River backflooding into a karst resurgence (Loiret, France).

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Abstract

The group of springs located in the west part of the Val d'Orléans exemplifies a type of karstic emergence which has the particularity to get most of its recharge water from a single surface water source, which in this particular case is the River Loire. Hence the flow of this group of springs is known to fluctuate in a close relationship with the water level of the River Loire. Since the second half of the 1990s, the conduit of the upstream spring of the Loiret river (so-called Le Bouillon) has been periodically seen to be invaded by the turbid waters of a small surface tributary (Le Dhuy) flowing back from the confluence to the spring, which then functioned as a swallow-hole. Plotted in a Dhuy versus River Loire diagram, stages of backflooding days describe a domain limited by a curve of the form $H_{Dhuy}=c+e^{(aH_{Loire}+b)}$. The exponential form of the relation corresponds to the increasing resistance of the emerging flow of the spring to the backflooding of the tributary waters, as the River Loire stages rise. The equation above was used to compute a daily backflow index enabling the effective reconstruction of all occurrences effectively counted during the regular period of observation of the spring. Extended to 1985, one can observe that the early 1990s do not appear as a favorable period to backflow events but some may have occurred during the years 1986 to 1989. The observation of rainfall intensity preceding backflooding shows that in a short time span there is no necessity to evoke intrinsic changes inside the Val d'Orléans basin to explain what might appear as a troublesome new phenomenon. In conclusion backflooding has probably existed for a long time and is simply under the control of local heavy rainfall during low River Loire stages.

Author Keywords: Karst; Reversing flow spring; Resurgence; Inversac; Backflooding; River Loire; Loiret river

1. Introduction

Although reversing flow springs have been described in many karst regions in text books ([Ford and Williams, 1989]), perhaps the most famous case might be the estavelles of Cerknicko Polje (intermittent lake Cerknica) examined in details since the late 16th century, there has been little quantitative evaluation of the function of such features in the literature. Modern observation networks may now allow quantitative surveys of episodic karstic phenomena such as temporarily overflowing springs and alternatively discharging or absorbing conduits which used to be seen as hydrologic regional curiosities ([Gèse, 1987, Gaberscik and Urban-Bercic, 1996 and Monbaron and Bouvier, 1999]). To the south of the city of Orléans, the Bouillon de La Source resurgence, the main vauclusian spring of the river Loiret, belongs to a well-known group of resurgence points of River Loire water lost in the eastern part of the Val d'Orléans ([Sainjon, 1880, Caudron et al., 1965 and Chéry, 1983]). Recently (since the year 1997), surface waters drained from the local watershed by a small tributary of the river Loiret (Le Dhuy) have been observed on several occasions to flow back up the karst spring and to be swallowed underground. A single reversal flow event can last several days, causing the swallowing of tens of thousands of cubic meters of turbid waters per day, before the karstic emissive flow returns to normal. Sudden swallowing of surface drainage waters into karst aquifers at location where water normally emerges, especially close to urban water well supplies, is a potential risk of pollution for the water resource. Following [Gèse, 1987], the word 'inversac' may be used for this kind of cave entrance instead of the more accepted name estavelle. Beside comprising a risk of contamination of local water resources as did sinking spots in the riverbed of the Dhuy river in the past ([Marboutin, 1902 and Caudron and Desprez, 1974]), that occasional functioning of the spring if recent, may be an early warning sign of intrinsic basin alteration. Very similar base-level backflooding has been studied qualitatively in the Mammoth cave area of Kentucky ([White and White, 1989]). In the long run, fine grained sediments deposited in caves may have record backflooding periods ([White and White, 1968, Granger et al., 2001 and Milske et al., 1983]). Impact of backflooding river water onto cave fauna has also been described ([Elliott, 2000]). The hydrological conditions relevant to backflooding were examined in this study to try to evaluate the main factors capable of constraining the phenomenon and to eventually predict its occurrence. The quantitative approach used to analyse the behaviour of that particular spring may offers a guideline for calculating conditions under which backflooding might occur in other karst regions. The question of the newness of the phenomenon or its possible recurrence is tentatively discussed. Preliminary results of this study were presented at the 7th conference on limestone hydrology and fissured media ([Albéric, 2001]).

