In situ monitoring of karst springs in Wallonia (southern Belgium)

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Abstract The implementation of the Water Framework Directive, as well as the forthcoming entry into force of other European water policies focusing on water resources, require a thorough reorganization of groundwater resources monitoring in most European countries. In Wallonia, monitoring programs were initiated in 2005 to control the quantitative and chemical statuses of groundwater bodies, as well as the effectiveness of management plans aimed at achieving environmental objectives. In karst aquifers, springs are preferential monitoring targets even if, as a result of the high heterogeneity of this type of aquifer, the interpretation of time series and spatial data remains a challenge. Since 2006, a "springs" monitoring network has been progressively set up in the southern part of Belgium. Currently, in situ measurements of discharge, temperature, conductivity, turbidity and fluorescence of water are conducted at nine karstic outlets in the Devonian and the Carboniferous limestone aquifers of Wallonia. The main objective of this ongoing research is to evaluate the suitability and the robustness of such standard measurements to discriminate anthropogenic impacts from natural variations, at both short- and long-term scales. Discharge and temperature data revealed being useful in the assessment of regional hydro-climatic trends. Groundwater proved to be a better natural filter for the assessment of long-term climatic changes than mathematical filtering of noisy surface signals. Investigations of such data at a European scale could therefore give additional insight into the impacts of climate change on groundwater resources. Conductivity, turbidity and fluorescence data characterize the particulate, mineral and organic health of water and a better understanding of their natural dynamics could help in the early detection of anthropogenic deviations. However, the current reproducibility of these measurements is too low to ascertain observed trends and fluctuations, and further research is still needed.

Keywords Karst · Spring · Groundwater resource · Monitoring · Water policy · Europe

Introduction

Karst aquifers are main contributors to the total flow of fresh groundwater in the world (Margat 2008; Ford and Williams 2007), and their consequent economic relevance is reputed. Groundwater flow in karst aquifers is usually mainly directed to springs, sometimes having a mean discharge that can reach several tenth of m³/s. The paradox between the high yield of these aquifers and their high vulnerability towards anthropic pressures was soon identified, for instance in Belgium (Van den Broeck et al. 1910), and remains a crucial point for their exploitation as drinking water (Agence de l'Eau Rhône-Méditerranée-Corse 1999). This high vulnerability is due to a recharge through fast and massive infiltration of surface water in preferential absorption features and a lack of natural attenuation of potential contaminants. The mean age of groundwater does not usually exceed a yearly hydrologic cycle. Nevertheless, such a rapid mean transit time does not allow cases of groundwater pollution to be easily and successfully remediated simply by reducing the source of

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pollution. Vesper et al. (2001) showed that contaminant transport processes in karst aquifers are very complex, contaminant-specific, and still require investigations and research to be fully understood. Major springs have since a long time been recognized as relevant monitoring points for water quality and quantity in this type of aquifer (BRGM 2010; Quinlan 1989). The design of monitoring networks in karst aquifers is not a straightforward task. Quinlan (1989) already recommended "the use of an adequate sampling frequency, according to the high spatial and temporal variability, without which a waste of time and money would be guaranteed". Blavoux and Mudry (1988) also showed the importance of the sampling frequency in hydrochemical and hydrokinematic studies of karst aquifers. However, most of these studies have only been dealing with cases of monitoring for local groundwater assessment purpose, and few comparisons of the dynamics have been done simultaneously and for a long time period for a large set of springs.

The European Water Framework Directive WFD (EUROPEAN COMMISSION 2000), has set new standards for the monitoring and the reporting of groundwater quality and quantity, taking into account "groundwater bodies (GWB)" as management units. More recently, the EU water policy, with the "Blueprint to safeguard Europe's waters (EUROPEAN UNION 2011)", has made another step change by taking an integrated approach on the basis of the concept of sub-basin management. This last approach calls for an improved environmental monitoring at the catchment scale (FECs, for Fundamental Elementary Catchments, of a size of about 60 km^2) as well as a good coherence at a Pan-European scale. Quantitative aspects are also more emphasized, privileging water resource budgeting (water balance, water scarcity and droughts, climate change). Over the past few years, monitoring networks have been more efficiently coordinated in most European countries (OFEV 2012a; SPW 2012). Karst springs have been recognized as strategic monitoring points for assessing the status of karst groundwater bodies in the framework of the WFD (Quevauviller 2010). Their integrating character is well suited to the catchment-scale environmental assessment required by European legislations. However, sampling frequencies, adequate indicators (OFEV 2012b), and methodologies for status assessment have to be improved yet to satisfy water management requirements. Up-scaling the results from local observations also remain a challenge for karst hydrologists. This challenge is clearly linked to long-term trend identification in a context of global climate changes.

