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The Aubonne karst aquifer (Swiss Jura)

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Key words: Karst hydrology, tracer test, catchment area, folded Jura, Aubonne

ABSTRACT

A synthesis of the hydrogeological investigations carried out in an important karst region of the Jura Mountains led to the recognition of a major hydrological system: the Aubonne-Toleure-Malagne system. The continuous monitoring of hydraulic parameters at the main outlets established a mean discharge of the system of more than 6 m^3/s. A delimitation of the Aubonne catchment area is proposed in accordance with the water balance and the geology. Tracer tests outline the presence of a complex karst network which is closely related to the structural context. A schematic organisation of this network is proposed and a major divergence towards the nearby Montant system is set in evidence. Geological observations provide also evidences for a precise delineation of the catchment area: six major functional elements for the recharge of the aquifer are distinguished and transversal drainages towards the Aubonne spring system are outlined along major strike-slip faults. Combining hydrological information available on the Aubonne karst aquifer provides the indispensable background data for the management and the protection of this water resource.

RESUME

Une synthèse des données hydrogéologiques acquises dans une vaste région karstique de la chaîne Jurassienne a permis de reconnaître un système hydrologique majeur: le système Aubonne-Toleure-Malagne. L'enregistrement continu de paramètres hydrauliques aux principaux exutoires détermina un débit moyen de plus de 6 m^3/s. Une délimitation du bassin d'alimentation de l'Aubonne est proposée en accord avec le contexte géologique. Les essais de traçage suggèrent la présence d'un réseau karstique complexe, dépendant fortement du contexte structural. Une organisation schématique de ce réseau est proposée et une diffluence majeure est mise en évidence en direction de la source avoisinante du Montant. Six sous-bassins d'alimentation sont distingués pour la recharge de l'aquifère et des drainages transversaux en direction de la source de l'Aubonne sont mis en évidence le long des principaux décrochements. La synthèse des données hydrologiques disponibles sur l'aquifère karstique de l'Aubonne apporte les éléments indispensables à la gestion et à la protection de cette importante ressource en eau.

Introduction

About 20% of Switzerland's outcropping rocks are subject to intense karstification processes (Wildberger & Preiswerk 1997). Mostly constituted of Mesozoic limestone, the Jura Mountains represent one of the major karst regions. The resulting aquifers therefore constitute an important water resource for numerous communities (e.g. GEOLEP 1991; GEOLEP 1994; Perrin et al. 2000; CHYN 2002) but also raise specific problems for their protection (e.g. Aubert et al. 1970; Parriaux & Mayoraz 1990; Doerfliger et al. 1999). Hence, understanding the hydrological behaviour of such aquifers is essential in order to provide adapted management of this resource.

With a mean annual discharge estimated at more than 6 m^3/s, the Aubonne karst system is one of the largest in the Swiss Jura. Accessible portions of this aquifer have been explored and mapped by numerous speleologists for the last 100 years (Audétat et al. 2002). The few hydrological data available are former tracing experiments conducted in adjacent catchment areas (Aubert et al. 1970; Vuataz 1976; Rey 1985; Lavanchy et al. 1987; Perrin et al. 2000), discharge monitoring at the Aubonne dam a few kilometres downstream from the spring (SEFA, pers.comm.), and earlier publications mentioning a possible link with the temporary outlet of Toleure (Aubert et al. 1979).

Recently, new studies were conducted by means of tracing experiments (Luetscher & Perrin 2001; Perrin & Luetscher 2001), and monitoring of physical parameters at the springs. However no detailed hydrogeological investigations have been carried out so far. The present paper aims at:

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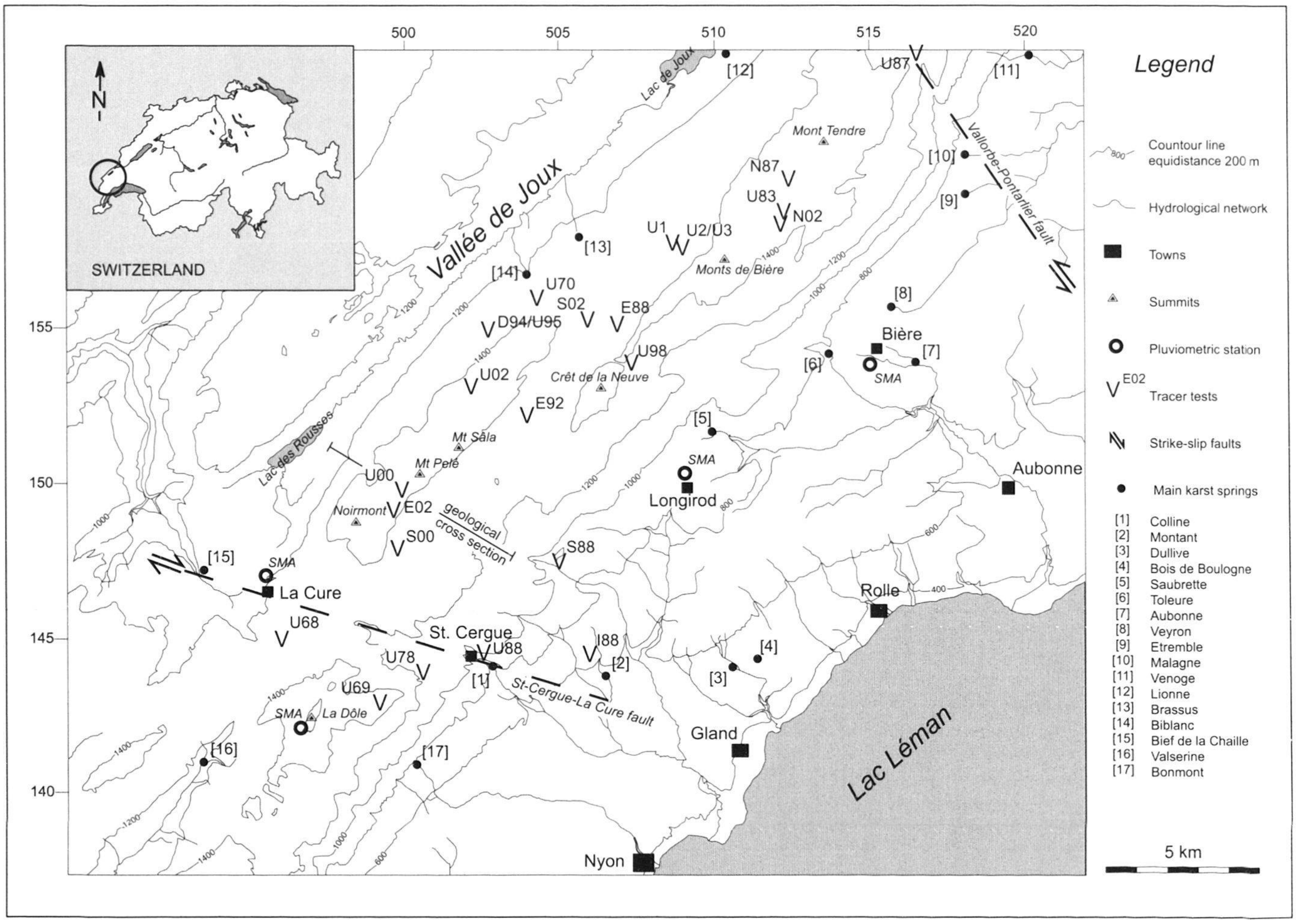

Fig. 1. Geographical situation of the study site and location of the tracer tests (spring numbers refer to table 1 and tracing experiments to table 4).

