Inference of the structure of karst conduits using quantitative tracer tests and geological information: example of the Swiss Jura

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Abstract Karst aquifers are known for being particularly heterogeneous with highly transmissive conduits embedded in low permeability volumes of rock matrix. Artificial tracer experiments have been carried out in a complex karst aquifer of the folded Jura Mountains in Switzerland with the aim of deciphering the conduit organisation. It is shown that tracer experiments with multiple injection points under different flow conditions can lead to useful information on the conduits' structure. This information has been combined with data from structural geology, spring hydrology, and speleological observations. A conceptual model of the conduit network shows that a detailed inference of the conduit organisation can be reached: geology controls conduit location and orientation; spring hydrology, including temporary springs, constrains conduit elevations and relative hydraulic heads in the aquifer subsystems; and tracer tests identify major flow paths and outlets of the system and dilution caused by non-traced tributaries, as well as the presence of secondary flow routes. This understanding of the Aubonne aquifer structure has important implications for the future management of the groundwater resource. Similar approaches coupling geological information, spring hydrology, and multi-tracer tests under various flow conditions may help to characterise the structure of the conduit network in karst aquifers.

Résumé Les aquifères karstiques se caractérisent par leur forte hétérogénéité créée par quelques conduits très trans-
missifs englobés dans des volumes de roche peu perméables. Des essais de traçage artificiels ont été réalisés au sein d'un système karstique du Jura plissé (Suisse) dans le but de déterminer l'organisation des conduits. Les résultats montrent que des essais de traçage avec plusieurs points d'injection sous différentes conditions hydrodynamiques fournissent des informations utiles sur l'agencement des conduits. Ces informations ont été combinées avec des données de géologie structurale, le fonctionnement hydrodynamique des différentes sources du système et des observations spéléologiques. L'organisation de ces conduits peut être estimée avec une certaine précision et un modèle conceptuel du réseau de conduits est proposé : la géologie contrôle la position et l'orientation des conduits ; le fonctionnement des sources, incluant les sources temporaires, détermine l'élévation des conduits et les charges hydrauliques dans les différents compartiments de l'aquifère ; les essais de traçage permettent d'identifier les écoulements principaux, les différentes sources du système, les dilutions créées par des affluents non tracés et l'existence d'écoulements secondaires. Cette compréhension de la structure de l'aquifère de l'Aubonne a des implications importantes dans le cadre de la gestion future de cette ressource en eau. Des approches similaires, couplant des informations géologiques, le fonctionnement des sources et des essais de traçage sous des conditions hydrodynamiques différentes peuvent efficacement caractériser l'organisation du réseau de conduits des aquifères karstiques.

Resumen Se sabe que los acuíferos cársticos son particularmente heterogéneos, con conductos de alta transmisividad incluidos en grandes volúmenes de matriz rocosa de baja permeabilidad. Con el objetivo de descifrar la organización de tales conductos, se han llevado a cabo ensayos de trazadores artificiales en un acuífero cárstico complejo de las montañas Jura en Suiza. Se muestra que los experimentos con trazadores y múltiples puntos de inyección, bajo diferentes condiciones de flujo, pueden proporcionar información muy útil sobre la estructura de los conductos. Tal información se ha combinado con datos de la estructura geológica, la hidrología de manantiales, y con observaciones espeleológicas. Se demuestra que puede lograrse un modelo conceptual de la red de conductos con inferencias detalladas de la organización de tales conductos: la geología controla la localización y orientación de los conductos; la hidrología de los manantiales, incluso los de

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régimen temporario, condiciona la elevación de los conductos y los niveles de agua en los subsistemas acuíferos; y los ensayos de trazadores identifican las principales vías de flujo y salidas de agua, dilución originada en tributarios no involucrados en el ensayo, al igual que rutas secundarias del flujo. La comprensión de la estructura del acuífero Aubonne tiene importantes implicancias para el manejo futuro de los recursos hídricos subterráneos. Aproximaciones metodológicas de este tipo, vinculando información geológica, hidrología de manantiales, y ensayos de trazadores múltiples bajo condiciones de flujo variable podrían ayudar a caracterizar la estructura de la red de conductos en acuíferos cársticos.

Introduction

The management of groundwater resources (aquifer modelling, groundwater abstraction, groundwater protection) requires a comprehensive characterisation of the aquifer. This task may become particularly difficult in the case of highly heterogeneous media such as karst aquifers, which are known to present a few high permeability conduits embedded in a rock volume of generally low permeability (e.g. White 1988). Artificial tracer tests have proven to be of great help for the characterisation of karst aquifers (e.g. White 2002; Birk et al. 2005). These tests are particularly powerful at determining flow directions, solute travel times, and transport characteristics of the conduit network. Qualitative tests (i.e. no continuous monitoring of tracer breakthrough curve and/or discharge at the spring) are adequate for catchment area delineation or simple vulnerability assessment as they inform on connections between injection points and springs as well as transport velocities. However, recent technical advances offer new potentiality for continuous monitoring of both spring discharges and tracer concentrations, making quantitative experiments more readily achievable (e.g. Smart and Zabo 1997; Schnegg 2002). With this approach, it becomes possible to infer the detailed conduit structure (Atkinson et al. 1973; Smart 1988a, b), which can be validated further with numerical simulations (e.g. Birk et al. 2005). This characterisation of the conduit network is essential for studies of contaminant transport because conduit flow carries large masses of solutes very rapidly and hinders degradation processes.

In complex geological settings typical of many mountainous areas, the role of tectonic structures on karst aquifer flow paths has been clearly illustrated by field observations and tracer experiments (Häuselmann et al. 1999; Herold et al. 2000; Goldscheider 2005). However, even if these studies underline the geological control on the aquifer structure at catchment scale (for instance flow directions and hydraulic gradients), no further details on the conduit structure are given. Other artificial tracer test studies carried out by Birk et al. (2005), Massei et al.

(2006), Geyer et al. (2007) present detailed interpretations of the transport processes along a single conduit (i.e. injection in a sinkhole, recovery at the spring), but do not account for complex three-dimensional karst systems.

In the present study, a complex karst aquifer of significant size is characterised by combining a series of tracer tests and information from structural geology, spring hydrology, and speleological observations. The resulting model offers a new insight into the aquifer with respect to conduit connections and hydraulic relations between the different springs. More generally, this study shows that a detailed characterisation of a karst conduit network can be obtained with quantitative tracer experiments.

Study site

The Aubonne study site is located in the Jura Mountains, in the extreme west of Switzerland (Fig. 1). The karst aquifer comprises a 400 m thick bioclastic Mesozoic limestone (Malm) series with intercalation of thin marleous beds. Its base is constituted by the Oxfordian marls aquitard. The structure comprises a succession of anticlines and synclines, typical of the folded Jura Mountains (Fig. 2): from East to West, the main folds are successively the Mt Chaubert anticline, La Palud syncline, St-George anticline, Cheneviere syncline, Marchairuz anticline, Amburnex syncline, Begnines anticline, and the Vallee-de-Joux syncline. In addition, a second order folding can be observed on the limb of these structures. This is the case of the Noirmont anticline that develops only in the western corner of the catchment between Begnines anticline and Vallee-de-Joux syncline (Fig. 2). The fold continuity is affected by regional strike-slip faults such as Pontarlier-Vallorbe in the northeast of the study site or St-Cergue-La Cure in the south and additional less extensive faults.

Mean annual precipitation over the study area is between <1,000 mm at the foot of the mountain and about 1,600 mm in the highest elevation zones. Although summer thunderstorms and autumnal precipitation represent a significant contribution to the annual aquifer recharge, most infiltration takes place during the spring with snow cover melting. The recharge is mainly diffuse through thin soils and karrenfields; in addition a few small streams issued from marleous interbeds disappear in sinkholes at the limestone contact. Evidence of karstification is abundant and over 700 caves have been mapped in the catchment (e.g. Audétat et al. 2002). Most caves develop vertically within the unsaturated zone of the aquifer, which can be up to 500 m thick. Only one of these caves (Longirod cave) gives access to a major active drain with a perennial cave stream (the Longirod river) at 500 m depth. This subsurface river has been explored over more than 2 km in distance and consists of a free flow stream with a mean discharge of 0.1 m^3 s^{-1}. Accessible cave passages are limited at both ends by major breakdowns associated with local folding.