2. Site description and sources of data

The Bouillon resurgence (upstream spring of the Loiret river) emerges in the Parc Floral (Domaine de la Source) in front of the campus of the University of Orléans (Fig. 1). The spring belongs to a large group of karstic resurgences situated to the south and west of the city of Orléans along the course of the river Loiret ([Caudron et al., 1965]). Recharge of the karst aquifer (aquitainian lacustrine limestones, 'Calcaires de Beauce') in the Val d'Orléans hydrogeological unit occurs principally at sinking areas (Fig. 1) along the course of the River Loire some 10 km upstream from Orléans ([Caudron et al., 1965, Zunino et al., 1980 and Chéry, 1983]). The relationship between the level of the River Loire and the discharge of the springs has been accepted as a fact for a long time. The higher the stream level, the higher the groundwater level and the larger the spring flow ([Sainjon, 1880, Marboutin, 1902, Caudron et al., 1965, Desprez, 1967, Desprez, 1976 and Chéry, 1983]). Moreover, the discharge water at the Bouillon resurgence has been shown to have directly inherited its chemical composition from the River Loire water sampled 3 days before ([Albéric and Lepiller, 1998 and Albéric, 1998]). In addition, since the beginning of 1300s, the course of the river Loiret has been dammed by several causeways built for mill works causing a stepped base level control of the emergence flow in the different basins, and earthworks have progressively moved downstream the confluence between the river Loiret and its tributary Le Dhuy ([Fontenu, 1736 and Sainjon, 1880]). Location of the upstream springs of the river Loiret, the confluence with Le Dhuy and the drinking water supply wells are depicted in Fig. 1. A threat to the supply wells was feared straight after the first backflooding events, but no impact on water quality was noticed during periods of reversal (Lyonaise des Eaux). As revealed by diving explorations, the eastward direction of the main cave conduits from the Bouillon entrance may explain the wells may keep safe.

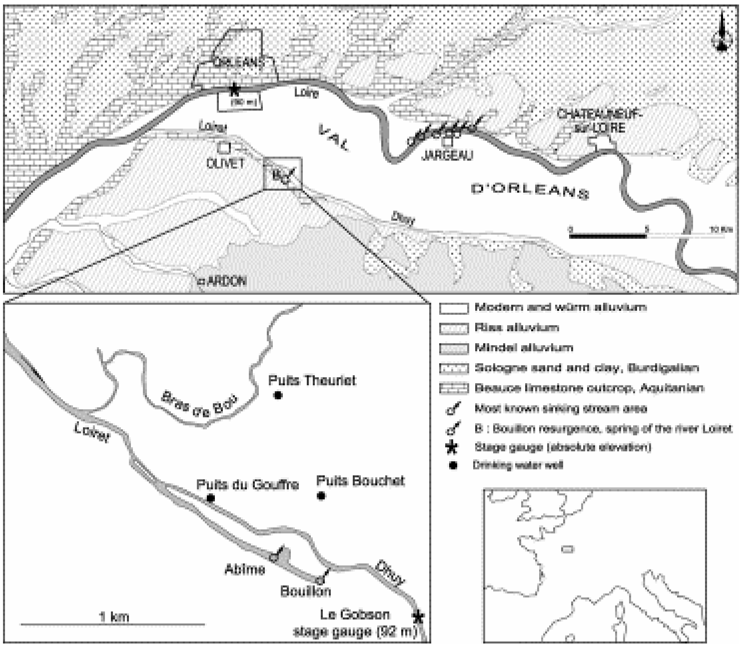

Fig. 1. (a) Section of the Loire River around Orléans with location of the main recharge area and the stage gauge station (adapted from [Albéric and Lepiller, 1998]) (b) Site of the springs of the river Loiret and the confluence with the stream Le Dhuy.