- Providing a synthesis of the observations made on this important karst aquifer;
- Proposing a catchment area for the Aubonne system in agreement with the adjacent basins, the tracer tests, the geology and the water balance;
- Proposing a simple model of the aquifer's functioning during recharge events.

A paper focusing on the interpretation of the tracing experiments and a conceptual model of the aquifer conduit network will be published in the near future.

Geographical and geological settings

Located at the foot of the Vaud Jura (Switzerland), the Aubonne karst spring and its related overflows drain a large surface of the folded Jura between the two major strike-slip faults of "St. Cergue–La Cure" and "Vallorbe-Pontarlier" (Fig. 1). The area studied is bordered on the north by the Polje of "La Vallée de Joux" and to its southern side by the Lemanic basin.

The catchment area, located between 1000 and 1600 m a.s.l., benefits from annual precipitation of around 1600 mm. Dense vegetation cover (forest and pasture) induces significant evapotranspiration, which has been estimated at about 30% of the annual precipitation (e.g. Jeanblanc & Schneider 1981). Summer thunderstorms and autumnal precipitations represent a large contribution to the annual aquifer recharge. However, as a large amount of the precipitation falls in the form of snow during the winter season and covers the area for more than five months a year, most infiltration takes place during snow melting episodes.

The Malm aquifer underlying the drainage basin is constituted of a 400 m thick bioclastic limestone series (Kimmeridgian-Portlandian) intercalated with small marleous beds (Fig. 2). Karst features on the surface have been well described (e.g. Aubert 1969) and speleological investigations have mapped over 500 caves within this aquifer (Baron 1969; Audétat et al. 2002).

A succession of anticlines and synclines intersected by few major faults characterizes the tectonic setting. Drainage is as-

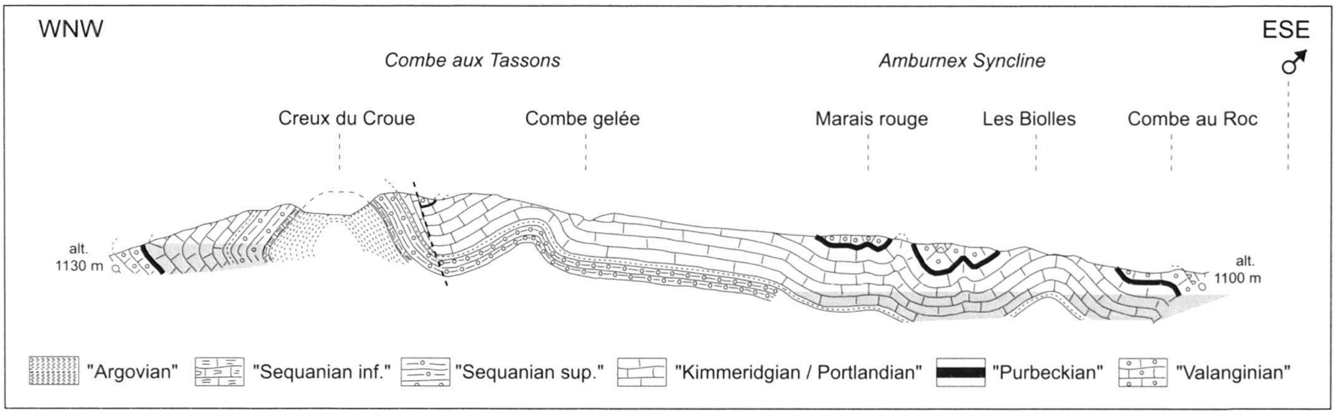

Fig. 2. Representative geological cross section within the Aubonne catchment area (adapted after Falconnier 1931). A perched aquifer is outlined within the Amburnex syncline (light grey).

sumed to follow the general structure of the top of the "Argovian" (Oxfordian marls), but tectonic complications significantly influence the karst network.

Regional hydraulic gradients are mostly controlled by the Tertiary aggradations of the Lemanic basin. The location of the different outlets is assumed to be closely related to the top of the Tertiary molasse and associated with the presence of major strike-slip faults.

Hydrogeological investigations based on physico-chemical characteristics of water (Aubert et al. 1979; Lavanchy & SCVJ 1987; Lavanchy 1990) recognized over twenty outlets discharging the Malm aquifer. Previous tracing tests demonstrated a hydrological link between several of them (e.g. Aubert et al. 1970). Therefore, it can be shown that the Aubonne spring is not an independent system but is closely related to other karst springs. Major karst springs (equivalent discharge higher than 10 l/s, even if some are temporary) recognized at a regional scale are: Montant, Dullive, Colline, Toleure, Aubonne, Malagne, Venoge, Lionne, and Brassus (Fig. 1, Table 1). Additional springs, also indicated in Fig. 1 and Table 1, were sampled during tracing experiments: Boulogne, Saubrette, Veyron, Etremble, Biblanc, Bief de la Chaille, and Bonmont. Boulogne is closely linked to Dullive, whereas Veyron and Etremble are related to Malagne. However, due to their low discharges (a few l/s), these springs are disregarded in the following discussion.

Earlier studies distinguished three basins adjacent to the study area: Venoge, Lionne (CHYN 2002), Brassus (Perrin et al. 2000). However, those are independent between each other and will not be discussed further here. Yet, former studies distinguished two additional karst systems:

1. A tracer test carried out by speleologists in the "Glacière de Druchaux" (Lavanchy & SCVJ 1987) showed a close relation between Aubonne, Toleure and Malagne. Further springs of secondary importance which are associated with this system are Saubrette, Etremble and Veyron.
2. Lavanchy (1990) first identified the Colline as a possible overflow of the Montant spring and observed a chemical similarity with water from the Dullive. This author suggested that the Dullive spring as well as the Boulogne spring act as underflows of the Montant spring. This Colline-Montant-Dullive system is estimated to be in close relation with the "St-Cergue-La Cure" strike-slip fault.

Both of these systems are sustained by their own catchment area, but recent tracer tests demonstrated a hydrological connection between them (Luetscher & Perrin 2001). The present study provides a general synthesis of the aquifer structure in the light of these new data.

Springs hydraulics

Detailed discharge data are available for Aubonne, Toleure and Malagne. The discussion will mainly focus on the hydraulic behaviour of these three springs, but a short paragraph provides also some qualitative information on the other springs.