The main outlets of the Aubonne aquifer are located at the foot of the Mt Chaubert anticline close to the contact with the Tertiary sandstones (Molasse) and Quaternary till deposits.
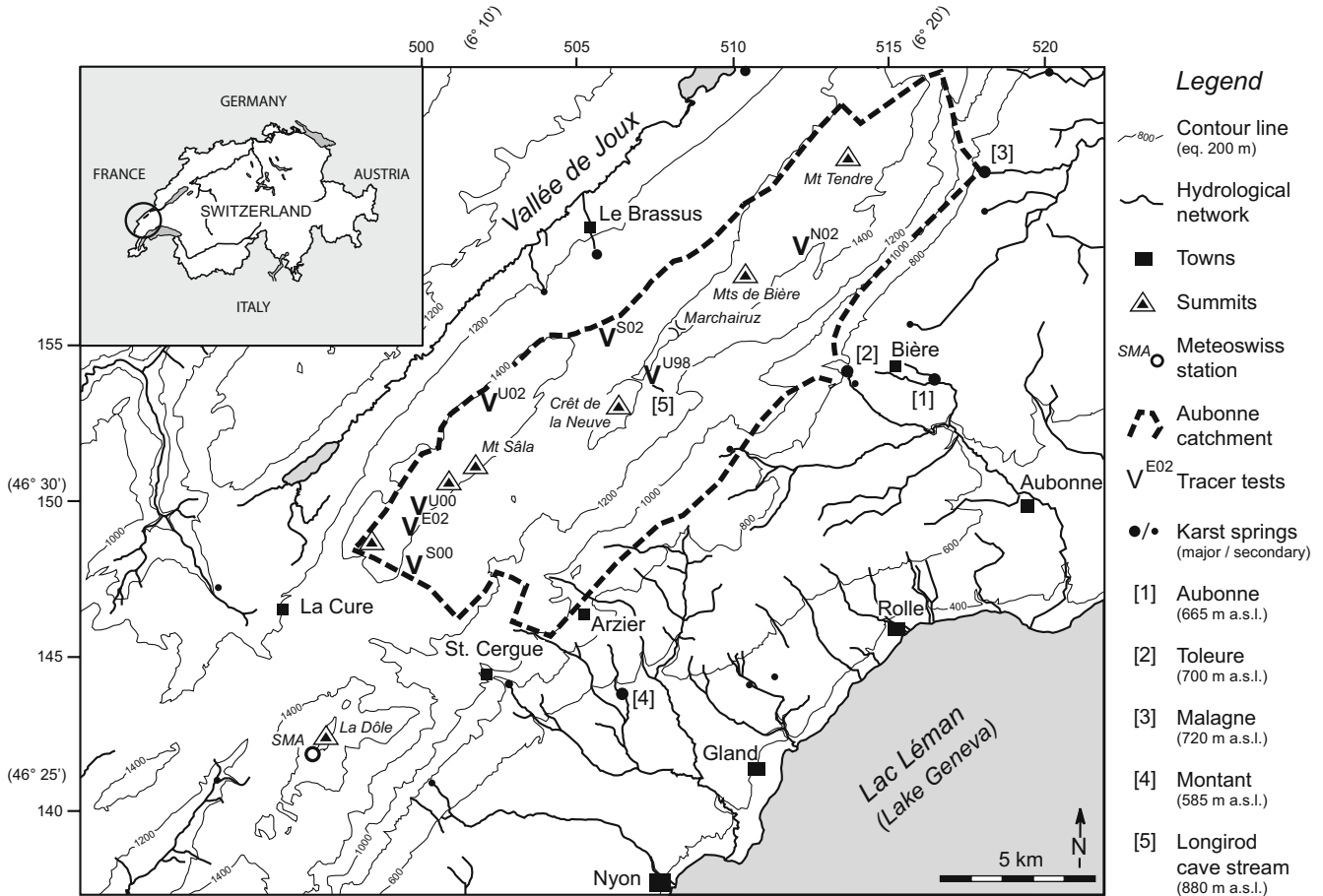
Fig. 1 Geographical situation of the study site. The Aubonne catchment and the location of the major springs are indicated together with tracer injection points

The springs are located in the vicinity of regional strike-slip faults traces, thus suggesting a tectonic control on flow paths directions (Fig. 2). Four major karst springs (>0.1 m³ s⁻¹ average discharge) were identified at different elevations. At the lower level, perennial springs (Aubonne: 665 meters above sea level (m asl), Montant: 585 m asl) are located either at the contact with Tertiary sandstones, which are covered by Quaternary deposits or along tectonic discontinuities. At a higher level, temporary springs are observed at the contact between limestone and Quaternary deposits (Toleure: 700 m asl, Malagne: 720 m asl).

Aubonne spring, the largest perennial outlet of the aquifer, has a discharge ranging between 0.2 and 10 m³ s⁻¹ and a mean annual discharge of 2.5 m³ s⁻¹. Two temporary springs become active when two respective flow thresholds are reached at Aubonne spring (Luetscher and Perrin 2005): Toleure spring starts flowing when Aubonne discharge becomes higher than 2.1 m³ s⁻¹ and its own discharge can reach up to 25 m³ s⁻¹; Malagne spring starts flowing when Toleure discharge exceeds 4.9 m³ s⁻¹ and its own discharge can reach up to 8 m³ s⁻¹.

From the synthesis of 24 tracer experiments conducted between 1897 and 2002, Luetscher and Perrin (2005)

delineated a catchment area for the Aubonne karst aquifer of nearly 142 km² (Figs. 1 and 2); a similar area has also been computed by dividing the yearly water volume flowing out of the aquifer by the average aquifer recharge (Luetscher and Perrin 2005). Based on this synthesis, the Aubonne catchment was delineated into six local recharge areas (Luetscher and Perrin 2005). It was concluded that flow paths within these catchments are chiefly controlled by the topography of the top of the Oxfordian marls aquitard and by strike-slip faults (Fig. 2). Some tracer experiments also demonstrated the presence of a major divergence towards the adjacent Montant system (13.5 km to the SW of Aubonne spring): tracers were detected at Montant spring (discharge Q=0.1–0.8 m³ s⁻¹) as well as at Aubonne and Toleure springs (Luetscher and Perrin 2005).

The present report focuses on the characterisation of the conduit network structure of the Aubonne karst aquifer using tracer experiments, spring hydrology, structural geology, and speleological information. For more general information on the Aubonne karst aquifer, the reader may refer to Luetscher and Perrin (2005) where regional geology, aquifer delineation, and spring hydraulics are described in detail.
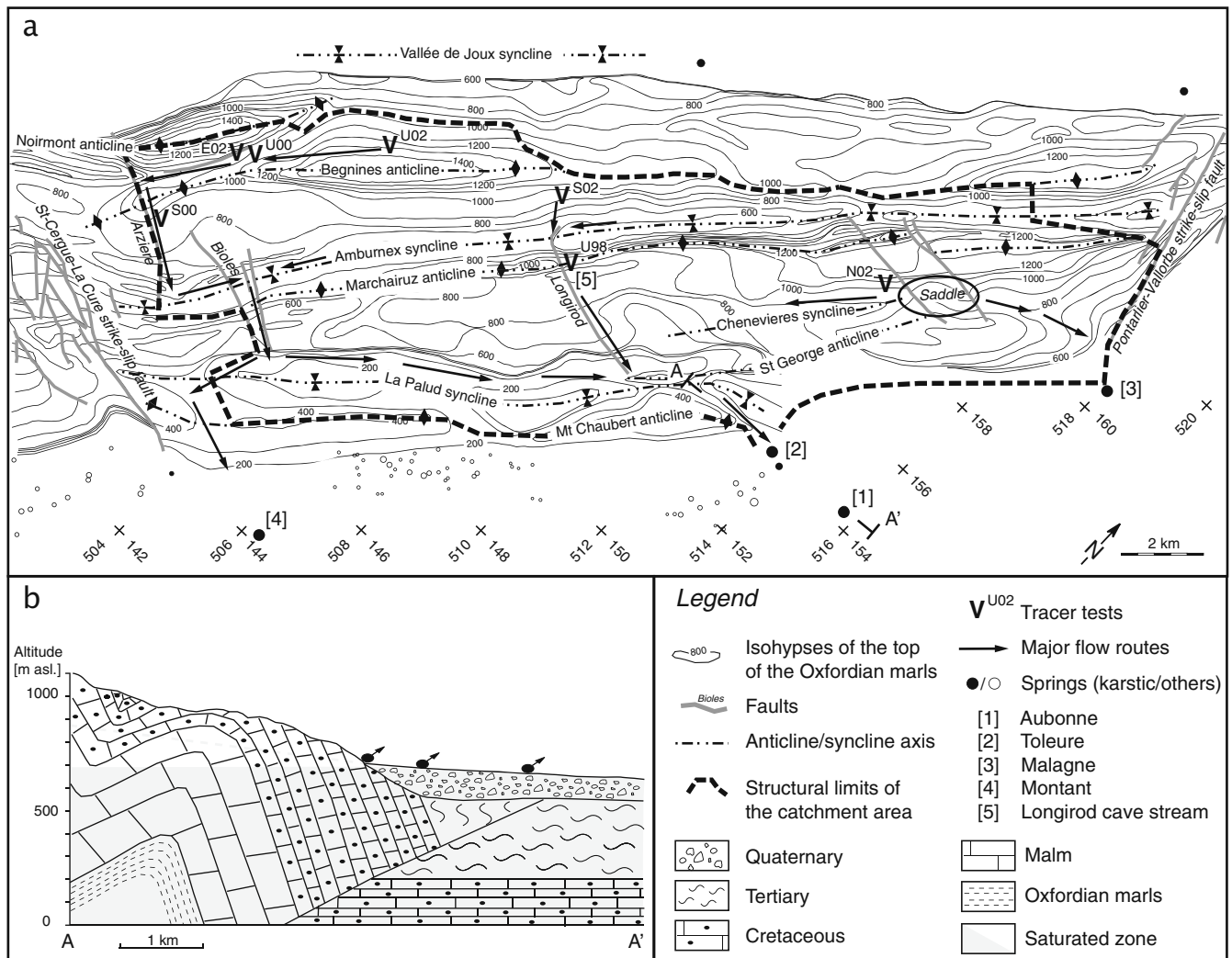
Fig. 2 **a** Hydrogeological map of the Aubonne karst aquifer catchment area and **b** geological cross section of the spring area

Methods

Discharge measurements

Aubonne spring was equipped with a pressure probe connected to a datalogger and an autographic water level recorder during the whole study period, from 1998 to 2002. Toleure spring was equipped with a pressure probe connected to a datalogger from November 1999 to the end of year 2002. The discharge of both springs was determined from rating curves based on measurements using a current meter for lower flows and the tracer (uranine) dilution technique at higher rates. Discharges are accurate to ±10%.

Since Toleure spring discharge was not monitored in 1998, it was calculated from the total discharge Aubonne+Toleure measured at a dam downstream subtracted by the measured discharge at Aubonne spring (Luetscher and Perrin 2005). The discharges at Montant spring and in the Longirod cave stream were determined in April 2002 by tracer (NaCl) dilution technique. The latter data were used to calculate tracer recoveries in Longirod River assuming a constant discharge during the tracer breakthrough duration.