The watershed of the stream Le Dhuy has an extent of about 216 km^2, covering the east farmland of the Val d'Orléans. Daily mean water flows estimated at the Gobson gauging station (Fig. 1) by DIREN-Centre were used to compute daily mean water stages, to be compared to those of the River Loire observed each morning at the gauging station of Orléans (DDE-Loiret, then DIREN-Centre). Absolute elevation (above sea level) of the zero level of the stage gauges are 90 and 92 m, respectively, for the Orléans Loire station and the Dhuy station. Zero level of gauge stations along the River Loire were put at low-water marks during the nineteenth century but deepening of the river bed accounts now for negative stages. Raw arbitrary gauge data were used since absolute elevation was not essential to work out computation and no more indicative of hydraulic gradients, River Loire water levels from the recharge area upstream Orléans would be more useful to this end. Daily rainfall data from three stations inside the Dhuy watershed were obtained from Météo-France.

Since July 1997 (date of the first observation in present time), an exhaustive inventory of the backflow events at the spring has been established with the help of eyewitnesses, regular or occasional observers of the spring (riverside residents, members of the park staff, cave divers, students). Only minor short episodes during night may have escaped observation.

3. Results

3.1. Period of reference (1997–2001)

During the years 1997–2001, 10 swallowing episodes have been observed, their inventory will be used later (open circles in Fig. 4). In Fig. 2, one single event is depicted with more detail as an example. Prevalent typical meteorological conditions responsible for the phenomenon appear clearly to be a combination of heavy local rainfalls and low River Loire water levels. Floods of the Dhuy river (as registered at the Gobson gauge station, 1.5 km upstream the confluence with the Loiret river) lead to an elevation of the water level at the confluence and backflooding of the stream to the ‘Bouillon spring’ conduit which becomes then temporarily a swallow-hole. As shown with the shaded rectangle in Fig. 2, backflooding is possible only if the River Loire water level is low enough, so is the flow of the resurgence (Dec 13–15). During the second Dhuy river flooding episode (Dec 19–20), River Loire stages were higher and no backflooding was observed.

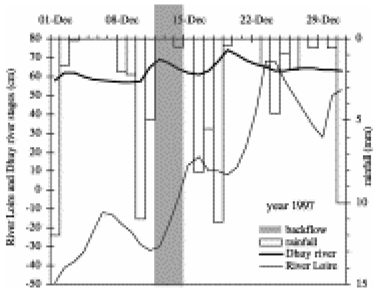

Fig. 2. Typical hydrological conditions of the swallow hole functioning of the Bouillon resurgence (note that their is no backflooding during the 20 December flood of the Dhuy river because of the higher water levels or the River Loire).

As can be seen in Fig. 3, the intrusion of surface waters into the spring may impact drastically ground water characteristics and especially increase organic matter inputs into the karst aquifer ([Albéric, 1998 and Batiot et al., 2001]).