The present paper aims at giving an insight into the potentialities of karst springs monitoring for environmental assessment, with the example of an in situ monitoring network of a set of karst springs in the primary limestone aquifers of southern Belgium.

Geological and climatological setting

The volume of drinking water produced from carbonate rock aquifers in Wallonia is about 250 hm^3/y, more than 60 % of the total drinking water consumption (SPW 2012; Meus et al. 2002). Carbonate aquifers extend over about one-third (4,570 km^2) of the territory (Fig. 1).

Annual precipitations in southern Belgium range between 700 and 1,400 mm. The climate is qualified as temperate with low seasonal variations and frequent depressions moving from the Atlantic Ocean towards the West. Recharge is mainly controlled by low atmospheric pressures typically linked to oscillations of polar fronts at mean latitudes.

The mean annual recharge to groundwater has been estimated by different methods (Bonniver and Hallet 2013). The minimum range of the estimation is 112 mm.

Mesozoic rocks (chalks and carbonated sandstones) are poorly karstified aquifers, while Palaeozoic limestones (Devonian and Carboniferous) show a higher degree of karstification. Surface karst features (exokarst) are mainly present in the Meuse River basin, due to a folded structure and a thin quaternary overburden. This area is consequently of high interest for speleological sciences. One should also expect a considerably higher recharge in these aquifers. Finally, because of their intense exploitation for drinking water production, they require an improved knowledge to ensure a sustainable protection and an adequate resource management.

For the above reasons, the Meuse River basin was selected to set up a specific monitoring network. Nine karst
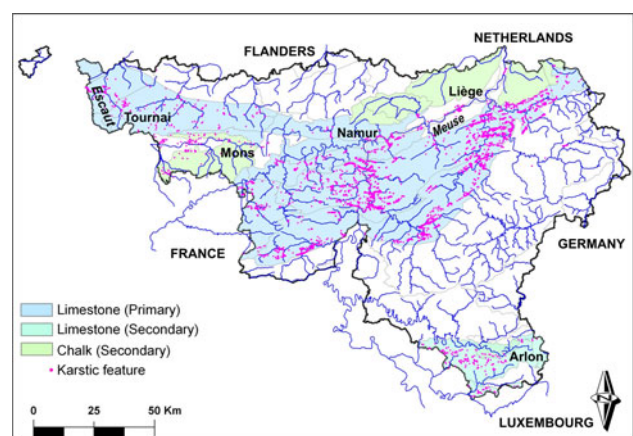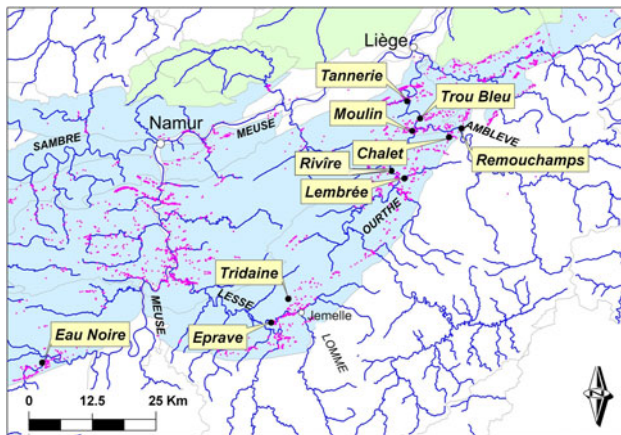

Fig. 1 Carbonate aquifers in Wallonia

Fig. 2 Situation of monitored springs

outlets are included in the network (Fig. 2). Their main features are reported in Table 1.

Most of these springs have never been used as drinking water supply, some of them are disused (Chalet, Moulin, Lembrée) and only one (Tridaine) is presently still being exploited for a brewery.

The Eprave spring has the highest mean discharge. It is characterized by an allochtonous recharge through sinks along the Lomme River (Meus et al. 2011a, Fig. 3). This is also the case for the Eau Noire spring. Most of the other springs are located at the outlet of typical syncline structures, with a main recharge through swallow holes and secondary recharge component linked to diffuse infiltration through soils.

The Lembrée spring is the permanent outlet of a system with a temporary overflow. The Tridaine spring (Hallet and Meus 2011) is not a fully natural feature. It is the exit of a mine drainage tunnel used to lower the water table and allow subsurface metal ore exploitation in the area. However, considering flow velocities and a voids-and-conduits architecture, the abandoned mine can be qualified as karst aquifer. The river monitoring point (Fig. 2) is not included in the list because it is a cave lake rather than a spring. However, it has been monitored for level and temperature since 2007 and, as far as it gives interesting comparative results, it is also discussed in this paper.