The precipitation data were obtained from the Dole meteorological station, which belongs to the Meteoswiss (SMA) network. This station is located only a few kilometres away from the SW limit of the Aubonne catchment area (Fig. 1).

Tracer experiments

Seven quantitative tracer experiments were conducted between 1998 and 2002 (Table 1). Injection points are codified by a letter indicating the tracer (U=uranine, S=sulforhodamine B, E=eosine, N=naphtionate) followed by two numbers indicating the year the tracer test was conducted. Tracers were injected directly in known cave conduits in order to bypass the soil and the epikarst (Perrin et al. 2004).

In 1998, uranine (4 kg, code U98) was injected in the unsaturated zone of Longirod cave at a depth of 40 m below ground surface (Perrin and Luetscher 2001). The tracer followed the known speleological network formed by shafts in the unsaturated zone and the Longirod underground river before its recovery at the springs. Recovery at

Table 1 Injection conditions for the seven tracer experiments

Trace code	Site (coordinates, elevation)	Date (time)	Tracer	Injection data Local[a]	Hydrodynamic	Monitored springs
U98	Gouffre de Longirod (507'330/153'875, 1,350 m)	19.04.98 (13:00)	Uranine 4 kg	Cave: −40 m (1,310 asl) stream 5 l/min	High water after injection	Aubonne (AS, FL), Toleure (AS), Montant (MS), Malagne (MS)
U00	Gouffre Cathy (500'075/150'475, 1,500 m)	15.04.00 (15:00)	Uranine 6.5 kg	Cave: −157 m (1,343 m,asl) stream 13 l/min and 1 m³ water	High water, snowmelt	Aubonne (MS), Toleure (MS), Montant (AS, FL)
S00	Gouffre Combe Trébille (499' 500/147'850, 1,380 m)	15.04.00 (12:30)	Sulforhodamine B 5 kg	Cave: −120 m (1,260 asl) stream 13 L/min	High water, snowmelt	Aubonne (MS), Toleure (MS), Montant (AS, FL)
E02	Gouffre Dag's Bar (499'500/150' 210, 1,430 m)	20.04.02 (13:50)	Eosine 6 kg	Cave: −20 m (1,410 asl) stream 1 L/min and 3 m³ water	Medium water, snowmelt	Aubonne (AS), Toleure (AS, FL), Montant (AS, FL)
U02	Gouffre Masse (502'175/152' 900, 1,455 m)	20.04.02 (16:30)	Uranine 8 kg	Cave: −140 m (1,315 m asl)stream 15 L/min	Medium water, snowmelt	Aubonne (AS), Toleure (AS, FL), Montant (AS, FL)
S02	Gouffre Trois-Chalets (506'000/154'975, 1,340 m)	20.04.02 (14:40)	Sulforhodamine B 5 kg	Cave entrance (1,340 m asl) with 7.5 m³ water	Medium water, snowmelt	Aubonne (AS), Toleure (AS, FL), Montant (AS, FL)
N02	Gouffre Pierres-Pleines (512'760/158'610, 1,450 m)	20.04.02 (15:30)	Naphtionate 10 kg	Cave: −40 m (1,410 m asl) stream 2 L/min	Medium water, snowmelt	Aubonne (AS), Toleure (AS, FL), Montant (AS, FL)

[a]For injections inside caves, the depth and corresponding elevation of the injection point are given. Most injections were carried out inside cave streams and for U00 and E02 additional water was used for flushing. For S02, in the absence of natural stream, water was brought on site for flushing.

The major monitored springs are also indicated (*AS* automated sampling, *FL* automated fluorometer, *MS* manual sampling)

Aubonne spring was monitored continuously using an automated fluorometer backed up by an automated sampler. Grab samples were simultaneously collected from Toleure, Malagne and Montant spring.

In 2000, uranine (6.5 kg, code U00) and sulforhodamine B (5 kg, code S00) were injected in the active shaft system of the unsaturated zone through two different caves (Luetscher and Perrin 2001). Montant spring was monitored continuously and additional grab samples were collected from Aubonne and Toleure springs.

Finally, in April 2002 eosine (6 kg, code E02), uranine (8 kg, code U02), sulforhodamine B (5 kg, code S02) and naphtionate (10 kg, code N02) were injected in four different caves. The main springs (Aubonne, Toleure, Montant) were monitored with automated fluorometers measuring up to three tracers simultaneously and turbidity at 4-min intervals (Schnegg 2002). In addition, ISCO automated samplers were used to collect water samples at regular time intervals (4–6 h). During the 2000 and 2002 experiments, Malagne spring remained dry and thus could not be sampled.

The water samples were preserved in the dark and analysed within 2 weeks in the laboratory (Perkin-Elmer LS-50 B fluorescent spectrometer). Detection limits are 0.05 μg/L for uranine, 0.1 μg/L for sulforhodamine B, 0.05 μg/L for eosine, and 0.1 μg/L for sodium naphtionate. The latter detection limit increases to 2–3 μg/L in turbid water, limiting quantitative analyses during flood events. The Longirod cave stream was also monitored at a depth of 500 m below ground surface with an automated fluorometer. Although measured concentrations could not be cross-validated by manual sampling, its accuracy is estimated to be within 5% of the actual concentrations according to lab tests.

Tracer breakthroughs curves (TBCs) are codified by the two first letters of the spring where recovery occurred followed by an underscore and the code of the injection point defined earlier (e.g., au_U98 corresponds to the breakthrough curve of uranine injected in 1998 and recorded at Aubonne spring). TBCs were analysed with the QTRACER2 software (Field 2002). The hydraulic parameters are estimated by the method of moments applied to the TBCs: zeroth moment for tracer recovery calculation, first moment for mean residence time and mean tracer velocity. For better accuracy, the dispersion coefficient (D_L) estimation is not based on the second moment but on the Chatwin method using the following equation (Chatwin 1971):

$$\sqrt{T_i \ln\left(\frac{C_p \sqrt{T_p}}{C_i \sqrt{T_i}}\right)} = \frac{L}{2\sqrt{D_L}} - \frac{v_m T_i}{2\sqrt{D_L}} \tag{1}$$

where C_p is the peak concentration, T_p the time to peak tracer concentration, L the tracer distance or conduit length, v_m the mean tracer velocity, and C_i the concentration at time T_i.

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The required inputs include the injected mass of tracer (M_{inj}), the conduit length (L) which was estimated from the inferred flow paths (Fig. 2), the observed discharge (Q) and the tracer concentration (C) measured at the springs. Selected model outputs include tracer mean residence time and velocity, the dispersion coefficient (D_L), the Peclet number (defined as $L\, v_m\, /\, D_L$), and the tracer recovery.

Results

Spring discharges

The 1999-2000 hydrographs of Aubonne and Toleure springs (Fig. 3) show highly variable discharge rates typical of mature karst aquifers (i.e. well developed high-transmissivity conduits). Low flow conditions are observed during the summer months but can be disrupted by "flashy" floods due to thunderstorms or periods of intense rainfall like in July 2000. High flow conditions are observed (1) at the end of autumn when recharge is maximised by low evapotranspiration and possibly snowmelt (i.e. rain fallen on snow accumulated a few days before), and (2) in spring during the main snowmelt period. During this period (April–May 2000), a diurnal periodicity of Aubonne discharge rates is clearly visible and is attributed to snowmelt which is at maximum in the afternoon and stops at night. During a flood event, the discharge at Toleure increases faster than Aubonne, reaches higher values, and decreases faster. This is a typical behaviour for a temporary spring.

Discharges at Malagne are illustrated qualitatively by time periods where the spring is active, which happens only a few times over the hydrological year (Fig. 3). Flood events at Malagne spring are shorter and less frequent than at Toleure spring.

Tracer experiments

U98 was recovered at Aubonne spring as well as at Toleure and Malagne temporary springs (Table 2), which were both active due to high-flow conditions caused by snow melting. This shows that Aubonne, Toleure, and Malagne springs are not only hydraulically connected but also that the same traced water feeds these three springs. The tracer arrived in the same time range at the three springs and tracer breakthroughs occurred in phase with the discharge increase.

U00 and S00 were both detected at Montant spring but also at Aubonne and Toleure springs where two grab samples showed significant tracer concentrations. This connection between Montant and Aubonne karst systems was unexpected as they were considered as two separate catchments so far.