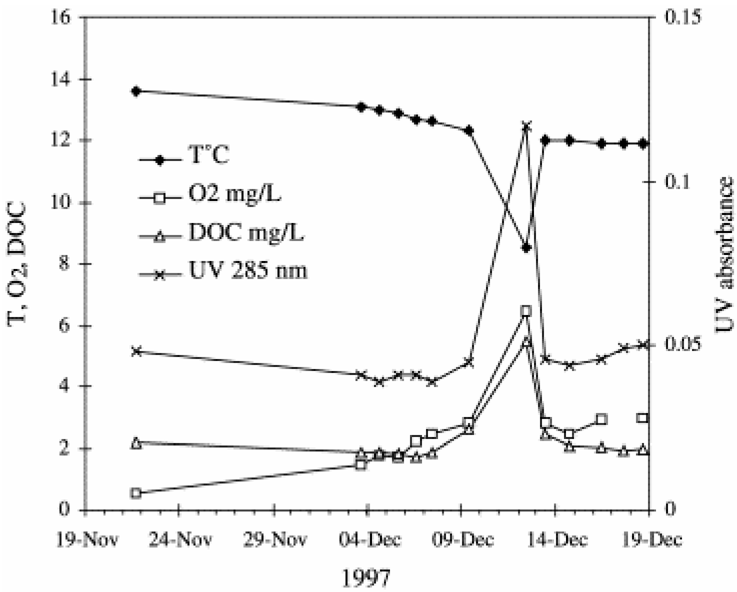

Fig. 3. Variation of temperature, dissolved oxygen, dissolved organic carbon (DOC) and UV absorbance of the Bouillon waters (sampled at the spring basin) during the backflow event of December 1997.

The method consisted in comparing the water levels of the River Loire and the Dhuy river during days of normal resurgence of the spring or inverse swallowing flow. The plot in Fig. 4 of the River Loire versus Dhuy river water levels for each day of the reference period, shows two distinct domains, according to the emergence or the swallow-hole functioning of the conduit. The limit between these two domains may be equalised by an exponential function corresponding, as the River Loire flow rises, to the higher resistance of the normal emerging flow of the spring against the intrusion of the Dhuy surface waters. A non-linearisable exponential function of the form $e^{(ax+b)}$ was found to better fit the data. The limit in Fig. 4 may be drawn by the relation:

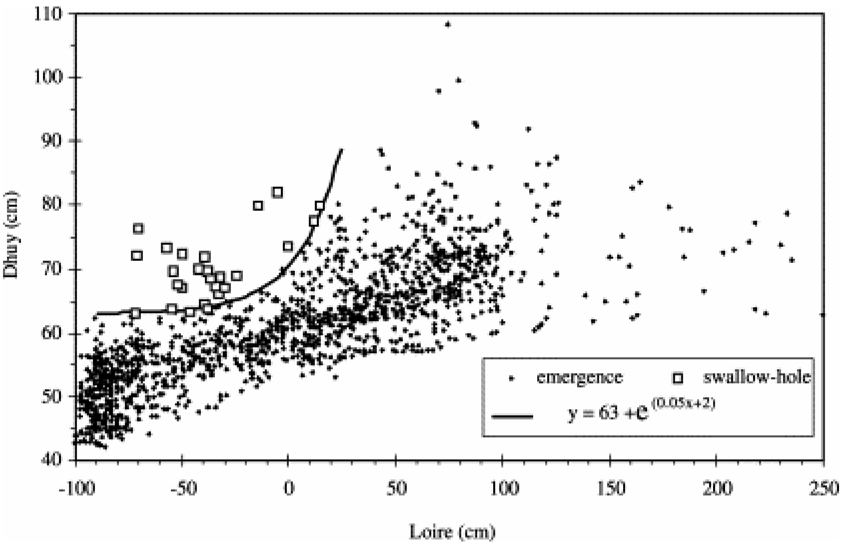

Fig. 4. Water-levels of the Dhuy (at the Gobson) versus the River Loire (at Orléans) from June 1st 1997 to June 30th 2001 with indication of the emissive or absorbing functioning of the karstic spring conduit.

$$H_{\mathrm{Dhuy}}=63+e^{(0.05H_{\mathrm{Loire}}+2)}$$

here H_{Dhuy} and H_{Loire} are, respectively, the water levels in centimeters of the river Loire and the Dhuy river. Data plotted in Fig. 4 are daily mean water levels computed from the mean water flows for the Dhuy river and the water level observed in the morning the day before for the River Loire. Taking into account the River Loire value of the day before gives a better simulation (Fig. 5) of the occurrence of some single events located at the beginning of a flood of the River Loire and is in accordance with the delay observed between the water level variations of the stream and the water table ([Desprez, 1967]). Plotting absolute elevations of the river levels in meter would lead to a relation like