Methods

Aubonne and Toleure springs were equipped with automated stations simultaneously recording water level, specific conductance, and water temperature every 30 minutes. Each month temperature and specific conductance (SpC, 25°C) were manually measured with a calibrated probe at Aubonne and Toleure springs. Their discharge was determined by a flow meter for lower rates and by tracer (uranine) dilution technique at higher rates. A rating curve was then constructed for both Toleure and Aubonne in order to convert water levels to discharges. Discharges are accurate at ± 10 %, and relative variations of SpC used in this paper are accurate at ± 2 µS/cm. Daily discharge measurements from the Aubonne dam downstream were used for cross-

Tab. 1. List of main karst springs in the studied area (n.d.: no data).

	Spring	Coordinates CH Y / X / Z [m]	Equivalent discharge [l/s]	Maximum discharge [l/s]	Minimum discharge [l/s]	Mean SpC [µS/cm, 25°C]	Mean temperature [°C]	Remarks
1	Colline	502'800 / 144'280 / 760	~50	2000	0	300	6.8	Temporary overflow of Montant system
2	Montant	506'330 / 144'260 / 585	400	800	10	330	7.2	Malm
3	Dullive	511'500 / 143'850 / 432	75	~100	~50	370	8.2	Underflow of the Montant system
4	Boulogne	511'350 / 144'250 / 430	1	5	0.25	380	9.4	Underflow of the Montant system
5	Saubrette	509'600 / 152'100 / 920	10	~50	0	510	6.3	Cretaceous, temporary spring
6	Toleure	513'775 / 153'900 / 700	~4000	25000	0	324	6.7	Temporary overflow of the Aubonne system
7	Aubonne	515'750 / 154'075 / 665	2500	10000	200	313	6.9	Malm
8	Veyron	517'750 / 156'900 / 685	<10	n.d.	0	446	8	Partially fed by the Quaternary
9	Etremble	518'000 / 159'035 / 708	<10	n.d.	0	400	7.6	Partially fed by the Quaternary
10	Malagne	518'070 / 160'620 / 720	~500	~8000	0	330	6.8	Temporary overflow of the Aubonne system
11	Venoge	521'025 / 163'510 / 665	820	7500	10	351	7.2	Malm
12	Lionne	514'540 / 166'760 / 1040	500	7000	50	305	5.8	Malm
13	Brassus	506'175 / 159'250 / 1055	400	5000	50	320	5.8	Malm
14	Biblanc	503'800 / 157'260 / 1120	10	n.d.	0	408	6.2	Cretaceous, probable overflow of Brassus
15	Bief de la Chaille	492'250 / 148'900 / 900	<5	n.d.	0	334	6.1	Cretaceous
16	Valserine	494' 050 / 141'625 / 1160	~50	n.d.	n.d	n.d.	n.d.	Malm
17	Bonmont	500'775 / 141'175 / 746	<5	~20	0	385	6.5	Malm
	Longirod river	507'330 / 153'875 / 880	~100	~1000	~50	275	5.3	Subsurface river sampled during tracing tests

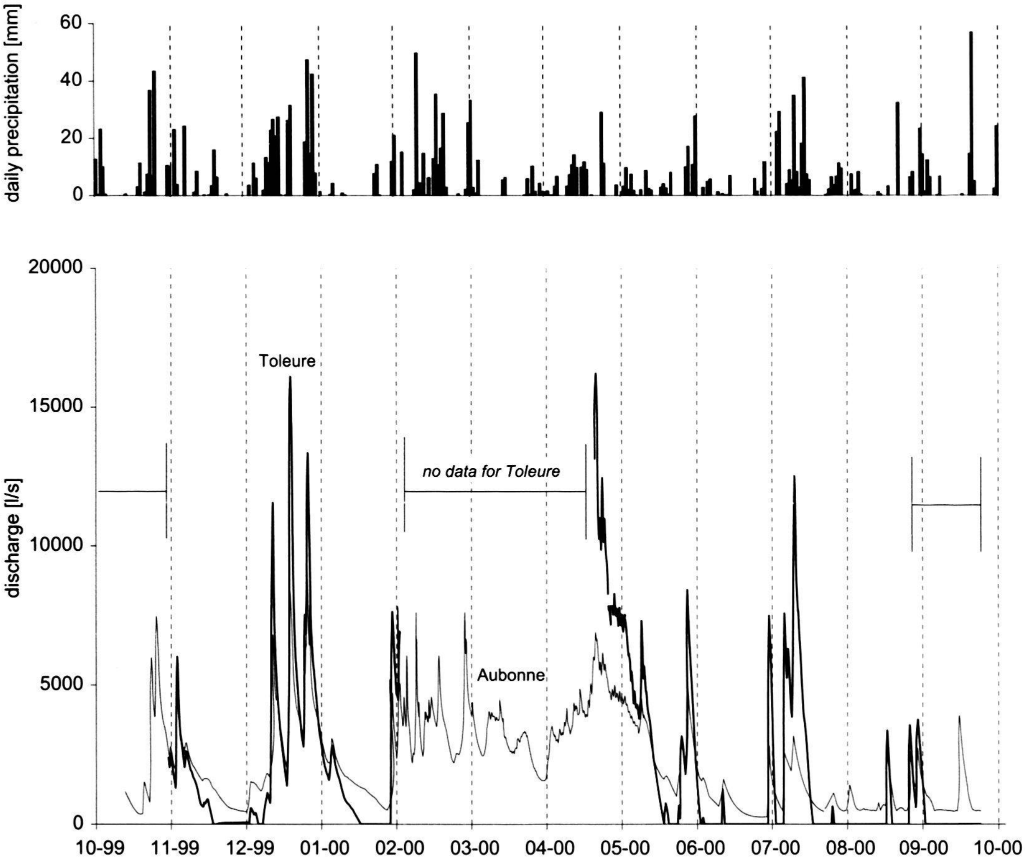

Fig. 3. Hydrographs of Aubonne and Toleure springs for the hydrologic year 1999–2000 and daily precipitations at La Dôle meteorological station (top).

checking. Values from Malagne spring were kindly supplied by the Geology laboratory of the Federal Institute of Technology, Lausanne (Geolep). Precipitation data are issued from the Meteoswiss stations (Bière, La Cure, Dôle, Longirod, Fig. 1).