Fig. 3 Hydrographs of Aubonne and Toleure springs for the hydrological year 1999–2000 and daily precipitation at La Dole meteorological station; times when Malagne flows are qualitatively indicated by *grey rectangles* (modified from Luetscher and Perrin 2005)
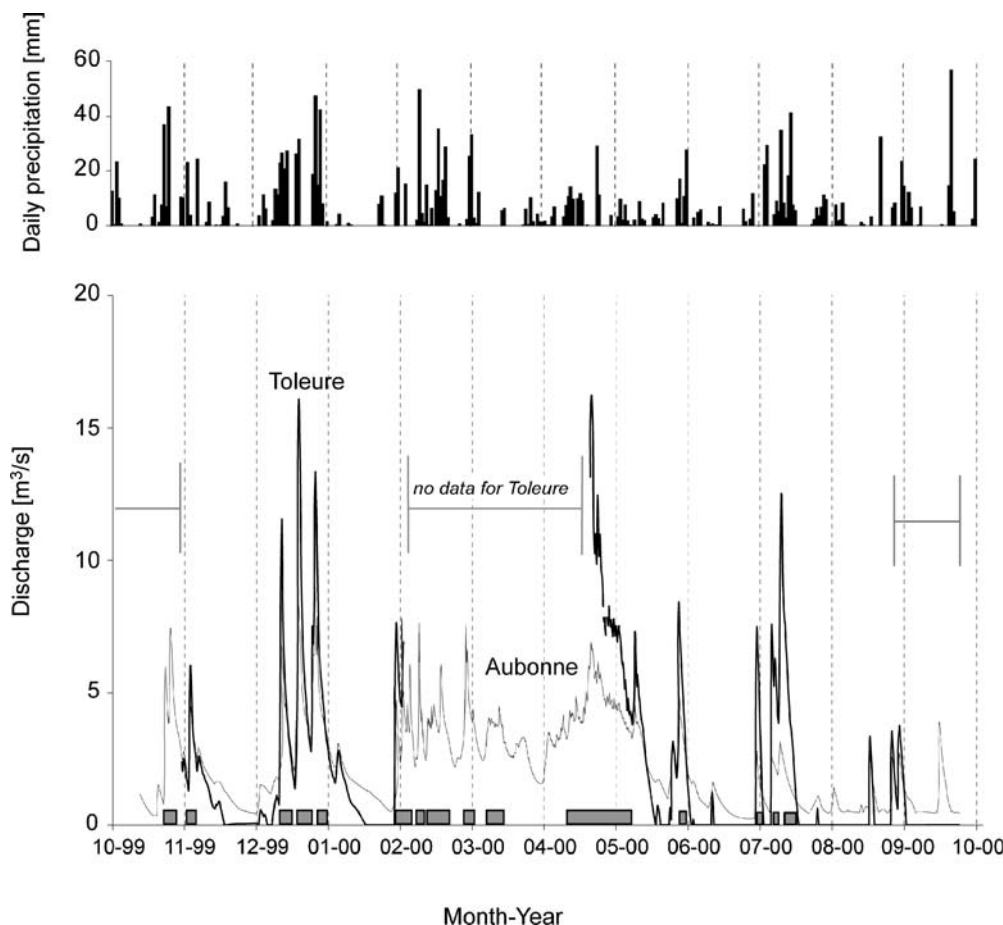
Table 2 Main characteristics of the tracer breakthroughs curves (TBCs)

| Trace code	Conduit length, L (m)	$T_{first} T_f$ (h)	$T_{peak} T_p$ (h)	$T_{resid.} T_r$ (h)	$(T_r-T_p)/T_r$ (%)	Peak C (ppb)	V_{max} (m/h)	V_{mean} (m/h)	Dispersion (m²/s)	Peclet number	Mass (g)	Recovery (%)	$T_{sec. peak}$ (h)	Remarks
au_U98	13,550	29	38	67	0.43	2.4[a]	467	202	10.93	69.6	4,000	43	47	Recovery at Malagne too
to_U98	11,650	25	34	57	0.40	2.1[a]	466	204	17.85	37.0	4,000	45	(44)[c]	
mo_U00	14,400	92	125	167	0.25	2.0	157	86	7.00	49.1	6,500	11		
mo_S00	10,500	88	119	183	0.35	2.7	119	57	2.82	59.0	5,000	17		
au_U02	27,400	166	190	226	0.16	6.3	165	121	2.14	430.3	8,000	22		
to_U02	25,600	156	220	250	0.12	5.6	164	102	5.33	136.1	8,000	35	220	
mo_U02	17,500	178	222	257	0.14	6.9	99	68	1.03	320.9	8,000	11		
au_E02	23,600	159	182	212	0.14	5.4	148	111	0.99	735.0	6,000	28	(282)	
to_E02	21,800	154	175	229	0.24	5.1	142	95	1.32	435.8	6,000	42	208	
mo_E02	13,700	174	215	251	0.14	8.2	79	55	0.83	252.2	6,000	17		
au_N02	17,000	170	199	239	0.17	6.7	100	71	1.09	307.6	10,000	21		
to_N02	15,100	170	212	289	0.27	5.5	89	52	2.07	105.4	10,000	42		
au_S02	18,200	173	202	268	0.25	4.4	105	68	3.03	113.5	5,000	43		
lo_S02	16,300	168	215	275	0.22	4.3	97	59	1.44	185.5	5,000	50		
lo_S02	4,650	86	117	127	0.08	256.0	54	37	0.16	298.7	5,000	66		Recovery calculated with 90 L/s
lon_au_02[b]	13,550	87	85	141	0.40		156	96						
lon_to_02[b]	11,650	82	98	149	0.34		142	78						

[a] Indicates semi-quantitative data

[b] Indicates results obtained between Longirod cave and the springs (code 'lon_au_02' is the flow path from the cave to Aubonne spring and code 'lon_to_02' is the flow path from the cave to Toleure spring)

[c] In brackets, secondary peaks that can only be inferred due to gaps between samples

The mean velocity (V_{mean}) is calculated with the mean residence time (T_{resid}). $T_{sec. peak}$ indicates significant secondary peaks on the TBC (i.e. supported by more than one sample)

Fig. 4 Tracer breakthrough curves at Aubonne, Toleure, and Montant springs respectively. The au_N02 and to_N02 data beyond 310 h are not shown because concentrations were influenced by turbidity increase at the springs. The 1998 Toleure spring discharge data are indicative and were back-calculated from measurements at a hydro-electrical plant downstream. At Montant spring, discharges were not recorded and hence Aubonne spring discharges are shown as an indicator of the flow conditions in the aquifer during the tracer tests
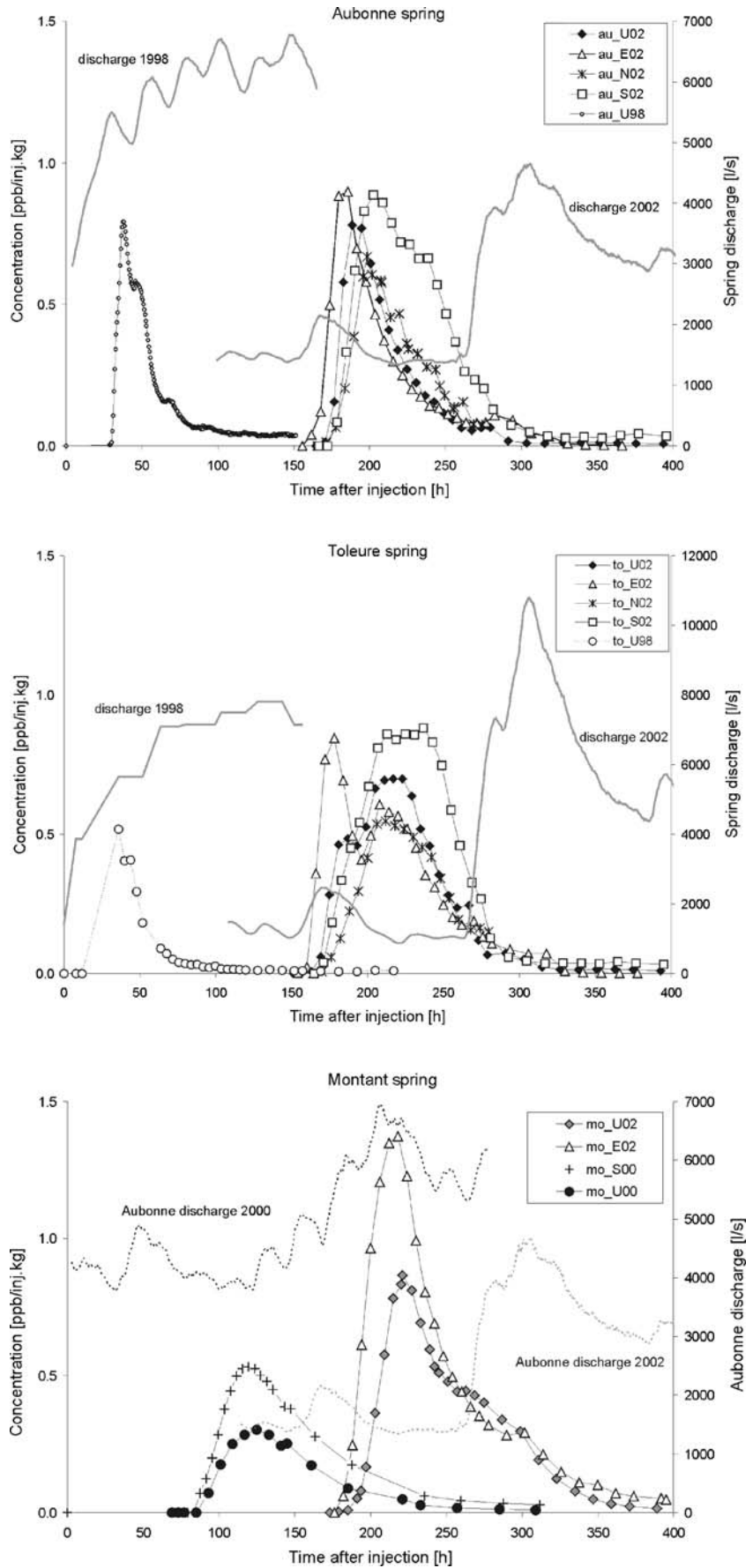
To study this further, a multi-tracer experiment was organised in 2002 where all the large springs were equipped with fluorometers and automatic sampling devices. All the injected tracers (U02, E02, S02, N02) were detected at Aubonne and Toleure springs and two tracers at Montant spring (U02, E02), thus confirming the divergence observed in 2000. One tracer (sulforhodamine B, S02) was also detected in the Longirod cave stream. For these 2000 and 2002 tests, medium-high flow conditions prevailed and Malagne spring was dry.

All seven tracers injected between 1998 and 2002 were at least recovered at Aubonne and Toleure springs. Mean velocities are systematically lower at Montant spring, even for the 2000 tracer experiment conducted under higher flow conditions than the 2002 experiments (Table 2). Tracer velocities were usually slightly higher at Aubonne spring as compared to Toleure spring except for the trace U98 for which maximum and mean velocities were in the same range. At both Aubonne and Toleure springs, much higher tracer velocities were recorded under high-flow conditions (U98) than under medium-flow conditions (U02, E02, N02, S02). For trace S02, the computed velocity between the injection point and Longirod cave is much slower than between Longirod cave and the springs (Table 2). This is attributed to the change in hydraulic conditions as the flood event arrived after the tracer had travelled across Longirod cave.