$$H_{\mathrm{Dhuy}}=92.63+e^{(4.971H_{\mathrm{Loire}}-450)}$$

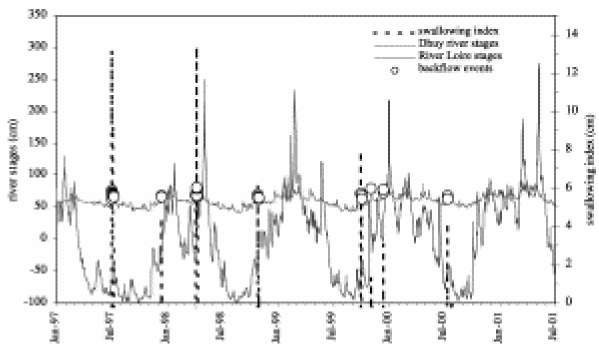

Fig. 5. Backflow events and calculated occurrences during the reference period (January 1997 to June 2001). Swallowing is predicted when the index ($H_{Dhuy}-e^{(0.05H_{Loire}+2)}-63$) is>0.

Relation (1) is allowing computation of a 'swallowing index' enabling to redraw all the recorded events with a good indication of the intensity of the phenomenon (Fig. 5). The index was computed as follows:

$$\text{swallowing index} = H_{Dhuy} - e^{(0.05H_{Loire}+2)} - 63$$

Backflooding of Dhuy river water into the spring is predicted when Dhuy river stages stand above the limit drawn Fig. 4, that is when the index is>0.

During the period of reference (the period of regular observation of the regime of the spring, since July 1997) every event actually observed has been correctly simulated in Fig. 5 and no extra event has been predicted. Two parameters only seem sufficient to explain the direction of the flow and to predict the risk of swallowing at the entry of the conduit. The condition required for the reversal to occur is Dhuy river stages standing above a variable threshold level which depend on the spring flow and which may be quantitatively determined by relation (1).

3.2. Period 1985–1996

Extending this method of predicting the backflow events to the past may be useful to see if the phenomenon is peculiar to the end of the 1990s, and to look for the general environmental conditions mostly related.

Numerical data for the Dhuy river are only available from 1985. Working out the swallowing index from this date does reveal only one more possible small swallowing event during the 1990s, at the end of the year 1996 and no occurrence until the beginning of 1989 (Fig. 6). The uncertainty of the prediction made with the swallowing index is higher at the beginning of the series since different rating curves were in use. The first set of data (from January 1985 to September 1986) was corrected to make up for the shift of the water level ruler (M. Ghio, DIREN-Centre, personal communication). Nevertheless, it seems very probable that no backflow event occurred during the first half of the 1990s and that at least a major one should have been seen during two or three days at the end of 1986.

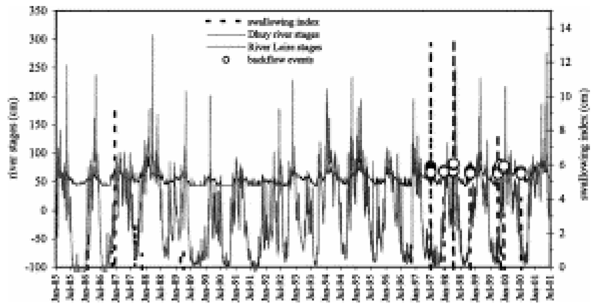

Fig. 6. Backflow events and calculated occurrences since 1985.

4. Discussion

Although some backflow events may be suspected during the years 1986–1989, the phenomenon has seemed to become more and more common since the end of the 1990s and during the present years (2000–2002). Is this apparent increasing frequency of the Bouillon inversac functioning the warning sign of drastic changes having affected the hydrologic system or simply a result of meteorological uncertainty?