Monitoring network

The monitoring network entered into operation in 2006 and has been progressively improved since then. All springs are equipped with automatic probes recording parameters every 10–30 min. Several of them are also equipped with automatic data transmission systems (GSM or GPRS systems).[1] Frequent calibrations are performed for water

levels. Where it is possible, levels are linked to a gauging station or to a weir (Chalet, Tridaine) to obtain absolute values of water discharge. In several cases (Eprave, Trou Bleu, Moulin), the use of a velocity-indexing method[2] was mandatory, as simpler level-velocity relationships failed during high water periods due to interferences with the collecting stream. The main physico-chemical parameters that are continuously measured are temperature, conductivity, turbidity and fluorescence. Dissolved oxygen, pH and nitrate content were also measured with in situ probes but their calibration and the management of drifting phenomena were so challenging that the data could not be included in a long-term evaluation.

The manufacturers of probes usually set the accuracy of temperature at 0.1 °C.[3] However, the resolution is as low as 0.001 °C and the consistency of the measured data, provided that the probe is not moved from the field, indicates a good relevance of measurements within this order of magnitude. Since no data are provided with regard to potential long-term instrumental drift of the probes, one should, however, remain cautious while interpreting long-term data.

The most innovative aspect of this monitoring network is the measurement of field fluorescence. The measurement devices are GGUN FL-30 field fluorometers with 4 fluorescence channels. Three channels are dedicated to three spectral domains using 470, 525, and 365 nm centered light emitting diodes (LEDs) and specific emission filters. A fourth system with a 660 nm excitation wavelength is used for turbidity measurements. While the 525 nm LED is obviously in correlation with the turbidity, the 365 nm and the 470 nm LED integrate a part of the DOM[4] fluorescence in the UV domain (Coble 1996; Baker and Lamont-Black 2001). The 365 nm excitation LED has a half-height bandwidth of 15 nm, while the emitted light is filtered through a Kodak Wratten No. 44 (light blue-green) gel filter with a bandpass centered on 490 nm and a significant response from circa 430 unto 560 nm. Other spectral domains are currently under consideration for future implementation in the network, including 280 and 316 nm centered excitation LEDs.

UV intrinsic fluorescence involving laboratory measurements has already been successfully used for the characterization of infiltration processes towards karst springs (Mudarra et al. 2011), for characterization of background fluorescence in tracer tests (Smart 2005; Meus et al. 2006) or for the assessment of organic pollutants (Hudson et al. 2007; Baker et al. 2003). UV in situ fluorescence involving filter fluorometers already proved to be

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[1] Data loggers are TRMC models from Tétraèdre company.

[2] ISCO 2150 and SonTek Argonaut SL-3000 instruments are used for velocity-stage measurements.

[3] It is the case for GGUN-FL30 and In Situ Troll devices used in this study.

[4] Dissolved Organic Matter.

Table 1 Main characteristics of selected karst springs in the Devonian and Carboniferous limestone formations

| Outlet (spring)	Main river basin	Aquifer	Groundwater body	Estimated annual discharge (m³/s)	Altitude (m a.s.l.)	Type of recharge	Monitored parameters
Tannerie	Ourthe	Devonian	RWM021	0.306	90	Concentrated/swallow holes	Level, temperature
Moulin	Ourthe	Carboniferous	RWM021	0.225	110	Concentrated/swallow holes	
Trou bleu	Ourthe	Carboniferous	RWM021	0.230	105	Concentrated/swallow holes	
Chalet	Amblève	Devonian	RWM023	0.110	158	Concentrated/swallow holes	
Remouchamps	Amblève	Devonian	RWM023	0.322	140	Concentrated/swallow holes	Level, temperature, conductivity, turbidity, fluorescence
Lembrée	Ourthe	Devonian	RWM023	0.249	155	Concentrated/swallow holes	
Tridaine	Lomme	Devonian	RWM023	0.025	211	Diffuse	
Eprave	Lomme	Devonian	RWM023	0.800	150	Concentrated/main river sinks	
Eau noire	Eau Noire	Devonian	RWM023	n.a.	160	Concentrated/main river sinks	
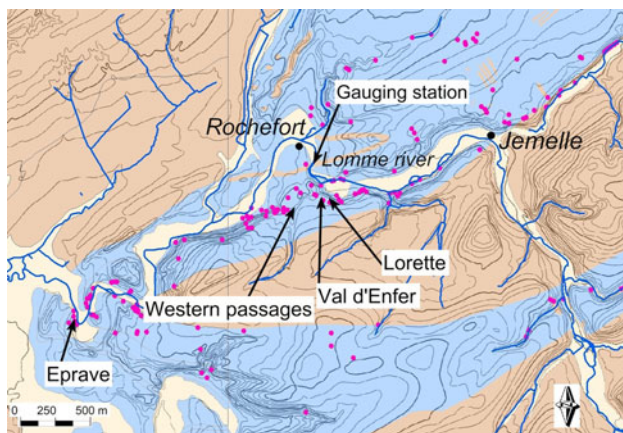
Fig. 3 Situation of the Eprave cave system along the Lomme River near Jemelle and Rochefort towns. The *points* are surface karstic features while monitoring places in the caves (Lorette, Val d'Enfer, Western passages), the spring (Eprave) and the reference gauging station of the Lomme River in Rochefort are indicated by *arrows*