The total tracer recovery at Aubonne and Toleure springs ranges between 60 and 90% (Table 2). Recovery at Malagne and associated secondary springs during the 1998 experiment (U98) was less than 10% (Perrin and Luetscher 2001). In 2000, both injected tracers were simultaneously recovered at Montant spring (11% for U00 and 17% for S00), and in 2002 the two tracers detected at Montant showed similar recoveries (11% for U02 and 17% for E02). Thus for 1998, 2000, and 2002 experiments, water divergence occurred either towards Malagne spring or towards Montant spring. This result reveals the aquifer connectivity at a large scale (i.e. the distance between Montant and Malagne springs is 20 km).

Montant spring displays the highest peak concentrations for traces U02 and E02, which were also recovered at Aubonne and Toleure (Table 2). Tracer concentrations at Toleure spring are systematically slightly more dilute as compared to Aubonne spring concentrations. The longitudinal dispersion calculated with the Chatwin method (Field 2002) is between 0.16 and 17.85 m^2 s^{-1}, and is positively correlated with the maximum tracer velocity (correlation r^2=0.74, 15 observations). Longitudinal dispersion observed at Aubonne spring is generally lower than the one observed at Toleure spring with the exception of trace S02. The Peclet number is between 37.0 and 735.0, which clearly indicates advective transport.

As shown in Fig. 4, the measured TBCs at Aubonne and Toleure springs for trace U98 exhibit at least one secondary peak (t=45 h) on the main falling limb and possibly a third peak at the beginning of the tailing part of the curves (t=68 h). In contrast, the TBCs measured at Montant spring in 2000 (traces U00 and S00) are single-peaked and clearly

asymmetric with a well-defined tailing part. Two different shapes were obtained for the 2002 TBCs at respectively Aubonne and Toleure springs (Fig. 4): au_U02 and au_E02 display a sharp rise and smooth falling limb, with a secondary peak, whilst for au_S02 and au_N02 the rising limb is less steep despite the higher peak concentration and the falling limb is more complex; the TBCs to_U02 and to_E02 show sharper peaks with a secondary peak, whilst the TBCs to_S02 and to_N02 show flatter but smoother peaks. The TBCs recorded at Toleure spring present the lowest peak concentrations, which indicate higher dilutions. At Toleure spring, the 2002 traces also showed longer tails compared to Aubonne spring.

Trace S02 was monitored inside Longirod cave and at Toleure and Aubonne springs (Fig. 5). A strong dilution effect is observed between the upstream cave and the springs with concentrations dropping from 256 parts per billion (ppb) in the cave to 4.3–4.4 ppb at the springs. This dilution is firstly attributed to the observed 25 fold increase in discharge caused by the contribution of tributaries connecting between Longirod cave and the springs. The additional dilution is due to further dispersion along the flow path between Longirod cave and the springs.

In summary:

– Maximum tracer velocities range between 54 m/h (lo_S02) and 467 m/h (au_U98), typical values for karst aquifers.
– Recoveries are generally well above 60% (U98, U02, E02, N02, S02), indicating that the springs sampled were the major springs of the system, the noticeable exception being the 2000 experiments (11% recovery for mo_U00 and 17% recovery for mo_S00), where it is suspected that the main tracer recovery was at Aubonne and Toleure.
– The tracers injected in 2002 arrived within the same 28 hrs at the different springs even if the distances between springs and injection points can be significantly different. The arrival of the tracers is triggered by the first flood event occurring after the injection. This shows that transport in conduits is much faster during flood events and thus breakthrough times occur during the same span. Similarly, tracers injected in 1998 and 2000 were also recovered at the springs at the onset of a flood event (U98) or following a flood pulse (U00, S00).
– The TBCs exhibit secondary peaks and plateaus suggesting complex transport processes at least partly caused by transient flow conditions: secondary flow routes, dilutions, highly turbulent flow, etc.

Discussion

The used fluorescent tracers (uranine, sulforhodamine B, eosine, naphtionate) showed similar recovery rates and breakthrough curves (Table 2), which indicates predomi-

Fig. 5 Sulforhodamine B breakthrough curves recorded at Longirod cave and Aubonne and Toleure springs. Note that the spring concentrations are increased by a factor of 10 (*right ordinate axis*) for better readability
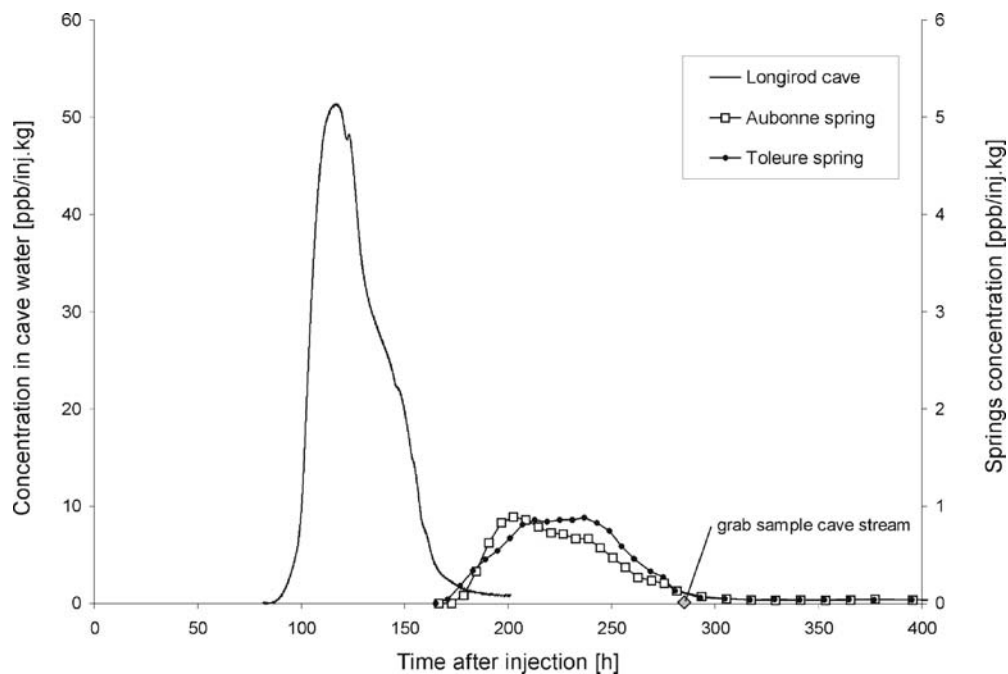
nance of conservative transport by advection and dispersion. This may not be surprising as the traced flow routes were karst conduits only (i.e., injections directly into conduits) and experiments were conducted under medium to high flow conditions. Under these conditions, reactive transport processes such as sorption seem limited. In contrast, Geyer et al. (2007) reached different conclusions from a multi-tracer experiment (uranine, sulforhodamine G, tinopal) as only uranine behaved as a conservative tracer. However, in their case, low-medium flow conditions may explain higher sensitivity of sulforhodamine G and tinopal to sorption. Naphtionate has the lowest recovery with 63% (N02) but its concentration in spring water could only be quantified for the first 280 h because of interference with spring turbidity at the onset of a flood event.

The TBCs measured at Aubonne and Toleure are interpreted further by plotting recovered masses, which correspond to the actual tracer mass fluxes divided by the injected tracer mass (Fig. 6). The eight mass curves obtained for the 2002 tracer experiments can be compared directly because hydraulic conditions were identical and the injection procedure was similar (Table 1). The differences between recovered mass curves U02, E02 (i.e. also recovered at Montant spring) and curves N02, S02 are significant: the first arrival of N02, S02 is delayed and the rising limbs are less steep than for curves U02, E02; the 300-h secondary peaks are higher for N02, S02. Moreover, au_N02 and au_S02 exhibit more complex multi-peaked curves than au_U02 and au_E02, which seems also true for curve au_U98 where two secondary peaks are visible. Therefore, it is proposed that two well-differentiated drains feed Aubonne and Toleure springs: one issued from the south-western part of the basin, traced by E02 and U02 and also connected to Montant spring, and the other issued from the northern part of the basin and traced by U98, S02,

and N02. These two drains will be named respectively the "Arzier drain" and the "Marchairuz drain".

Even if the shapes of mass curves are complex, two main tracer mass peaks can be identified: the first is associated with the flood event peaking at about 170 h, and the second is associated with the flood at about 300 h. In absence of tracer dilution, this suggests that for both events that water participating in the flood is mainly issued from the traced system (i.e. the conduits), which indicates a significant storage capacity of the traced conduits.

Significant mass flux increase is interpreted as the activation of epiphreatic conduits (i.e. secondary flow routes), which become temporarily flooded during the events, hence increasing the transmissivity of the system, and therefore leading to the successive mass fluxes peaks. All recovered mass curves present a characteristic multiple-peak response, which is attributed to the respective contribution of epiphreatic conduits (Fig. 6).

It can be deduced that: (1) epiphreatic conduits exist on the Marchairuz drain upstream of the divergence Aubonne-Toleure to account for the systematically observed multi-peaks, (2) epiphreatic conduits exist near Toleure spring to account for the observed differences in the mass flux responses between Aubonne and Toleure for traces U02 and E02. These epiphreatic conduits are further evidenced in the field by the presence of several temporary outlets at Toleure: these outlets become successively active at the onset of a flood event ("multi-conduits" spring).