The most important modification having affected recently the Val d'Orléans hydrologic system has certainly been the digging of the bed of the River Loire since the mid-nineteenth century. More recently, the consequence of the intensive ballast extraction since the mid-twentieth century was more than 1 m lowering of low-water levels upstream of Orléans, with probably a marked drying-up effect on the springs ([Gasowski, 1994]). However, the legal suspension of ballast extraction in the river bed from 1992 and the trend to stabilisation of the water line (Reinbold, DIREN-Centre, unpublished data) cannot explain the recent functioning of the Bouillon resurgence as an inversac.

Though the aim of this study is not the runoff characteristics of the Dhuy catchment, which would lie outside the scope of this work, we would like to test as simply as possible the hypothesis that the occurrence of flow-inversion in the Bouillon conduit depends basically on the existence of sufficient rainfall intensity during low-water levels of the River Loire rather than reflecting new characteristics of the drainage or groundwater basins. Rainfall in the Dhuy watershed was expressed as the antecedent precipitation index ([Organisation Météorologique Mondiale, 1994], p 485) calculated from the weighted mean (Thiessen polygon method, [Organisation Météorologique Mondiale, 1994], p 455) of the data collected at Marcilly-en-Vilette, Orléans-la-Source and Villemurlin precipitation stations. Rainfall and River Loire stages were compared in Fig. 7 for summer and winter seasons separately, setting apart backflooding days from normal resurgence days for the three periods distinguished previously: the reference period, 1997–2001; the backflow-free period, 1989–1996 and the inferred former backflooding period, 1985–1989. The result is that rainfalls (precipitation antecedent index) greater than 40 mm are frequent for low River Loire stages during summer at the present backflooding period (Fig. 7a) conversely to what was observed during the years 1989–1995 (Fig. 7b). Moreover precipitation indexes up to 50 mm were observed during the inferred backflow event of the period 1985 to 1988 (Fig. 7c) leading to the conclusion that it is the distribution of heavy rainfall events and low River Loire stages which determines backflooding in the present days. The conclusion probably also holds for the winter period although less firmly (Fig. 7d–f).