Long-term monitoring

The 1999–2000 hydrographs of Aubonne, Toleure and Malagne springs (Fig. 3) show a typical karst spring response to flood events: discharges increase rapidly after recharge, and

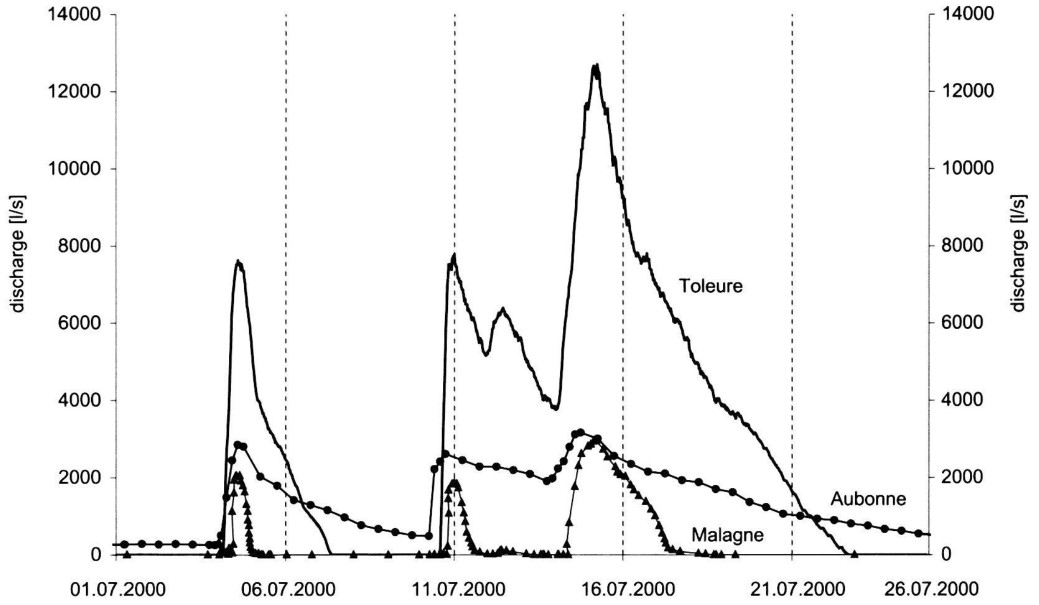

Fig. 4. Respective flood events for Aubonne, Toleure and Malagne springs in July 2000. The temporary spring of Toleure acts as a first overflow of the perennial Aubonne spring. Malagne spring starts flowing only during major discharge events. The discharge is determined after water levels measured at intervals of 4 hours at Aubonne, 30 minutes at Toleure and between 1 and 4 hours at Malagne.

variations are very strong. The low flow is limited to the summer months, but no real recession occurs as this period is interrupted by limited flood events. Hence the flood events frequency does not allow the determination of a significant recession coefficient.

Toleure spring acts as an overflow of Aubonne, and starts flowing when Aubonne discharge becomes higher than 2130 l/s (standard deviation (StD) of 332 l/s, 11 observations). Toleure then dries up when Aubonne discharge decreases below 2090 l/s (StD = 301 l/s, 8 observations). For most of the flood events, the discharge reached by Toleure is higher than Aubonne. Toleure remains dry about 40% of time (134 days in 1999–2000).

Malagne, the second main temporary spring, is located 7 km apart from Aubonne. It starts flowing when the Toleure discharge exceeds 4865 l/s (StD = 593 l/s, 17 obs.), and it dries up when the Toleure discharge drops lower than 4831 l/s (StD = 437 l/s, 13 obs.) Flood events at Malagne spring are flashy (figure 4); this spring remains dry about 75% of time (270 days in 1999–2000).

Daily mean discharges are recorded at the Aubonne dam, downstream of the confluence between Aubonne and Toleure (SEFA S.A., pers. comm.). These data allow the comparison of mean annual discharges at the dam with those recorded at the springs (Table 2). Missing data at the springs were reconstructed from the dam discharges. This adds uncertainties to the discharge measurements at the gauging stations, but values are coherent. There is a discharge increase of 5–10 % between the springs and the dam, which corresponds to observed tributaries draining alluvial aquifers (the major one is Saubrette river). Toleure annual discharge is about 12 % higher than Aubonne discharge, even if the spring dries up part of the year.

Tab. 2. Annual mean discharges at Aubonne dam, Aubonne, Toleure and Malagne springs. The difference is attributed to uncertainties in discharge measurements and small tributaries draining alluvial aquifers.

	Q_{dam} [m^3/s]	$Q_{aubonne}$ [m^3/s]	$Q_{toleure}$ [m^3/s]	$Q_{malagne}$ [m^3/s]
1998	4.58	2.10	n.d.	n.d.
1999	6.14	2.74	3.26	0.035
2000	5.70	2.13	2.84	0.023

For computing the water balance of the Aubonne aquifer, the yearly water volume discharged at the Aubonne dam has been considered as the most representative. The sum of Aubonne and Toleure springs is represented and we considered that the 5–10 % volume increase due to the quaternary aquifers approximates the water volumes discharging from the other karst springs (i.e. Dullive, Montant, Malagne, Etremble). Yearly rainfall was estimated from the data of four meteorological stations located in the vicinity of the catchment area (Fig. 1). The two higher stations (Dôle and La Cure) were given more weight as their data are representative of a large part of the catchment. Rainfall (P) was hence approximated by (1):

$$P = \frac{1}{8}\left(P_{Bière} + P_{Longirod} + 3 \cdot (P_{Dôle} + P_{Cure})\right) \quad (1)$$

The actual infiltration was estimated to be 70 % of the total rainfall based on studies carried out in adjacent areas (Petch

1970; Jeanblanc & Schneider 1981). Estimation of the catchment area surface (S) is given by:

$$S = \frac{V_{dam}}{0.7 \cdot P} \qquad (2)$$

where V_{dam} is the water volume at Aubonne dam given by the integration of daily discharges through one year. Results for several years are given in Table 3. The differences between years are due to inaccuracies in actual infiltration and to possible changes in groundwater storage from one year to the next. However, the computed catchment area of the whole aquifer is on the order of 140 km^2.

Tab. 3. Yearly water volume discharged at Aubonne dam, annual rainfall, and estimate of the catchment area surface. Variations in the catchment area size (mean value of 139 km^2) are mostly attributed to changes in groundwater storage and uncertainties in the actual recharge.

	Water vol. [m^3]	Rainfall [mm]	Catch. area [km^2]
1998	144'359'712	1657	124
1999	193'708'800	2079	133
2000	179'724'960	1828	140
2001	205'109'712	1946	151
2002	192'037'824	1865	147

Flood events

Analyses of 15 flood events at Aubonne and Toleure springs showed several tendencies:

i) Discharge increases earlier at Aubonne: the delay at Toleure is comprised between 30 min and 14 hrs. However, water volumes issued from Toleure are much higher than from Aubonne: the discharge increases more rapidly and maximum discharges are higher at Toleure.
ii) Recessions are more rapid at Toleure spring, illustrating its temporary nature.
iii) The decrease of SpC is proportional to the increase in discharge, i.e. the larger the flood, the more the spring water will be diluted by freshly infiltrated water of low SpC. This correlation is given by (3):

