic zone; **b** mimic of the radial hydraulic gradient to the main spring (orientation and intensity, O); **c** vadose inputs (VPNs and PbNs) and their respective weight (I); **d** intersection of inception 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**)

Grétilat 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

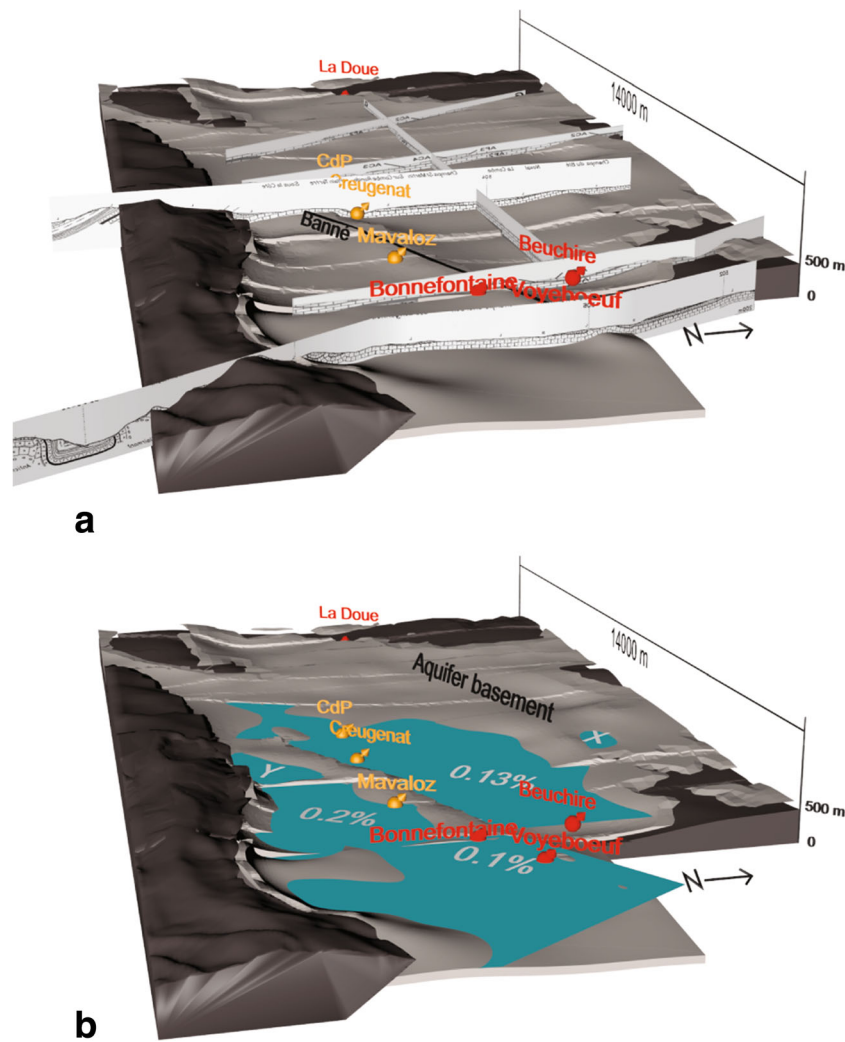


Fig. 6 **a** Perspective view of the 3D geological model of the aquifer basement; the model shows a series of horsts and grabens along a NS axis. A NW–SE anticline (*Banné*) crosses the model. **b** Delineation of the BC and the BV saturated zones and their respective maximum hydraulic gradients for 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 information 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 groundwater 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; however, nothing contradicts their presence. Obviously, according 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 southeastern 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.

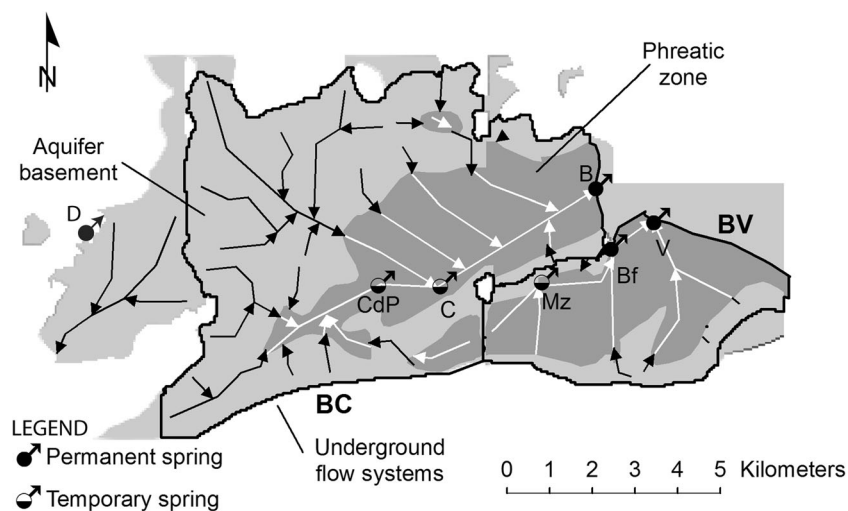


Fig. 7 Sketch of the main supposed vadose (*black arrows*) and phreatic (*white arrows*) flow paths of the BC and BV karst systems and delineation of the underground flow systems by assembling all vadose parts feeding the saturated zones drained by the springs