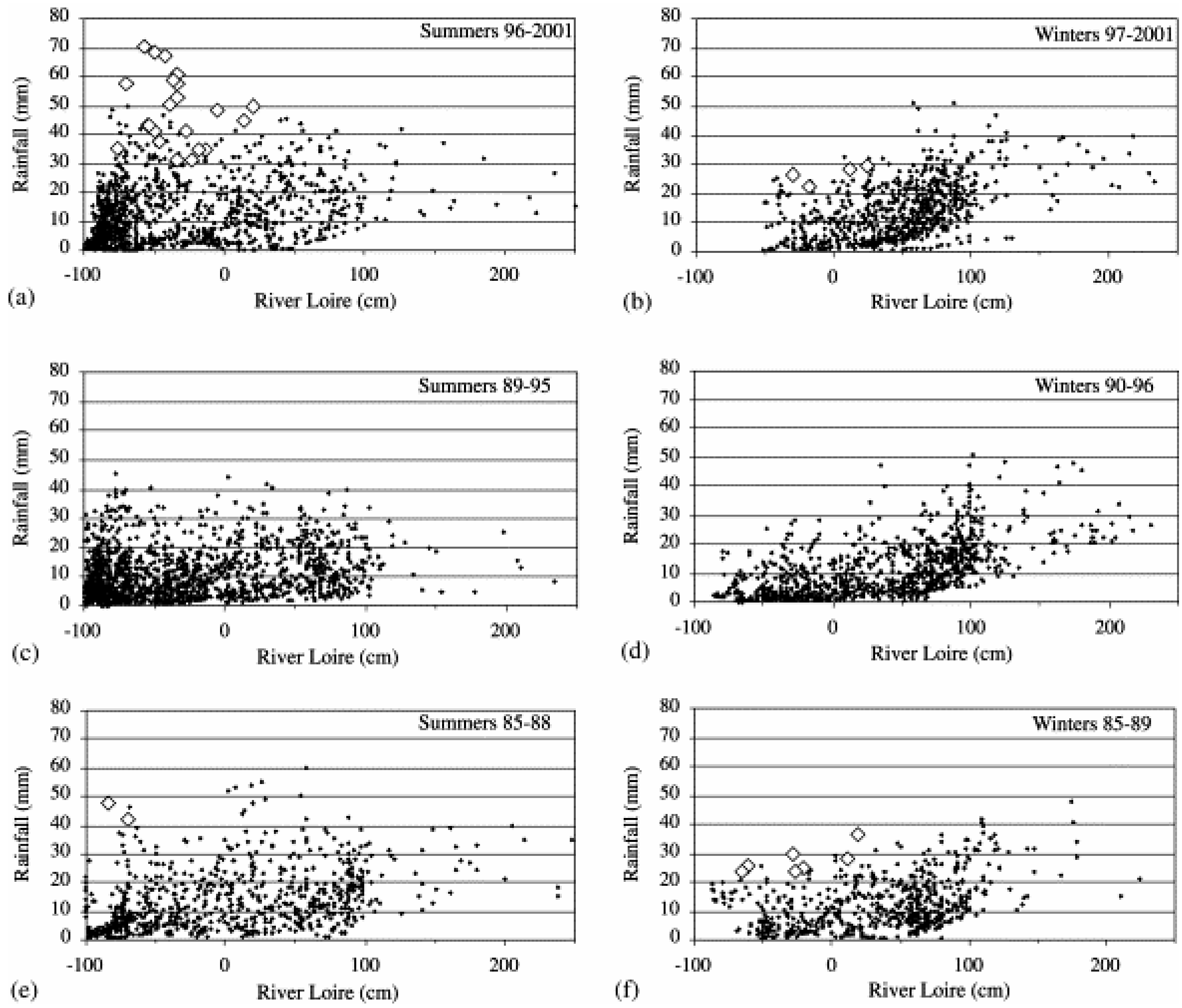

Fig. 7. Rainfall versus River Loire stages with indication of the emissive or absorbing functioning of the spring conduit. Antecedent precipitation index was calculated assuming a recession constant of 0.84. 1997–2001: period of reference. 1989–1996: no backflooding period. 1985-1989: former backflooding period. River Loire stages are plotted with the rainfall data of the day before. Winter period is between November 11 to April 3 (Nov 15 in 1997, Dec 24 in 1989 because of dry weather conditions).

The fact that meteorological uncertainties (heavy rainfall) are put forward to explain backflow occurrence during the last 25 years does not mean that intrinsic causes peculiar to the hydrologic system, like perturbation of the superficial local drainage network or modification of the River Loire bed (as mentioned above), may not have made the phenomenon possible in the long term. Backflooding is described at the beginning of the nineteenth ([Hugo, 1835]) for an other resurgence (Le Gouffre) which is heavily collapsed now but not for the two main springs Le Bouillon and l'Abîme which were probably flowing more in the past ([Beauvais de Préau, 1784 and Fontenu, 1736]). Swallowing of turbid surface waters inside the conduit of the Bouillon is however, probably an old phenomenon since clayey deposits with beds of leaves>1700 BP are known (F. Salièges, unpublished carbon dating).

5. Conclusion

This work exemplifies that monitoring of two river stages may be sufficient to explain and eventually anticipate backflooding of a major karstic resurgence. On a local level, considering the potential deterioration in water quality resulting from the swallowing of drainage water into the drinking water catchment, the determination of a swallowing or backflow index may contribute to protect the water supply.

In a short time span, meteorological uncertainties (heavy rainfalls on the Val d'Orléans and low River Loire stages) determine the occurrence of the backflow events. Nevertheless long term disruptions of the basins (River Loire and local drainage basins) and climatic fluctuations may create favorable conditions to make backflow events more common. Reconstruction of a swallowing index before 1985 is made possible in theory by means of available graphical data (DIREN-centre) but validation would be more difficult.

Acknowledgements

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