$$SpC = 0.0081 \cdot Q + 16.82 \qquad (3)$$

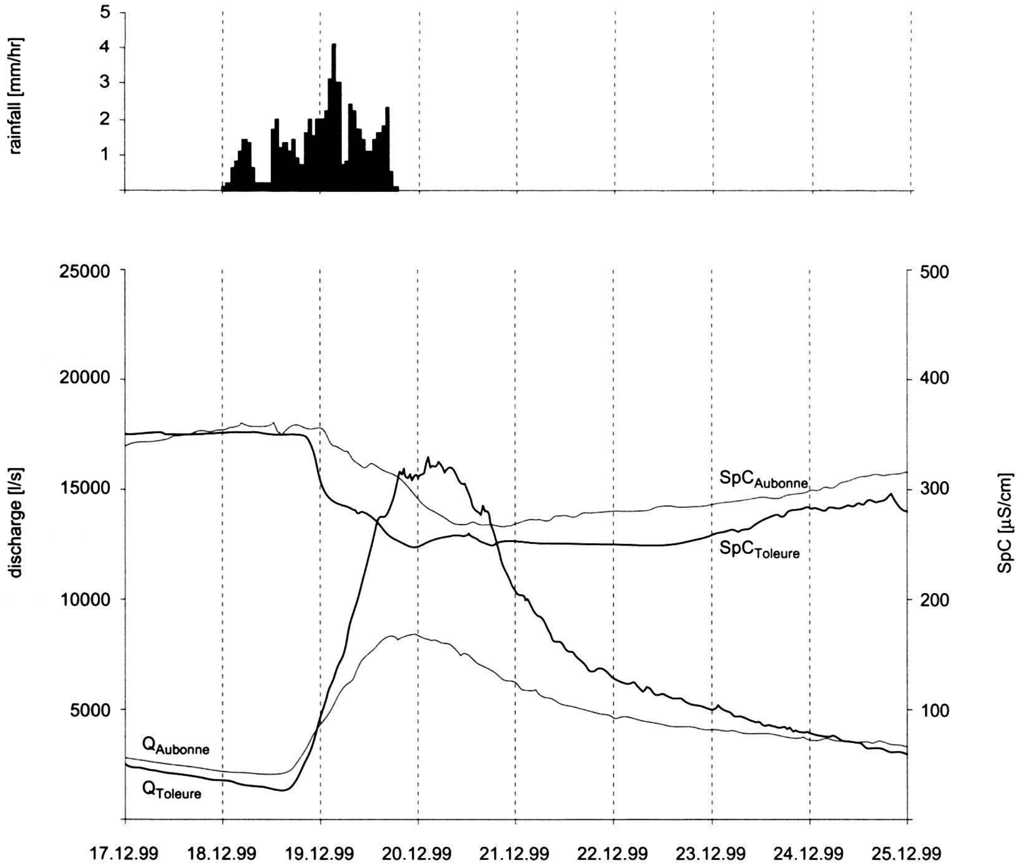

Fig. 5. Wet season flood event. The arrival of freshly infiltrated water causes a significant drop in the SpC values at both springs. The pluviometric data were recorded at Dôle meteorological station (top).

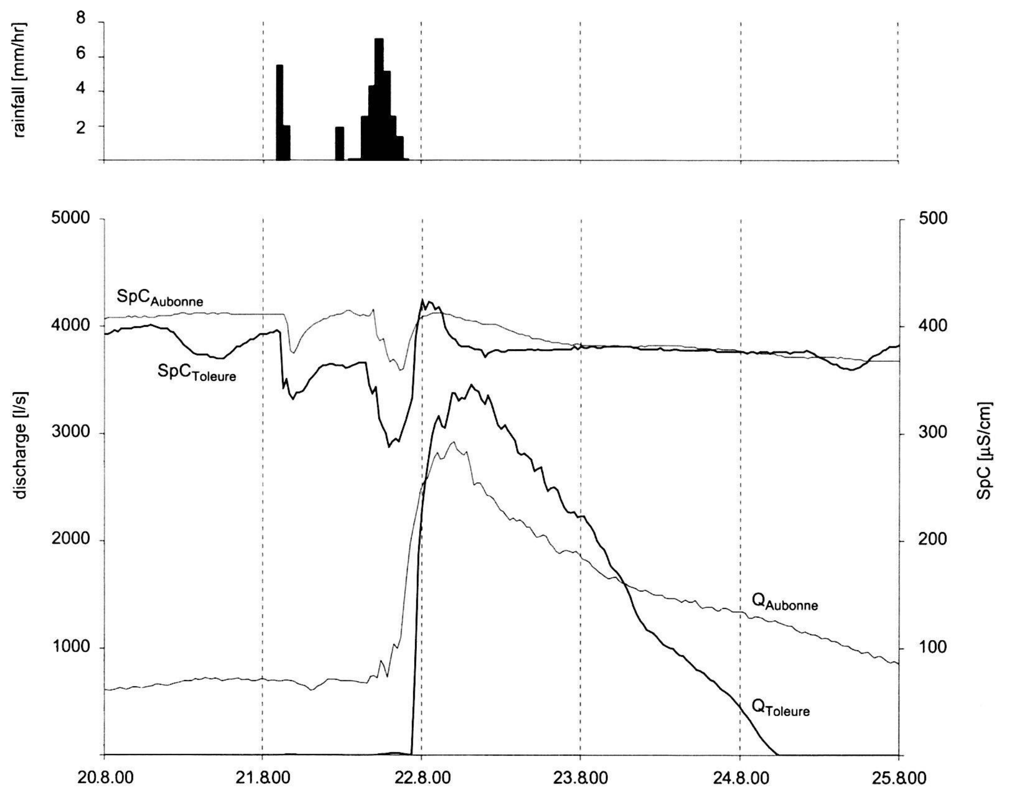

Fig. 6. Dry season flood event. Local infiltration may generate early dilution. Increasing SpC during the flood event may be related to a pressure pulse through flooded pipes. The pluviometric data were recorded at Dôle meteorological station (top).

with *SpC* in µS/cm at 25°C and *Q* in l/s. This relation is based on 13 observations, and the correlation coefficient is 0.83. Borsato (2001) observed a similar behaviour in an alpine karst system.

iv) The SpC decreases systematically earlier at Toleure than at Aubonne spring. The offset is comprised between 2 and 10 hours depending on the type of recharge. This can be interpreted as a shorter route to Toleure spring for freshly infiltrated water during high water episodes. It is confirmed by the tracing experiments: the arrival of tracer is observed at Toleure first. The SpC decrease is stronger at Toleure spring and the recovery during recession generally more rapid. This is probably due to the temporary character of Toleure which is mostly fed by highly transmissive conduits.

v) The SpC response to a flood event varies according to the season: during the wet season (autumn to spring), SpC shows a typical decrease due to the arrival of freshly infiltrated water (Fig. 5). During the dry season (Fig. 6), when Toleure is initially dry, local infiltrations may generate early dilutions, explaining the negative peaks on the SpC curves (discharges increase slightly in parallel). When the major flood starts, the increasing SpC may be related to a pressure pulse through flooded pipes. Delayed dilution occurs for both Toleure and Aubonne, but the shapes of the SpC curves are quite different.

vi) Unfortunately, no meteorological stations are located within the catchment area. However, the Dôle meteorological station, located a few kilometres to the SW, indicates a very rapid reaction of the springs to recharge events (Fig. 5 and 6). Discharges increase only a few hours later than the start of significant rainfall.