a valuable tool for characterizing DOM in aquatic environment, for instance to study infiltration (Charlier et al. 2010) or for removing DOM interferences from uranine (Schnegg and Le Doucen 2006; Amez-Droz and Schnegg 2007) or sulfonates (Meus et al. 2011b) measurements during tracer tests.

In addition, laboratory analyses of water samples were conducted, either during specific campaigns included in the monitoring program of the WFD, or during other studies (Loos et al. 2010). Major ions, PAH compounds, TOC and polar organic persistent pollutants were tested. In the case of the study of PAHs during the floods at the Chalet spring, samples were collected with an automatic refrigerated ISCO Avalanche sampler triggered by a level probe. Samples were analyzed for polycyclic aromatic hydrocarbons (PAHs) using standard methods in the laboratory.

Results and data interpretation

Water temperature

Time series of water temperature recorded in the springs with the longer coherent datasets are shown in Fig. 4. The signature of the annual cycle of temperature can be clearly seen in each series. During spring and summer, there is a slow increase of temperature with sharp positive impulses at each significant rain event. At the end of the autumn, opposite trends can be observed. Mean temperature starts to decrease and rain events provide a concentrated recharge of colder temperature resulting in negative sharp peaks in the data. The reversal of impulses is typically occurring with the first important rain events in autumn. A new cycle starts when recharge water warms up again.

Amplitude of seasonal cycles and peak events does not only depend on the degree of karstification of the system but it also most probably results from a combination of factors such as water mean residence time in the system, altitude of the recharge area, type of recharge (concentrated or diffuse, with more or less surface water infiltration), or mixing processes within the karst system.

The magnitude of the seasonal amplitudes can also be used to assess the effectiveness of the groundwater system to filter out annual climatic variations. Temperature series characterized by reduced annual variations, such as the ones recorded at the Chalet and Trou Bleu springs, could give more insight into long-term climatic changes.

The slopes of the linear fits do not show any clear global tendency (Fig. 4). Several springs show an increase in average temperature, while others show a decrease. Considering that undetected instrument drift can also occur, no clear conclusion can be drawn here.

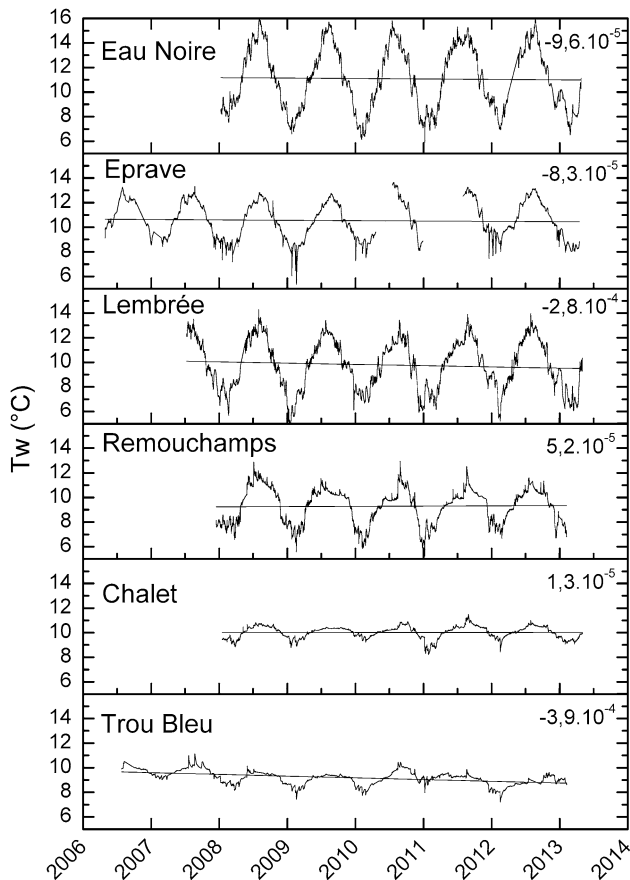A closer look at thermal processes within the karst system of the underground Lomme River system is given