Additionally, the higher dilutions observed at Toleure spring (Table 2) suggest the presence of a conduit connected to Toleure only and fed by an independent aquifer. Higher tracer concentrations observed at Montant spring are explained by the more upstream location of Montant spring on the Arzier drain: concentrations are not diluted by tributaries further downstream.

Fig. 6 Recovered tracer mass at Aubonne and Toleure springs for **a** traces recovered at Aubonne, Toleure, Montant springs and **b** traces recovered at Aubonne, Toleure springs only
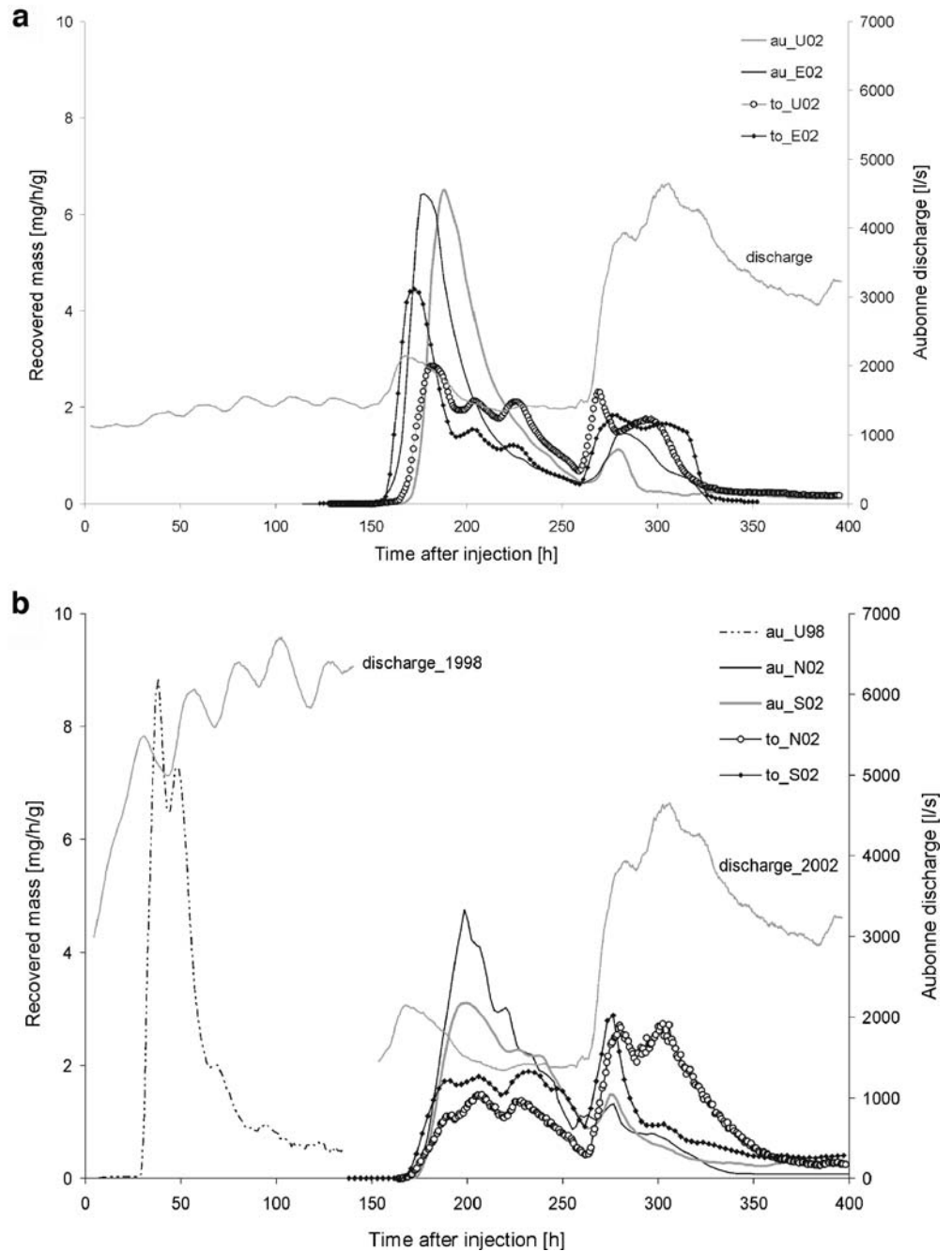
The Marchairuz drain

More insight can be gained for the Marchairuz drain because it is partly accessible through Longirod cave (Perrin and Luetscher 2001), and was the object of a higher number of tracer experiments. The general position of the drain is controlled by the Longirod strike-slip fault oriented W–E (Fig. 2). The drain can be split into three sections namely the upstream zone (i.e. before Longirod cave), the accessible zone in Longirod cave, and the non-accessible downstream zone.

As suggested by trace S02, the upstream part of Marchairuz drain is mostly fed by groundwater issued from the Amburnex syncline (Fig. 2). This structure is perpendicular to the Longirod fault and extends several kilometres on both sides of the fault. The aquifer base (i.e. top of the Oxfordian marls) along the Amburnex syncline axis reaches an elevation of about 600 m asl and is bounded by two anticlinal ridges where the top of the Oxfordian marls culminates at about 900 m asl. Therefore, an up-gradient phreatic zone (i.e. disconnected from the main phreatic zone in the springs zone) exists which may act as a storage element participating to the Marchairuz drain base flow. However storage in the Amburnex syncline seems limited as shown by the reduced tailing and low dispersion observed on trace S02 after crossing the syncline width (compare with lo_S02; Fig. 5). This

suggests the presence of a well-organised karst conduit system in the phreatic zone of the Amburnex syncline.

Downgradient of Amburnex syncline, Marchairuz drain crosses the Marchairuz anticline and can be accessed via Longirod cave (Fig. 7). The master conduit traced by S02 as well as two major tributaries are issued from the Amburnex syncline whereas other low-discharge tributaries have a more local origin (i.e. small catchment areas in the vicinity of the cave).

Conduit locations are only partially controlled by the strike-slip fault. Meandering occurs along zones of sub-horizontal bedding planes and some tributaries are parallel to the syncline axis (Fig. 7). During flood events, the most downstream part of the cave gets flooded up to an elevation of about 870 m asl. This is indicated by the presence of thick mud deposits in the large room marking the end of the cave; this mud is most probably issued from the desegregation of marleous beds intercalated in the limestone series. The mud is wet and refreshed several times per year and contains small worms as well as other fresh organic deposits of surficial origin.

Downstream of Longirod cave (i.e. inaccessible part), Marchairuz drain reaches the permanent phreatic zone and is connected to at least two tributaries contributing to the strong dilution observed on au_S02 and to_S02 (Fig. 5): the conduit connecting to N02 injection point (hereafter called the "Petit Pré" drain) and the Arzier drain. The observed similarity between N02 and S02 TBCs suggests a common flow path over a large part of their entire travel. It is inferred that Petit Pré drain connects to Marchairuz drain far away from Aubonne spring (i.e. slightly downstream of Longirod cave end point as sketched on Fig. 7). It is suggested that Petit Pré drain follows the steeply dipping bedding planes, which connect Cheneviere syncline with St-George anticline (Fig. 2). On the common flow path downgradient of the Petit Pré drain connection,

the master drain is assumed to display a complex structure with epiphreatic conduits explaining the observed multi-peak mass curves for N02 and S02.

It is also in this zone that the divergence towards Malagne temporary spring is likely to occur. Tracer experiments demonstrated that the Marchairuz drain can partially feed Malagne (U98) and that the Petit Pré drain either directs water to Aubonne when Malagne is dry (N02) or preferentially towards Malagne when the latter spring is active (Lavanchy and SCVJ 1987).

It is thus proposed that the divergence towards Malagne spring occurs through the same Petit Pré drain, which describes a saddle at approximately 850 m elevation in order to accommodate the topography of the Oxfordian marls (Figs. 2 and 8). During low water conditions, Petit Pré drainage follows the conduit slope (unsaturated zone flow conditions), connects to Marchairuz drain, and ends up at Aubonne-Toleure (e.g. N02); under higher flow conditions, hydraulic heads on the SW side of the saddle increase due to the large catchment area feeding the Marchairuz drain (i.e. sustained by the Amburnex syncline). As soon as the water level reaches the saddle Malagne starts flowing, and water in Petit Pré drain is preferentially redirected towards the latter spring (phreatic flow conditions). This interpretation is supported by the flooding observed in the downstream part of Longirod cave (i.e. at an elevation of about 870 m asl) and was tested by U98 tracer test which was detected at Aubonne, Toleure, and Malagne springs.