Other temporary springs

Springs of secondary importance (Etremble and Veyron) seem to flow during the same periods as Malagne. Their base flow is sustained by local aquifers in the quaternary deposits. During this time, karst groundwater does not participate in their discharge as it is only directed towards Aubonne and Toleure springs. Despite the links outlined between the Aubonne and the Montant systems, the Montant spring cannot be considered an overflow as its base flow is sustained by a distinct catchment area.

These temporary outlets of the system increase the total annual groundwater outflow. This point was already considered in the water budget calculation (2).

The contribution of tracing experiments

Previous studies

Hydraulic observations can be confirmed by numerous tracer tests carried out within the study area. The first tracing experiments reported in this region go back to the end of the

n°	Site	Lithology	Date	Tracer	Injection data: local	Injection data: hydrodynamic	Observed springs	Type and duration of observation	Detection	Recovery	Literature
U1	Fontaine Froide 508'800/157'400/1330	Cretaceous	n.d.	Uranine ?	n.d.	n.d.	n.d.	n.d.	[6];[7];[13]	?%	Aubert et al. 1979
U2	Pré de Bière 509'100/157'270/1350	Cretaceous	05.11.1897	Uranine 8 litres (0.25%)	sinkhole 2 l/sec	low water	[13]	visual	not detected	0%	Aubert S. & Forel F.A. 1898
U3	Pré de Bière 509'100/157'270/1350	Cretaceous	29.05.1898	Uranine 8 kg (0.25%)	sinkhole	n.d.	[13]	visual	not detected	0%	Aubert S. & Forel F.A. 1898
U68	La Trélasse 496'920/144'990/1220	Cretaceous	14.09.1968 morning	Uranine + NH3 8 kg + 2 l	sinkhole ~30 l/min with 110 l water	n.d.	[1]; [2];[14];[15];[16]	FC 6 months	not detected	0%	Aubert et al. 1970
U69	La Barillette 498'500/142'810/1500	Malm	19.07.1969 10:50-14:05	Uranine+NaOH 20 kg + 20 kg	sinkhole with 11 m^3 water	high water	[2];[17]	FC	[2]; [17]	?%	Aubert et al. 1970
U70	Gouffre de la Cascade 504'430/155'420/1335	Malm	05.07.1970 12:00	Uranine 12 kg	Cave -40 m stream	n.d.	[13]; [14];	visual + FC	[13]	?%	Baudet 1974
U78	En Guinfard 501'060/143'675/1135 501'025/143'655/1140 m	Malm	20.06.1978 morning	Uranine + NH3 5 kg +15 kg	2 sinkholes with 15 m^3 water	medium water	[2]; [17]	FC	[2]; [17]	?%	Aubert et al. 1979
U83	Gouffre du Petit Pré 512'865/158'840/1455	Malm	29.05.1983 14:30	Uranine 5 kg	n.d.	high water, snow melt	[2];[5];[6];[7];[8];[9]; [10];[11];[12];[13];[15]	FC	[5]; [9];[10]	?%	Rey & SCVJ 1985
N87	Glacière de Druchaux 513'085/159'555/1495	Malm	17.05.1987 16:00	Naphtionate 10 kg	Cave 1 m^3 water	n.d.	[5];[6];[7];[8];[9];[10]; [11];[12]	MS + FC	[5];[6];[7];[9]; [10]	?%	Lavanchy & SCVJ 1988
U87	Pré de l'Haut 516'100/164'200/1300	Malm	18.05.1987 11:00	Uranine 5 kg	30 l/min	n.d.	[5];[6];[7];[8];[9];[10]; [11];[12]	MS	[11]	?%	Lavanchy & SCVJ 1988
U88	Crévaz Tsévau 502'050/144'750/980	Malm	22.06.1988	Uranine 4 kg	temporary stream (1 l/min) with 20 m^3 water	low water	[2];[3], Bof	MS	[2];[3]	<1%	Geolep 1994
S88	ruis. de la Combe 505'165/147'160/840	Malm	21.06.1988 09:00	Sulforhodamine 5kg	temporary stream with 32 m^3 water	low water	[2];[3];[4]	MS	[2];[3];[4]	<5%	Geolep 1994
E88	Amburnex 506'740/154'820/1290	Cretaceous	21.06.1988 09:30	Eosine 10 kg	sinkhole with 20 m^3 water	low water	[2];[12]	MS + FC 120 jours	not detected	0%	Geolep 1994
I88	Le Montant 506'160/144'390/590	Quaternaire	21.06.1988 09:00	Iodure 5 kg	Digging with 500 l water	low water	[2]	MS + AS 100 jours	not detected	0%	Geolep 1994
E92	La Bassine 504'125/152'200/1300	Malm	20.08.1992 09:00	Eosine 10 kg	sinkhole with 24 m^3 water	n.d.	[2];[13]	MS + FC 125 days	[2]	?%	Geolep 1994
D94	Gouffre Pleine Lune 503'375/154'520/1300	Malm	18.11.1994 22:45	Duasyne 5 kg	Cave -120 m stream 2 l/sec	medium water	[13];[14]	MS + FC 36 days	not detected	0%	Perrin et al. 2000
U95	Gouffre Pleine Lune 503'375/154'520/1300	Malm	23.05.1995	Uranine 3 kg	Cave -120 m stream 2 l/sec	medium water, snow melt	[13];[14]	MS + FC 51 days	not detected	0%	Perrin et al. 2000
U98	Gouffre de Longirod 507'330/153'875/1350	Malm	19.04.1998 13:00	Uranine 4 kg	Cave -120 m stream 5 l/min	medium water	[2];[5];[6];[7];[8]; [9];[10];[12]	FL, AS, MS, FC 11 days	[7];[8];[9];[10]	~100%	Perrin & Luetscher 2001
U00	Gouffre Cathy 500'075/150'475/1500	Malm	15.04.2000 15:00	Uranine 6.5 kg	Cave -157 m stream 13 l/min & 1m^3 water	high water, snow melt	[1];[2];[6];[13]; [14];[15];[17]	MS+AS+FL	[2];[6]	~15 % [2] ? % [6]	Luetscher & Perrin 2001
S00	Gouffre Combe Trébille 499'500/147'850/1380	Malm	15.04.2000 12:30	Sulforhodamine 5kg	Cave -120 m stream 13 l/min	high water, snow melt	[1];[2];[6];[13]; [14];[15];[17]	MS+AS+FL	[2];[6]	~5 % [2] ? % [6]	Luetscher & Perrin 2001
E02	Gouffre Dag's Bar 499'500/150'210/1430	Malm	20.04.2002 12:40-15:00	Eosine 6 kg	Cave -20 m stream 1 l/min & 3m^3	medium water, snow melt	[1];[2];[3];[4];[5];[6];[7]; [8];[9];[13];[15]; Lon,	MS+AS+FL 23 jours	[2];[3];[4]; [6];[7]	~90%	Luetscher & Perrin 2002
U02	Gouffre Masse 502'175/152'900/1455	Malm	20.04.2002 16:00-17:00	Uranine 8 kg	Cave -140 m stream 0.25 l/sec	medium water, snow melt	[1];[2];[3];[4];[5];[6];[7]; [8];[9];[13];[15]; Lon,	MS+AS+FL 23 jours	[2];[3];[4]; [6];[7]	~70%	Luetscher & Perrin 2002
S02	Gouffre Trois-Chalets 506'000/154'975/1340	Malm	20.04.2002 13:10-16:10	Sulforhodamine B 5 kg	Cave entrance with 7.5 m^3 water	medium water, snow melt	[1];[2];[3];[4];[5];[6];[7]; [8];[9];[13];[15]; Lon	MS+AS+FL 23 jours	[6];[7]; Lon	~90%	Luetscher & Perrin 2002
N02	Gouffre Pierres-Pleines 512'760/158'610/1450	Malm	20.04.2002 15:10-15:50	Naphtionate 10 kg	Cave -40 m stream 2 l/min	medium water, snow melt	[1];[2];[3];[4];[5];[6];[7]; [8];[9];[13];[15]; Lon,	MS+AS+FL 23 jours	[6];[7]	~70%	Luetscher & Perrin 2002