Fig. 4 Time series of water temperature (*vertical axes* proportional). Linear fits are shown with corresponding slope values
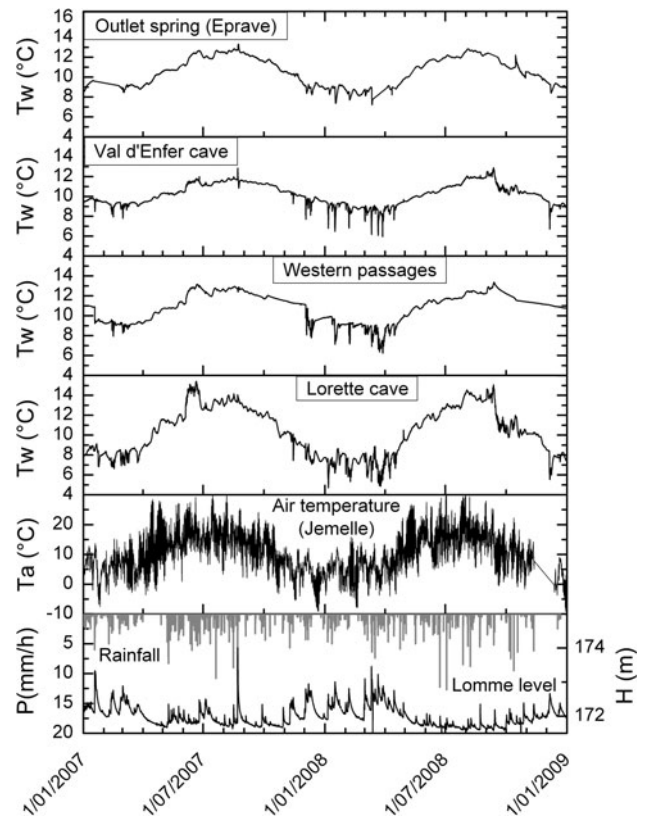

Fig. 5 Times series of water temperature during the years 2007–2008 along the Eprave cave system, compared with atmospheric temperature (*enlarged scale*) and rainfall from the meteorological station of Jemelle, and with the river stage of the Lomme River in Rochefort

in Figs. 3 and 5, where intermediate water points were monitored in caves between the sinks and the outlet (Eprave spring). Data are compared to air temperature and rainfall measured at the meteorological station[5] of Jemelle as well as to the stage of the Lomme River in Rochefort.[6]

Flow in the Lorette cave is highly influenced by external ambient air temperature since it is directly coming from several sinks located along the river. Water temperatures in the Val d'Enfer cave and in the Western passages exhibit smoother variations as a result of a more diffuse recharge. Remaining peaks are caused by surface water invasion during floods. It can also be seen on the graphs that the time of response to atmospheric seasonal variations is in the range of 1–2 months.

Considering heat exchange process within the karst aquifer would probably allow an improved understanding of the experimental results reported here. Luetscher and Jeannin (2004) have listed a series of mechanisms for heat transfer in karst systems, linked to air temperature in caves or to the effect of geothermal gradient on groundwater.

Luetscher and Jeannin (2004) consider that heat fluxes are dominated by air flow and they neglect recharge as a vector of heat. Moreover, mixing processes as identified in the Eprave system, probably introduce an additional complexity in the observed temperature distributions. Future work is intended to investigate these mixing processes with artificial tracer testing.

The results depicted in Fig. 6 are typical of a more efficient filtering of atmospheric temperature fluctuations by the groundwater system. In this figure, two additional groundwater temperature signals are shown. They are plotted either with groundwater level or discharge rates. Rivîre is a cave lake relatively isolated from the surface and with a very low renewal rate. The probe is installed about 1 m below the surface of the lake. An increase of temperature of 0.4 °C has been recorded between 2007 and end of 2012.[7] Temperature reached a maximum at the end of 2012 and decreased since then. Deviations from this trend can be observed at low stages, when the probe is very near water surface (it was even dry in August 2010).

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[5] Meteorological station of the PAMESEB network.

[6] Station of the Public Service of Wallonia network.