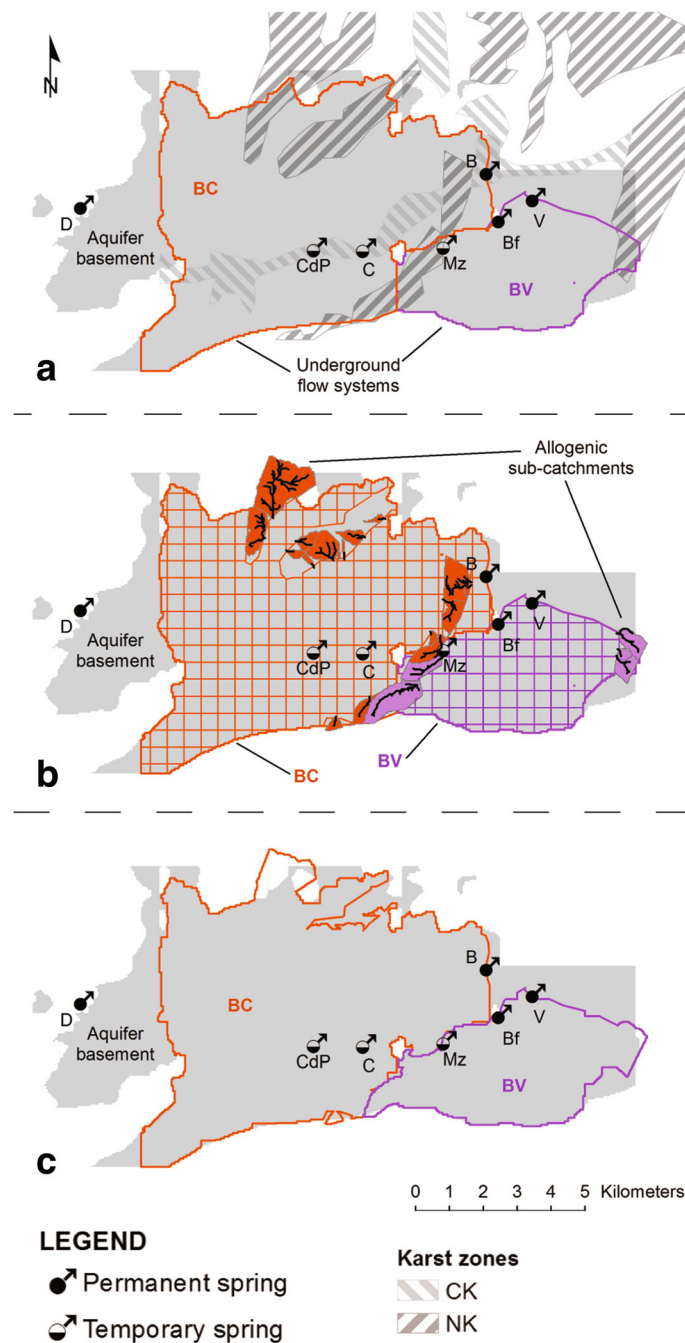


Fig. 8 Delineation process of catchment areas of the BC and BV karst systems: **a** NK and CK surfaces are compared to the extension of the underground BC and BV flow systems. **b** Surface streams are computed on NK surfaces. In the case where these allogenic streams contribute to the underground flow 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