Tab. 4. Synthesis of tracing tests carried out within the study site. Numbers of the springs refer to table 1, but not mentionned springs might sometimes have been observed without any positive results. FC: charcoal; MS: manual sampling; AS: automatic sampling; FL: fluorometer.

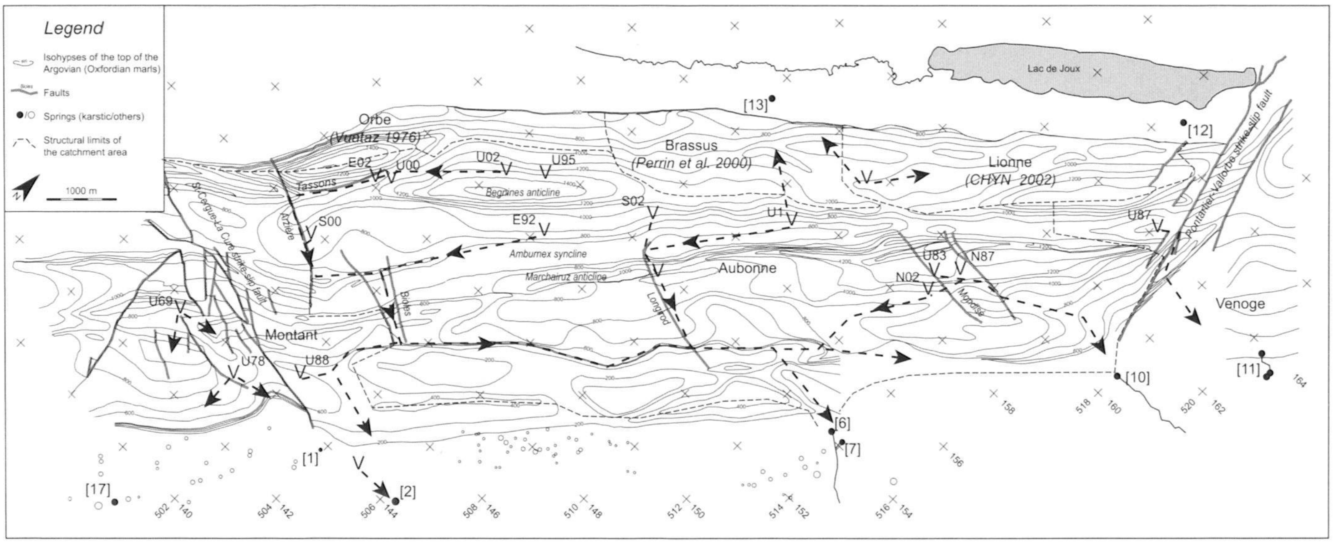

Fig. 7. Structural map of the top of the Oxfordian marls (adapted after Aubert et al. 1979, Falconnier 1951 and Lagotala 1920) and proposed limits of the catchment area of the Aubonne spring. This catchment area, based on structural criteria, is in good agreement with measured water balance and tracing experiments. Results of the tracer tests allow a first schematization of the main flow routes.

19th century, but without any positive result (U2, U3, Table 4). More recently, various tracer tests have been carried out in order to provide a risk assessment of the nearby harnessed springs (Geolep 1994, Perrin et al. 2000, CHYN 2002). Although these experiments enabled a better delimitation of the respective catchment areas, numerous questions remained open, mostly related to undetected tracers (e.g. D94, U95, Table 4). During the last twenty years, several tests were also completed by speleologists in order to acquire a better understanding of the explored aquifer (Rey et al. 1985; Lavanchy & SCVJ 1987; Luetscher & Perrin 2001; Perrin & Luetscher 2001). Results led to distinguish two major systems (Colline-Montant-Dullive and Malagne-Toleure-Aubonne) and provided evidences of an hydrological link between Montant-Dullive and Aubonne-Toleure (U00, S00, Table 4). Yet, these tracer tests have also shown that part of the springs' discharge must be fed by independent catchment areas. Thanks to these early investigations a general overview of the karst drainage system could be acquired. Nevertheless, the uncertainties with previous traces led to a new multi-tracing experiment in April 2004. During this experiment, all four tracers were detected at the active members of the Aubonne system and all of them support further the hydraulic observations presented earlier. Table 4 summarises the past traces made on the study area.

Tracer recovery

Atkinson et al. (1973) already pointed out that analysing the tracers' recovery provides a useful check on the accuracy of hydrological interpretations. Until recently, the few explicit estimates of tracer recoveries have shown that massive springs were probably not included in the observation during tracing experiments. Aubert et al. (1970) first suggested the presence of major divergences within the phreatic zone of the Jura foot. By demonstrating the link between the Montant system and the Aubonne-Toleure springs, tracing tests carried out in April 2000 provided first qualitative results for a better assessment of the regional karst system.

Considering the unavoidable imprecision in measuring the total discharge of an entire system, estimates of tracer restitution (70–90%) during the last multi-tracing test suggest that all principal outlets of the Malm aquifer are now controlled (U02, E02, S02, N02, Table 4). Furthermore, these last results demonstrate that about 20 % of the water drained from the western part of the catchment area to the Aubonne system is diverted to the Montant and Dullive springs. In other words, this means also that, at least during medium to high flow conditions, half of the water discharged through the Montant system has the same catchment area as part of the Aubonne system.