[7] These data were validated by a second probe installed since 2010.
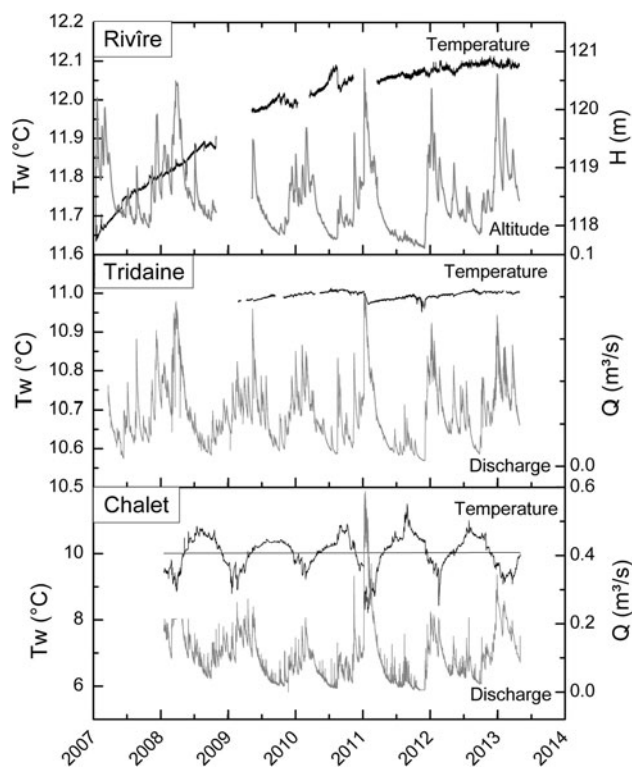
Fig. 6 Times series of water temperature in the Rivîre Lake and in the Tridaine spring. The stage of the lake and the discharge values of the spring are also given. Data from the Chalet spring are given for comparison purposes

The middle graph shows water temperature in the Tridaine spring. The same trend is observed, except that it is of a much smaller magnitude (only a few hundredth degrees). One can also notice a discontinuity in the trend during the large flood that occurred in the beginning of January 2011. Although the memory of the probe was lost for this period, it can be seen from available data that this discontinuity is probably also present at the Rivîre Lake. The above results show that in certain cases, karst aquifers can behave as efficient natural filters for extracting long-term temperature trends by smoothing out seasonal and fast infiltration effects. These observations should, however, be confirmed by additional measurements, instrumental drift checking and correlations with atmospheric records in different areas.

Spring discharge

Discharge measurements at 4 karst springs are shown in Fig. 7. All graphs show that the discharge had been decreasing since 2007 and that the trend reverted in 2011. As compared to other years, the year 2011 had an unusual hydrologic pattern, with the highest observed discharge peak in winter and the lowest values ever recorded in autumn. Although one should consider that measurements of extreme discharge values (high as well as low ones)
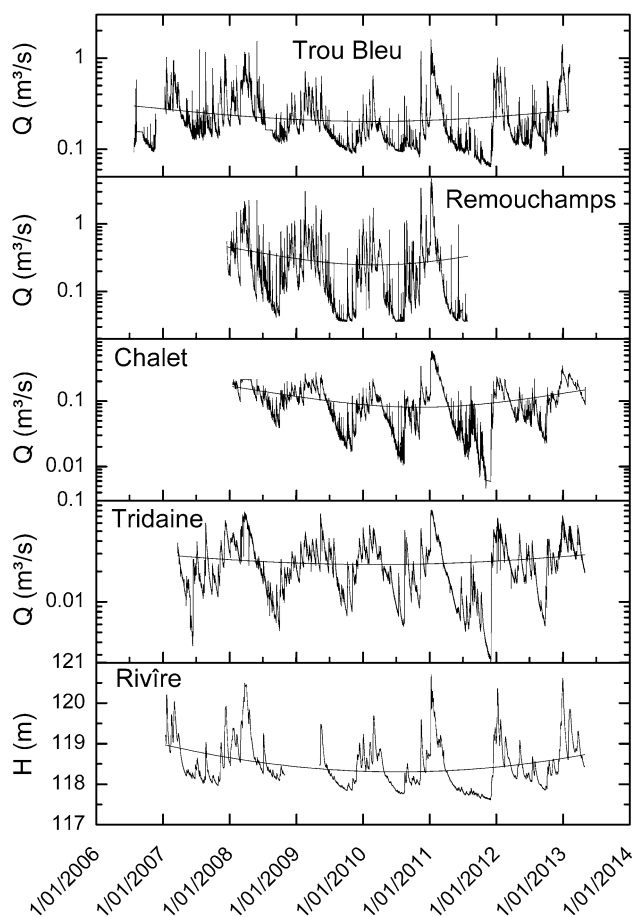

Fig. 7 Time series of discharge in 4 karst springs (*vertical logarithmic scale*) compared with groundwater level in the Rivîre Lake. Second-order polynomial fits all show a decrease until 2011 followed by an increase until 2013

always have a higher uncertainty, the similarity of the inversion observed in 2011, with the temperature inversion observed in 2012, suggests that both processes are linked and are probably due to an atmospheric change. This still has to be compared with atmospheric records.