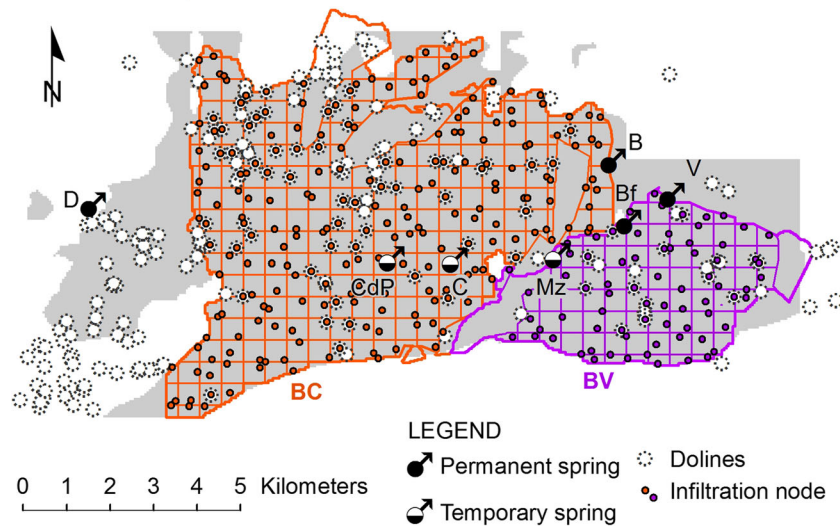


Fig. 9 Model of the distributed infiltration nodes in autogenic zones of the BC and BV karst systems; infiltration nodes are snapped to existing infiltration features within the cell (e.g., dolines) and randomly distributed where no infiltration features are known

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/km², 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.

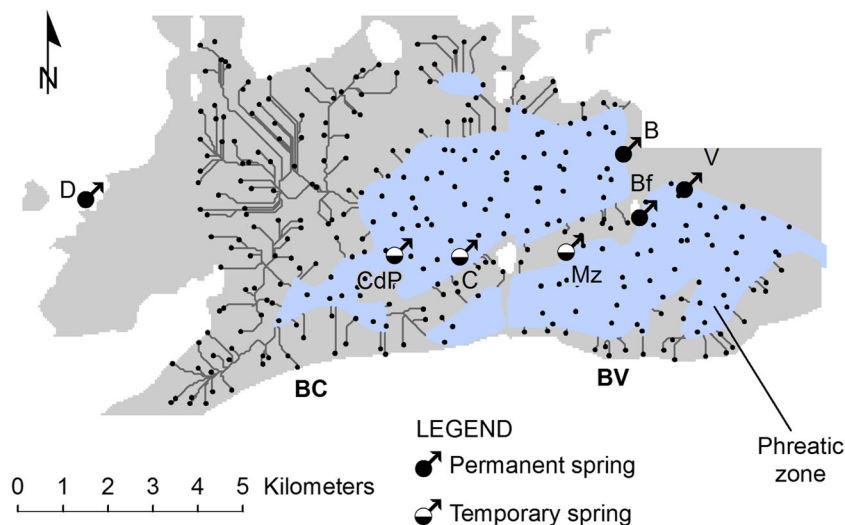


Fig. 10 Geometry of the modelled vadose conduit network for the BC and BV karst systems starting from the infiltration model (PbNs) Hydrogeology Journal (2015) 23: 1341–1357 DOI 10.1007/s10040-015-1287-5

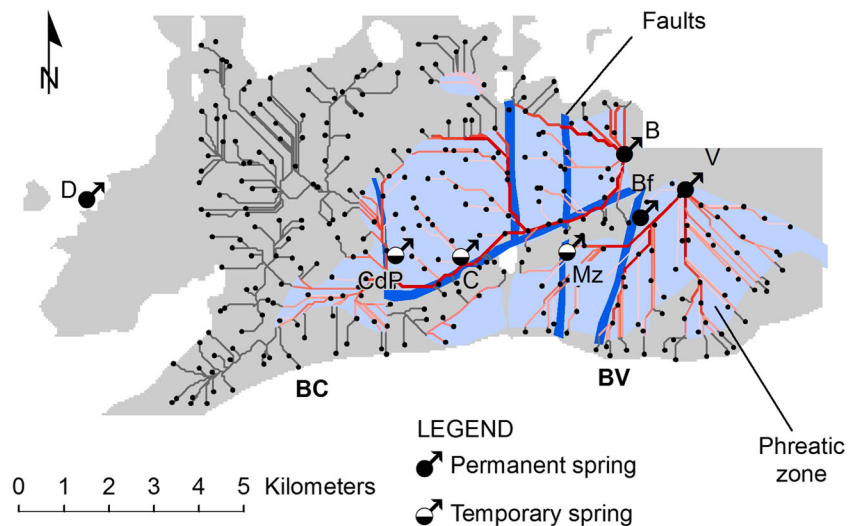


Fig. 11 Generated phreatic conduits of the BC and BV karst systems (*red lines*); the conduits are hierarchized according to the size of the drained area. The imprint of the NS faults and the SW-NE thrust considered as inception horizons are displayed (*blue strips*)

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 Grétilat (1998) (48 km² for BC, 29.5 km² for BV), BC is presently 10 km² larger, while BV is 10 km² smaller. This corresponds to the southern area where the Y phreatic discharge is to the BC system instead of the BV system. Grétilat (1998, p. 63) pointed out a surplus of water for the BC system by nearly 1/6. This probably corresponds to the additional 10 km² (nearly 1/6 of the total catchment area: 58 km²) 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