Delineation of the Aubonne aquifer catchment area

A delimitation of the Aubonne catchment area based on tracing experiments and structural characteristics can now be proposed (Fig. 7). On the Lemanic side, the basin's limits are provided by the top of the tertiary aggradations located at the foot of the Jura range. The Aubonne basin is delimitated on its eastern side by the strike-slip fault of Vallorbe-Pontarlier which makes the border with the adjacent Venoge catchment area. Previous studies (Vuataz 1976; Perrin et al. 2000; CHYN 2002) provided the necessary elements for the delimitation of the Aubonne catchment area on the north-western side, which follows more or less an anticline. However, conversely to the

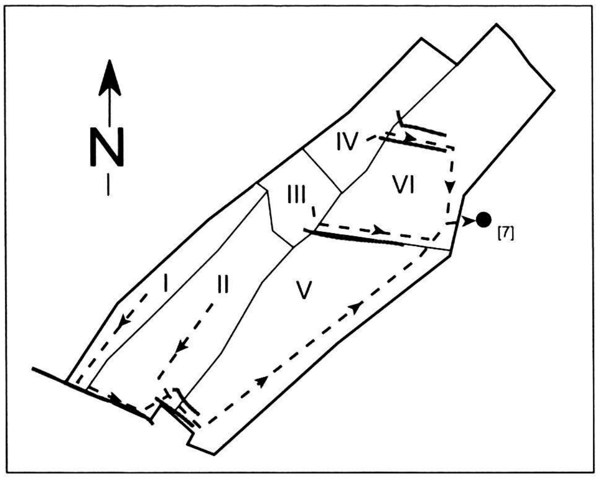

Fig. 8. Delimitation of six functional elements at the origin of the aquifer recharge. Hydrological links between these elements are provided by major faults (grey). Main flow routes are indicated by dashed lines.

interpretations suggested by the structural map of the Oxfordian marls, tracer tests (U00, S02, Table 4) have shown that flow routes must be influenced by a major tectonic discontinuity on the south-western limit. The Arzière strike-slip fault is supposed to constitute this south-western limit, but no tracer results are available in order to validate this assumption.

Nevertheless, the defined area covers about 142 km^2, which is in good agreement with the observed tracer tests and the calculated water balance (e.g. Table 3).

Flow routes and divergences

Groundwater flow in karst aquifers is broadly directed by regional hydraulic gradients, but actual flow routes are controlled by geological structure and organized patterns of drainage conduits that develop over time (Smart & Ford 1986). Water circulations within the Malm aquifer can therefore be assumed to be closely related to the general structure of the aquiclude represented by the Oxfordian marls and will follow joint patterns issued from the syncline structures. Yet, speleological explorations demonstrated that major drains (for instance Longirod cave, Perrin 2002) can develop in the favour of tectonic discontinuities. Tracer tests carried out in the supposed catchment area of Longirod cave confirmed that these conduits also play a significant role in the regional drainage system (S02, Table 4). Therefore, structural elements which can be considered so far include:

1) Major horizontal vadose karst conduits in the most elevated parts of the catchment area;
2) Transversal drainage by horizontal vadose conduits along the major faults;
3) Coaxial phreatic drainage within the perched aquifer of the Amburnex syncline and along the syncline gutter of the Jura foot;
4) Divergence to the Montant spring system in the favour of a geological saddle within the saturated zone.

The following hypotheses can now be set on major flow routes within the Aubonne karst system (Fig. 7):

On the western part of the delineated catchment area, estimated flow routes run alongside the Begnine anticline and drain the water south-west towards the Arzière strike slip-fault. This tectonic discontinuity enables a transversal drainage across the Begnine anticline. Then, flow routes meet the phreatic system issued from the Amburnex syncline and cross the Marchairuz anticline in the favour of the Biole faults. There, about 20% of the water is diverged towards the Montant spring system while the balance is drained towards the Aubonne system.

Longirod fault has demonstrated to play a significant role by draining part of the perched aquifer of the Amburnex syncline. Also, major flow routes are expected along the last fault system (Mondisé faults). Tracer tests demonstrated that during low to medium water episodes water was directed straight towards the Aubonne-Toleure springs. During high water episodes, flow routes however are preferentially diverted towards the Malagne overflow.

Main recharge areas

The combination of tracer tests carried out within this catchment area and structural information allow the distinction of six major functional elements in the origin of the aquifer recharge (Fig. 8):

I) Recharge over a 10–15 km^2 area which is drained by the faults of the Arzière into the perched aquifer of the Amburnex syncline;
II) Recharge over a 25–30 km^2 area which is directly drained into the perched aquifer of the Amburnex syncline and discharged through the Biole faults;
III) Recharge over a 5–10 km^2 area which is directly drained into the perched aquifer of the Amburnex syncline and discharged through the Longirod fault;
IV) Recharge over a 10–15 km^2 area which is directly drained into the perched aquifer of the Amburnex syncline and discharged through the Mondisé fault;
V) Recharge over an about 40 km^2 area which is drained from the western part of the catchment area towards the Aubonne system;
VI) Recharge over an about 40 km^2 area which is drained from the eastern part of the catchment area towards the Aubonne system.

However, the role of the Cretaceous limestones in the recharge of the Malm aquifer is not yet fully understood as illustrated by the few tests presented in this study (U2, U3, U68, E88 and U88, Table 4). None of these experiments detected the injected tracers and, despite several active swallow holes, only few potential outlets are known. Tracer tests carried out on the adjacent catchment area of Brassus suggested that a hydrological connection exists between the Cretaceous and Malm aquifers (Perrin et al. 2000). In this context, the apparently inconsistent result of test U1 might be potentially attributed to a divergence towards the Brassus spring during high water episodes. Unfortunately, there is no report available on this earlier experiment and only a new tracing experiment might confirm this hypothesis.

Conclusions and perspectives

Combining the hydrogeological investigations carried out in a major karst region of the Jura Mountains led to the recognition of two distinct hydrological systems: the Aubonne-Toleure-Malagne system and the Dullive-Montant-Colline system. However, tracing experiments established that these springs are partially fed by the same catchment area.

Also, this study demonstrates the importance of large scale observations for karst aquifers: the presence of overflows of the main Aubonne spring was detected by tracer tests and provided evidence for distances of over 20 km between the different outlets of the aquifer.

Checking for the presence and investigating hydraulic characteristics of outlets other than the main spring appears to be indispensable for a better assessment of the aquifer discharge. Actually, a detailed temporal monitoring of hydraulic parameters is recommended as karst has a highly dynamic behaviour: discharges may change as much as 1000 l/s in less than one hour. Without these valuable investigations important issues (e.g. catchment size, mean discharges, aquifer reserves, tracer restitution, vulnerability assessment) would have been poorly evaluated.

Tracer tests display a good coherence with hydraulic observations (for instance links between Aubonne, Toleure and Malagne) and provide evidences for preferential flow routes. A structural approach revealed a complex karst network which is closely related to the geological context. Regional strike-slip faults play an important role in the network organisation and a major divergence towards the Montant system has also been outlined. Six major functional elements for the aquifer recharge could be identified during this study. Detailed analyses of the breakthrough curves acquired during the last multi-tracing test will constitute a useful tool for a better assessment of the karst network and therefore contribute to a better understanding of the genesis of this system.

These new data improve considerably our understanding of this aquifer and contribute significantly to the protection of its water resources. At present, the Aubonne aquifer remains however totally underused as a drinking water resource despite the presence of large quantities of water of rather good quality.

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