Transport processes

Physico-chemical series have been widely used in karst research in conjunction with hydrodynamical and isotopic methods (Mangin 1994). They were mainly used for assessing the degree of karstification and for qualifying mixing processes (Bakalowicz 1977). However, Kiraly (2003) showed that the interpretation of chemical data for characterizing groundwater flow in karst aquifers was often conducted in a too simplistic approach.

The diversification of the parameters used (Mahler et al. 2000; Massei et al. 2006) and an increased resolution of sampling rates greatly helped to better understand the dynamics of karst aquifers. Long-term in situ monitoring offers one more opportunity for validating this knowledge.
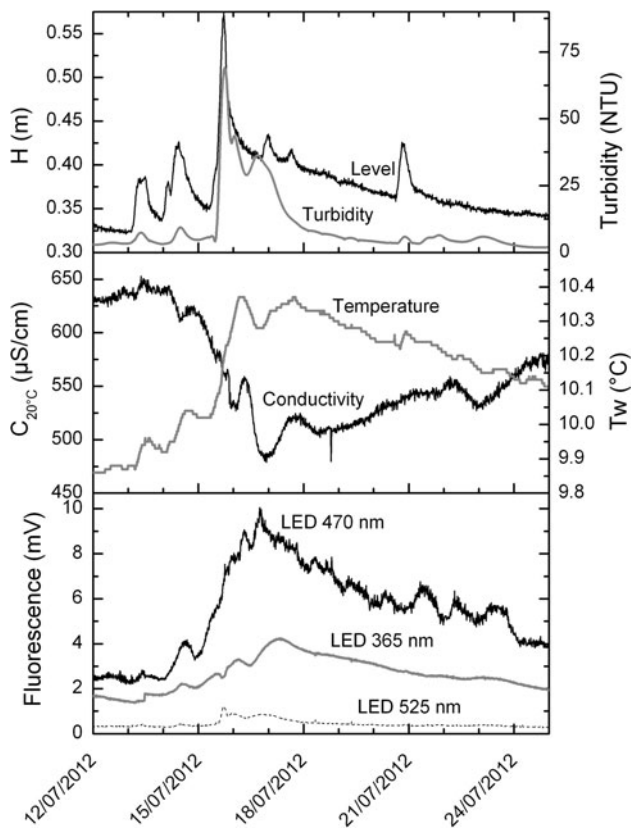
Fig. 8 Responses of water level, conductivity, temperature, turbidity and fluorescence during a flood in July 2012 at the Trou Bleu karst spring
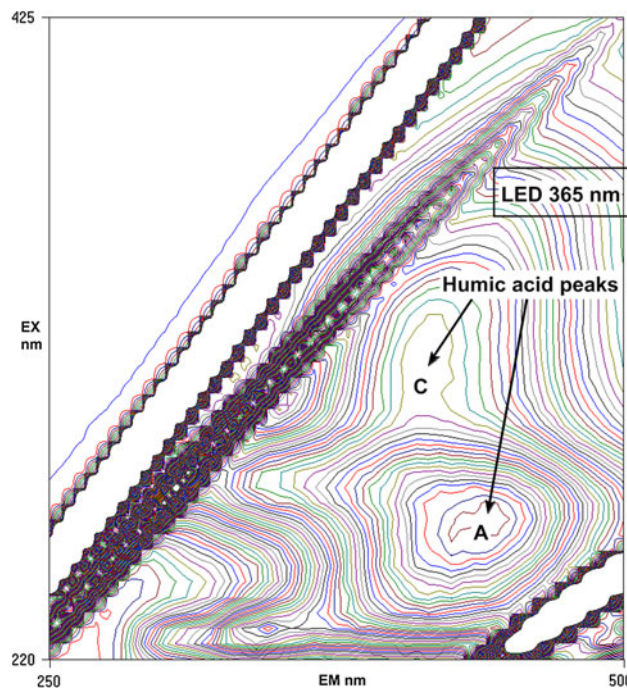

Fig. 9 Excitation emission spectrum of water from the Chalet karst spring. The spectral area integrated by the 365 nm channel of the fluorometer is shown near the C (humic acid) fluorescence peak

An example of multicomponent monitoring analysis is given in Fig. 8 with data coming from the Trou Bleu system during a moderate flood in summer. The discharge of the spring rose from 100 to 500 l/s.