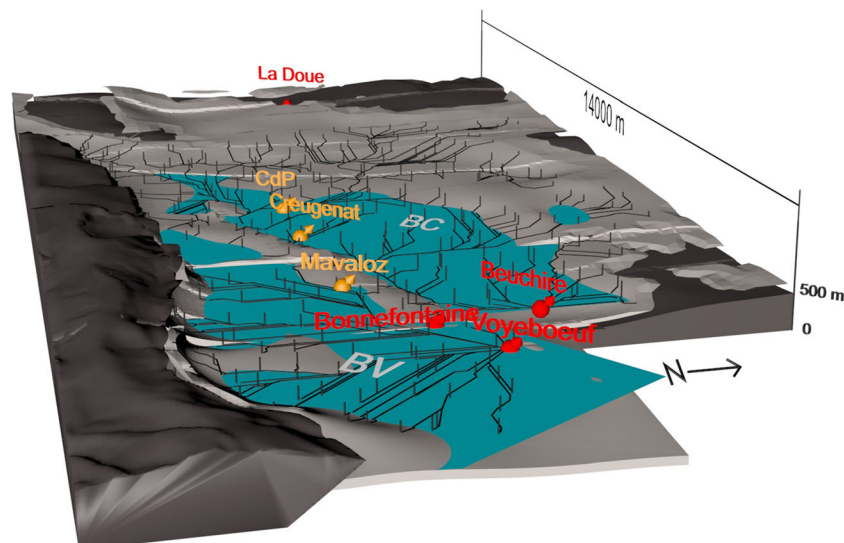


Fig. 12 Resulting 3D model of the generated conduit networks

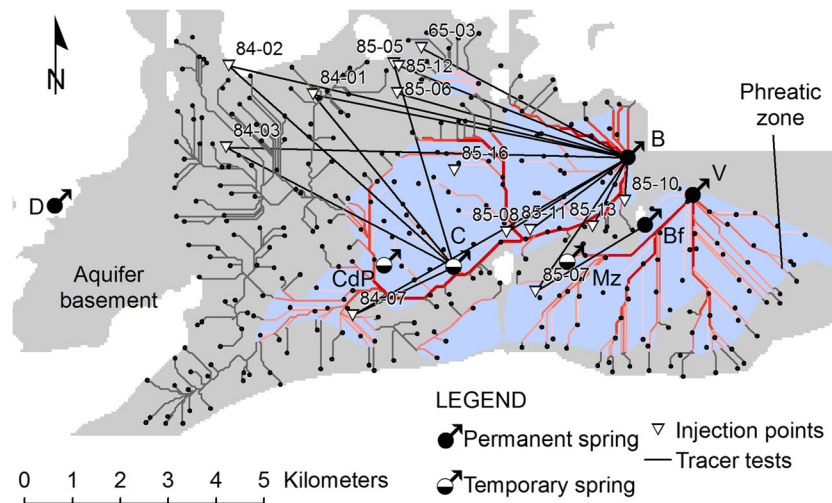


Fig. 13 Comparison between existing dye tracer connections (*black lines*) and the BC and BV karst conduit model (*grey* = vadose conduits, *red* = phreatic conduits). The *numbers* refer to the code of the tests which are further detailed in the text

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 real cave as well as in 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

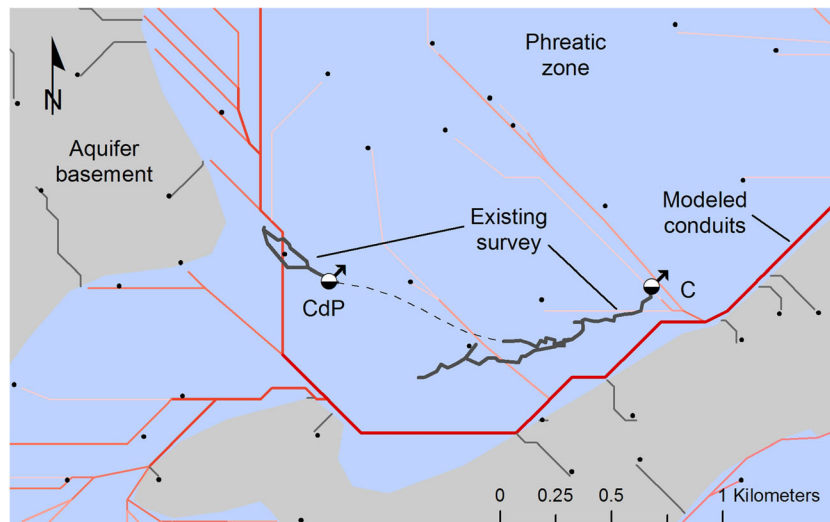


Fig. 14 Comparison between the existing cave surveys of the Creugenat (C) and Creux-des-Prés (CdP) and their supposed connection (respectively *black plain and dashed lines*) and the modeled conduit network (*red lines*)

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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