The Arzier drain

Less information is available on the structure of the Arzier drain: so far, there is no access through caves and the hydraulics of Montant spring has not been studied. However some structural elements can be inferred from

Fig. 7 Simplified map of Longirod cave indicating the master conduit and the main tributaries along with the structural geology elements. The injection point U98 is also indicated (*black diamond*) in the shaft zone part of the cave represented by a *thin black line*
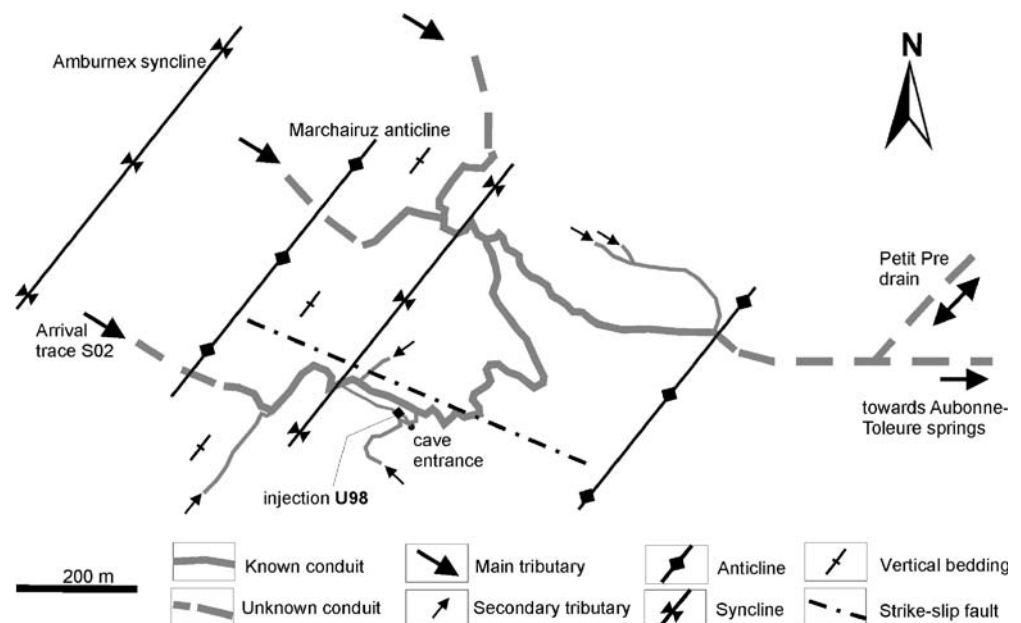
the hydrogeological map (Fig. 2) and the tracer test results. The upstream part of the drain is issued from the NW limb of Begnines anticline as proven by trace U02. Downgradient, the drain follows the syncline squeezed in between the Begnines anticline and the Noirmont anticline as the Oxfordian marls outcrop at the core of both anticlines (Fig. 2). On the way, tributaries traced by U00 and E02 connect to the drain. Then, most probably, the drain crosses Begnines anticline (collecting tributary traced by S00) along the Arziere strike slip fault in a similar way than Longirod drain crosses Marchairuz anticline along Longirod fault. Further downgradient, a tributary issued from the SW part of Amburnex syncline connects to Arzier drain. A tracer experiment conducted in 1992 by consultants showed the existence of this drain: 10 kg of Eosine were injected in a sinkhole and tracer was recovered at Montant spring; unfortunately Aubonne and Toleure were not monitored (trace E92 in Luetscher and Perrin 2005). The Marchairuz anticline is crossed along the Bioles faulting zone and Arzier drain enters the permanent phreatic zone, where a divergence towards Montant spring is observed. It is likely that the Arzier drain then develops parallel to St-George anticline along its SE limb, possibly following steeply-dipping bedding planes. Finally Arzier drain connects to Marchairuz drain some distance upgradient of Aubonne and Toleure springs (Fig. 8).

The conduit structural model

The drains presented in the previous sections can be combined at the scale of the Aubonne aquifer (Fig. 2) in order to end up with a conceptual model of the aquifer conduit network (Fig. 9). In this model, the presence of two main drain directions is suggested: the first is parallel to the fold axes and corresponds to the drainage of synclines; the second direction is more or less perpendicular to the first and corresponds to the traces of strike-slip

faults. It is only through these faults that groundwater can flow across anticline hinges where the top of the aquitard (Oxfordian marls) is usually higher than piezometric surfaces under low water conditions.

The Arzier drain starts on the NW limb of the Begnines anticline, collects traces U02, U00, E02, and then crosses Begnines anticline (trace S00) and connects to Amburnex syncline where tributaries issued from the syncline contribute probably to a flow increase; Marchairuz anticline is then crossed and the drain enters the permanent phreatic zone in the Cheneviere syncline; on the SE limb of St-George anticline, the drain divides: one branch leads to Montant spring and the other to Aubonne-Toleure springs. The one leading to Montant has a relatively slow flow, which may be attributed to the lower discharge directed towards Montant (indicated by lower tracer recovery) or a more complex flow route, significantly longer than the assumed straight line (Fig. 2). Additionally, Montant spring is also fed by the Dole drain (Fig. 9) which is issued from a catchment area distinct of the Aubonne basin (Luetscher and Perrin 2001).

Marchairuz drain begins in the Amburnex syncline (S02) and then crosses the Marchairuz anticline along the Longirod fault system (U98). Downgradient, it enters Cheneviere syncline and the permanent phreatic zone; it is also in this area that the Petit-Pre drain connects (N02) and diverts some flow to Malagne spring under high-flow conditions. Downgradient of this connection, secondary flow routes exist, Marchairuz drain and Arzier drain get connected, and the drain ends up at Aubonne spring and respectively Toleure under medium-high flow conditions. Malagne drain is partially fed by an independent conduit that may either discharge in the till deposits or recharge the confined limestone aquifer during low flow conditions when Malagne spring is dry.

The existence of two distinct spring levels can be explained in the light of the Quaternary karstification history: the base level is determined by the contact

Fig. 8 Schematic cross-section along the Marchairuz drain illustrating the proposed conduit model accounting for hydraulics and tracer tests observations (*note the vertical exaggeration*). The lowest potentiometric line corresponds to low-flow conditions (only Aubonne spring flowing), whereas the two other lines correspond to higher flow conditions when Toleure is flowing and Toleure+Malagne are flowing. The Cheneviere syncline axis plunges towards the SW, which explains the apparent discrepancy between the Oxfordian marls position along the cross-section and the Saddle 850 m located further to the NE (see Fig. 2)
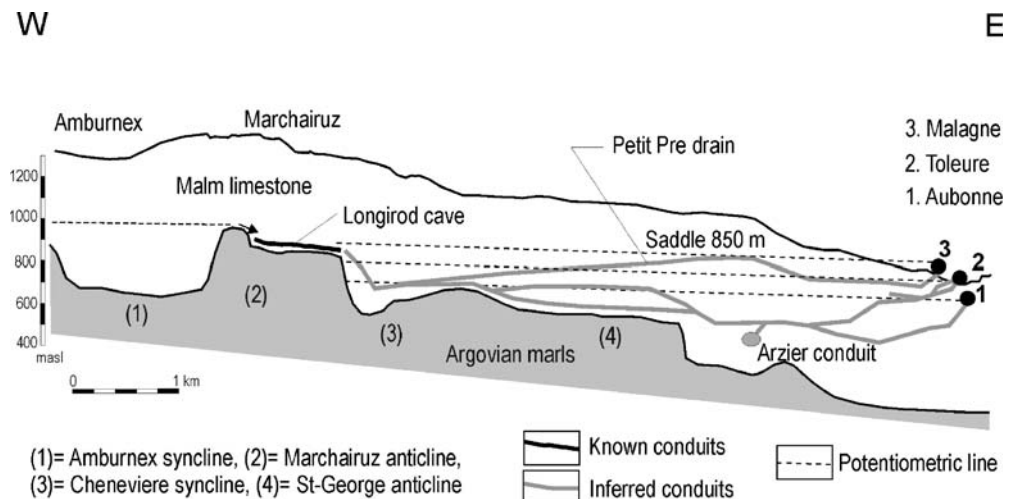
between Tertiary sandstones and limestone, and the aquifer discharges at this level through springs located in the axis of strike-slip faults (level 600 m asl). With the occurrence of glaciations and associated deposits, this base level became clogged and rose near the contact between Quaternary tills and limestone (level 700 m asl); new springs started to flow at this level either through newly developed conduits or reactivated fossil conduits. At a later stage, former springs at level 600 m asl were reactivated as a consequence of glacier melting and partial erosion of the overburden. This evolution was favourable to the development of conduits between the two levels and supports the presence of secondary flow routes upgradient of Aubonne-Toleure springs. These conduits become active especially during medium-high flow conditions when higher hydraulic heads distribute flow in these epiphreatic conduits.

Contrary to "classical" karst aquifers (Ford and Williams 2007), this system has two phreatic zones connected by an unsaturated zone system: the upper phreatic zone comprises the Amburnex syncline and represents a "perched aquifer" with a water-table elevation about 200 m higher than the main down-gradient phreatic zone which is in direct connection with the springs. These two phreatic zones are thick, about 300 m for Amburnex and more than 500 m near the springs (Fig. 8). Apparently this does not impact the springs' hydraulic response and the tracer transport, which are both rapid and sharp. This confirms clearly the prominent role of conduit flow in both the unsaturated and phreatic zones.

This conclusion is in total agreement with the observed changes in chemical at Aubonne and Toleure springs during flood events (Luetscher and Perrin 2005): very rapidly after the first arrival of the flood pulse, the specific electrical conductance starts to vary indicating the arrival of water having different chemistry than during base flow conditions.