Very shortly after the discharge rose, the turbidity also increased. This reaction was too short to be due to the contribution of surface runoff in swallow holes, as they were located several kilometers away from the spring. It was explained as a re-suspension of fine solid particles within the system. The dilution by newly infiltrated water is then proved by changes of conductivity and temperature. The time of response is about 1 day.

Fluorescence signals corresponding to different wavelengths do not show similar responses. While the red signal (525 nm) comes together with the turbidity and the 470 nm signal is quite correlated with the conductivity and temperature, the 365 nm signal is delayed of about 1 day. Such different reactions are systematically observed at all springs. The optical system with the 365 nm LED is integrating a part of the DOM fluorescence near the fluorescence maximum C, typical of humic acid fluorescence (Coble 1996; Baker and Lamont-Black 2001). The concerned spectral area is shown in Fig. 9 on a typical EEM
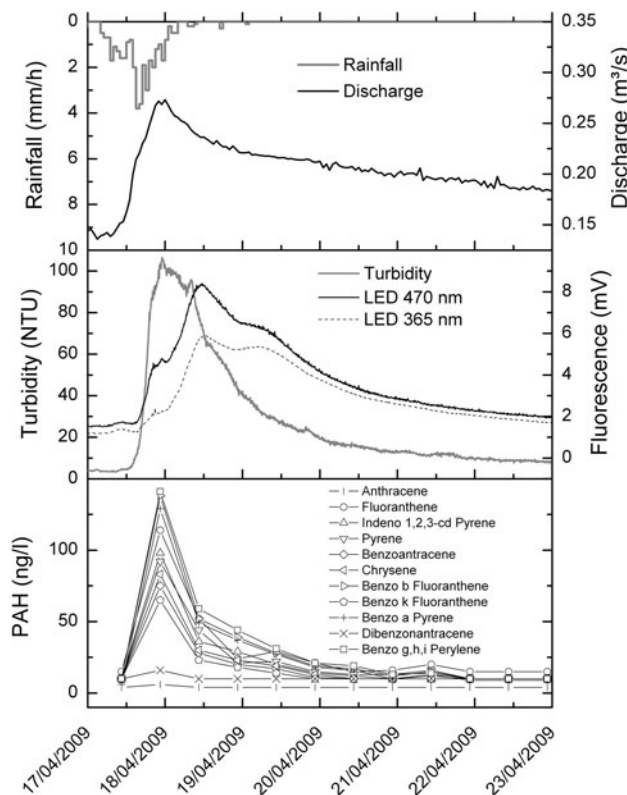

Fig. 10 Responses of discharge, turbidity, fluorescence and PAHs at the Chalet spring during a flood in April 2009

(excitation emission matrix) of the Chalet karst spring. The retardation of the 365 nm component suggests that chemical reactions are modifying the composition of DOM at the infiltration time scale (1–2 days). It also suggests that, despite higher limitations in spectral resolution, field fluorometers can be used to assess the attenuation of organic compounds in karst systems and they would benefit from more specific studies. One example of such investigation is shown in Fig. 10. This example is taken from a flood at the Chalet spring. The shift of UV fluorescence signals (about 12 h) is always present even if the difference between the 470 and 365 nm signals is not as clear as in the previous case. PAHs are clearly linked to the turbiditic phase and they are most probably associated with the particulate phase.

Conclusion

Karst springs are representative monitoring points for quantity and quality assessment of groundwater. An experimental monitoring network has been in operation in southern Belgium (Wallonia) since 2006 to test the suitability and the robustness of long-term in situ measurements in shallow karst aquifers. In most springs, long-term temperature changes were masked by seasonal and concentrated recharge effects. However, long-term atmospheric changes could be detected in temperature signals recorded in karst aquifers where recharge is dominated by slow diffuse infiltration. In the Rivîre Lake and the Tridaine spring, it was observed that temperature started to decrease in 2012, while it had been continuously increasing before. An opposite trend was detected in hydrologic data: discharge was found to steadily decrease before 2011 and has started to increase since then.

The records suggest that enlarging the monitoring network to other types of aquifers or to a wider geographical area would probably be useful for regional climate change assessment.

UV fluorescence data are related to DOM dynamics and they can be used to assess the attenuation processes of organic compounds.

Such monitoring network, thus, presents a great potential in terms of indicators of environmental changes and impacts, provided that the reproducibility of the measurements can be ensured and that processes can be cross-validated by other analytical methods.

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