The tailing generally observed after the falling limb of TBCs is explained by two different models: either it is related to the slow release of tracer temporarily stored in the rock matrix (i.e. aquifer low permeability volumes (LPVs); Seiler et al. 1989; Maloszewski and Zuber 1990; Goldscheider 2005), or it may result from a dual flow in the conduits (i.e. presence of immobile water zones, pools which slow down part of the tracer; Field and Pinsky 2000, Hauns et al. 2001, Massei et al. 2006, Geyer et al. 2007). In the present study, tailing lasts longer at Montant spring (about 150 h) than at Aubonne and Toleure springs (about 100 h) (Fig. 4). The tailing persistence seems little influenced by the hydraulic conditions as similar shapes and durations are obtained for the tests realised in 1998, 2000, and 2002. Additional insight can be obtained from trace S02 (Fig. 5). Although the tailing measured on the underground river in Longirod cave is incomplete, a grab sample was collected 285 h after the injection. This sample lies on the rising limb of a major flood event and
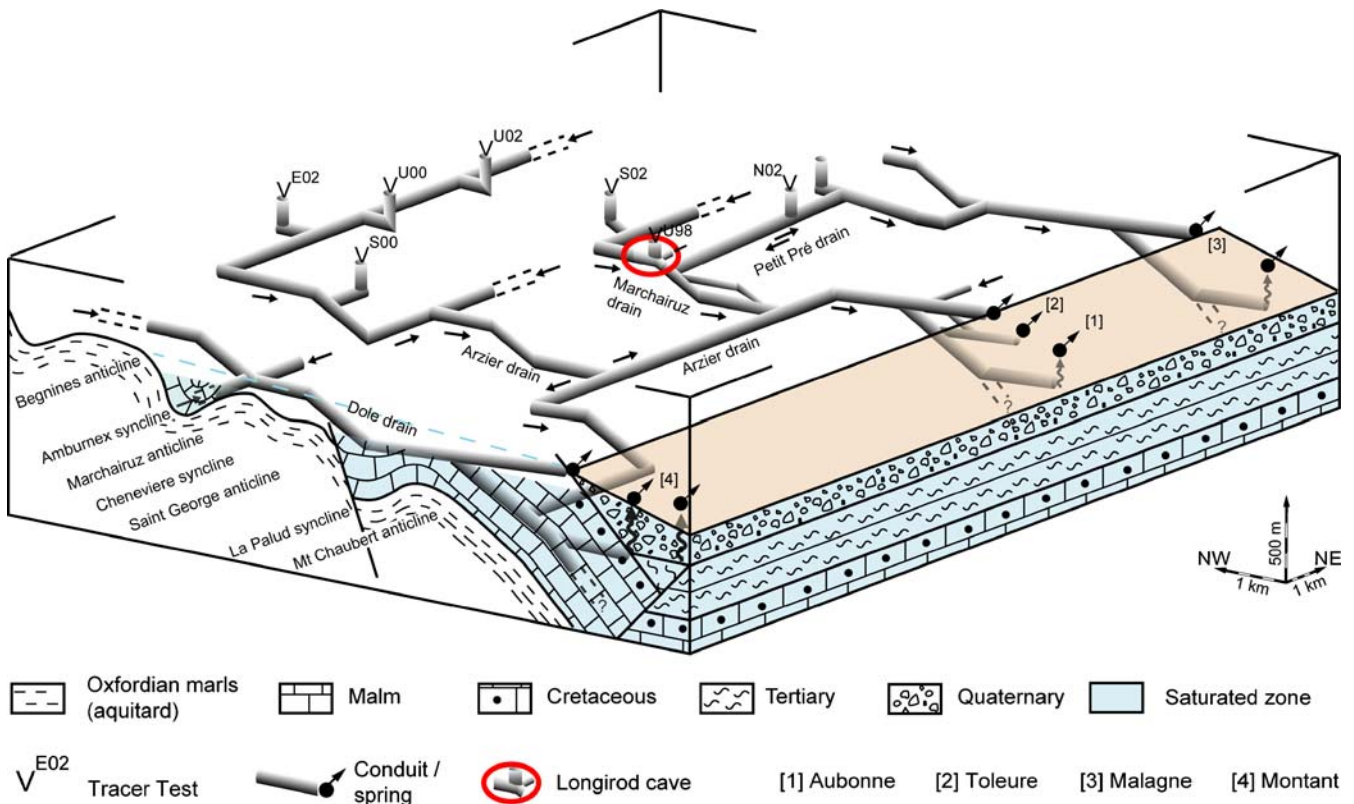

Fig. 9 Structural model of the Aubonne conduit network based on tracer tests, spring hydrology, geological and speleological information. Two major drains, *the Arzier and the Marchairuz drain*, were identified, showing divergences to *Montant* and *Malagne karst* springs respectively

shows a significant concentration in sulforhodamine B (0.58 ppb). This suggests that the tailing duration at Longirod underground river is at least about 100 h which is in the same range than at Toleure and Aubonne springs located downgradient of the main phreatic zone. These observations tend to favour the second model which explains tailing by heterogeneous flow velocities in conduits: (1) the hydraulic conditions have a limited impact on the tailing shape which seems to indicate the prominent role of the conduit morphology on tailing (if tracer storage in LPVs was important, maximum storage would be expected during flood events when LPV recharge is maximised), (2) the similar tailing obtained in Longirod cave upgradient to the main phreatic zone and the Aubonne and Toleure springs tends to reduce the role of the phreatic zone where temporary storage of the tracer could occur in LPVs.

This interpretation limits the role of phreatic storage in LPVs, which can be partly explained by the nature of the massive limestone constituting the aquifer, which has a very low effective porosity (<1%; Wenk and Wenk 1969). Conversely, conduit storage has probably some significance as hydraulic head rises by at least 200 m (up to the elevation of Longirod cave downstream part) during recharge events. This represents a large volume of limestone temporary flooded, which is likely to contain significant volumes of open space such as epiphreatic conduits.

The computed tracer recovery (Table 2) informs on the relative volumetric flows arriving at each spring in case of divergence. On the Arzier drain, 11–17% of the total flow is diverted towards Montant spring and the remaining 83–89% flows towards Aubonne and Toleure springs. Similar values were obtained for the 2000 and 2002 tracer experiments, which give some further confidence in this estimation. In the case of Aubonne and Toleure, the recovery is systematically higher at Toleure and is between 52 and 77% of the total volumetric flow (Aubonne and Toleure springs). This variability is attributed to changing hydraulic conditions. There is no systematic difference between recoveries computed for traces issued from Arzier drain as compared to traces issued from Marchairuz drain. This confirms the existence of a common flow path for traces issued both from Arzier and Marchairuz drains, which is located upgradient of the divergence between Aubonne and Toleure springs.

Implications of the model

The Aubonne aquifer complexity has been revealed by detailed field investigations including multi-tracer experiments, structural geology, spring hydrology, speleology, and regional geomorphology during the Quaternary. Only this combined approach allows to propose an adequate model of the conduit structure (Fig. 9): structural geology informs on flow directions and hydraulic gradients at catchment scale; spring hydrology indicates the existence of temporary springs and constrains conduit elevation, and tracer experiments provide more detailed information on

the conduit structure and the connectivity between springs but also validate assumptions based on geological information. Speleological surveys remain the best method for determining the exact location of conduits.

Hydraulic conditions control largely the tracer velocity and restitution (i.e. all tracer restitutions are associated with a recharge event) in agreement with previous studies (e.g. Kass 1998). This means that (1) it is of prime importance to monitor discharges during a tracer test for any quantitative interpretation (e.g. mass fluxes), and (2) multi-tracer experiments are of great interest because several conduits (or recharge zones) can be tested under identical hydraulic conditions.

Solute transport in karst aquifers is highly sensitive to transient flow conditions and conduit structure (e.g. secondary flow routes, epiphreatic conduits). It would be very useful to have simulation tools that can reproduce this complexity. So far, most analytical and numerical models used for transport simulations, even if they may be able to reproduce TBCs, present several limitations: (1) they do not combine hydraulic factors with transport, or only under steady-state conditions (Werner et al. 1997; Field and Pinsky 2000; Hauns et al. 2001); (2) they do not include the effects of the conduit structure, like divergence or mixing due to tributaries (Werner et al. 1998), and (3) they do not include dilution effect (Morales et al. 2007), which has a great impact on calculated dispersivities as shown by Rossier and Kiraly (1992).

This study illustrates the complexity of a conduit karst aquifer and the challenges that can be faced for its proper management: for instance, a same recharge area can be drained towards different springs depending on the hydraulic conditions. This behaviour should thus also be included in karst aquifer vulnerability methods (e.g. COST Action 620 2004).

Conclusions

Complex conduit organisation is an inherent characteristic of karst aquifers. A major difficulty in karst aquifer field investigations is to infer this conduit structure, which is of prime importance for an adequate management of the groundwater resource. This study shows that quantitative multi-tracer experiments hold much promise for a detailed inference of the conduit network. The monitoring of tracer concentrations and discharge at springs at high temporal resolution becomes more readily feasible with the development of in situ monitoring tools (pressure transducers and field fluorometers). Combining multi-tracer experiments under different flow regimes brings an in depth characterisation of the conduit organisation. Additional information from the structural geology, spring hydrology (e.g. presence of temporary springs) and Quaternary geology (e.g. base level evolution) provides further refinement and validation of the conduit model. This full characterisation of the conduit network is the only way to guarantee an adequate protection of the groundwater resource. It will, for instance, recognise the existence of

divergences and interconnections between adjacent catchment areas under high flow conditions.

In the authors' opinion, further understanding of karst aquifer conduit organisation could be obtained by combining speleogenetic models and tracer experiments. Speleogenetic models suggest that the conduit network develops in a dendritic shape: the spring is connected to a master conduit which is fed by numerous tributaries which in turn can be fed by additional second-order tributaries (e.g. Palmer 1991; Palmer 2003). It means that (1) tributaries should be considered in any conceptual/numerical model and (2) flow should end up at one point, the karstic spring. However, observed divergences during tracer experiments are indicative of a more complex conduit structure (e.g. several karstification phases under different boundary conditions). Moreover, the presence of secondary flow routes, suggested by multiple peaks during high-flow tracer tests, is an indication for epiphreatic conduits (e.g. from an antecedent karstification level). This implies that deep phreatic flow is probably limited which is in disagreement with the model of Worthington (2001), stating that deep flow paths in unconfined karst aquifers are favoured by a decrease in water viscosity caused by higher water temperature at depth (geothermal heating). This is especially significant for aquifer systems with steep dips and long flow paths (>3 km).

Observations on tailings and comparison between a TBC upgradient of the main phreatic zone (i.e. Longirod cave) and TBCs at the springs tend to indicate the limited role of phreatic storage in LPVs in the Aubonne karst aquifer under medium to high flow conditions. Therefore, it is believed that conduits represent a major storage element of the system especially because of the complex structure of the conduit network with different karstification levels and the presence of extensive epiphreatic conduits. An objective for future research could be the use of tracer tests under low water flow conditions to inform on the potential role of phreatic storage in LPVs.

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