SNO KARST: A French Network of Observatories for the Multidisciplinary Study of Critical Zone Processes in Karst Watersheds and Aquifers

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Published December 20, 2018

Special Section: Hydrological Observatories

Core Ideas

- SNO KARST is dedicated to the study of karst functioning.
- Hydrodynamics and geochemistry are measured at springs and in karst compartments.
- Process sampling was set up at nine sites in various climatic contexts.
- Continuous monitoring concerns timescales from 10 to >50 yr.
- New tools and findings are due to the complementarity of gathered data.

Received 30 Apr. 2018.
Accepted 29 Aug. 2018.
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Karst aquifers and watersheds represent a major source of drinking water around the world. They are also known as complex and often highly vulnerable hydrosystems due to strong surface–groundwater interactions. Improving the understanding of karst functioning is thus a major issue for the efficient management of karst groundwater resources. A comprehensive understanding of the various processes can be achieved only by studying karst systems across a wide range of spatiotemporal scales under different geological, geomorphological, climatic, and soil cover settings. The objective of the French Karst National Observatory Service (SNO KARST) is to supply the international scientific community with appropriate data and tools, with the ambition of (i) facilitating the collection of long-term observations of hydrogeochemical variables in karst, and (ii) promoting knowledge sharing and developing cross-disciplinary research on karst. This paper provides an overview of the monitoring sites and collective achievements, such as the KarstMod modular modeling platform and the PaPRIKa toolbox, of SNO KARST. It also presents the research questions addressed within the framework of this network, along with major research results regarding (i) the hydrological response of karst to climate and anthropogenic changes, (ii) the influence of karst on geochemical balance of watersheds in the critical zone, and (iii) the relationships between the structure and hydrological functioning of karst aquifers and watersheds.

Abbreviations: CADI, cellular automata-based deterministic inversion; Ex/Em, excitation/emission; NOM, natural organic matter; SLP, sea level pressure; SNO Karst, the French Karst National Observatory Service.

Karstified carbonate formations contain 25% of the world's water resources. They cover a very large extent of the continental surface: 10% of the global continental surface, 30 to 70% of the Mediterranean area, 22% of the land in Europe, and 50% in France (Chen et al., 2017). In carbonate karst hydrosystems, the presence of fractures, conduits, and surface solution features leads to strong surface–subsurface interactions that result in significant water, mass, energy, and contaminant transport within the critical zone. Such heterogeneous systems are highly dynamic, with complex hydrologic, geochemical, and biological processes occurring across a wide range of spatiotemporal scales. As a result, they

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Citation: Jourde, H., N. Massei, N. Mazzilli, S. Binet, C. Batiot-Guilhe, D. Labat, M. Steinmann, V. Bailly-Comte, J.L. Seidel, B. Arfib, J.B. Charlier, V. Guinot, A. Jardani, M. Fournier, M. Aliouache, M. Babic, C. Bertrand, P. Brunet, J.F. Boyer, J.P. Bricquet, T. Camboulive, S.D. Carrière, H. Celle-Jeanton, K. Chalikakis, N. Chen, C. Cholet, V. Clauzon, L. Dal Soglio, C. Danquigny, C. Défargue, S. Denimal, C. Emblanch, F. Hernandez, M. Gillon, A. Gutierrez, L. Hidalgo Sanchez, M. Hery, N. Houillon, A. Johannet, J. Jouves, N. Jozja, B. Ladouche, V. Leonardi, G. Lorette, C. Loup, P. Marchand, V. de Montety, R. Muller, C. Ollivier, V. Sivelle, R. Lastennet, N. Lecoq, J.C. Maréchal, L. Perotin, J. Perrin, M.A. Petre, N. Peyraube, S. Pistre, V. Plagnes, A. Probst, J.L. Probst, R. Simler, V. Stefani, D. Valdes-Lao, S. Viseur, and X. Wang. 2018. SNO KARST: A French network of observatories for the multidisciplinary study of critical zone processes in karst watersheds and aquifers. Vadose Zone J. 17:180094. doi:10.2136/vzj2018.04.0094

usually exhibit strongly nonlinear responses to external forcing. Characterizing, modeling, remediating, and managing groundwater resources in such hydrosystems is therefore a particularly difficult task. Specific challenges arise from the lack of knowledge and technologies needed to integrate heterogeneous processes and pathways across the surface and epikarst toward the vadose and saturated zones, and to address the hydrologic and biogeochemical responses of these systems to short- and long-term climate and environmental changes. A variety of complementary approaches is needed to understand and predict the hydrological behavior of karst hydrosystems. Multidisciplinary approaches using concepts and methods from surface hydrology, hydrogeology, geochemistry, and geophysics are thus required to achieve a comprehensive characterization of the spatiotemporal variability of karst hydrosystems.

The French Karst National Observatory Service (SNO KARST) was created by the National Institute for Earth Sciences and Astronomy (Institut National des Sciences de l'Univers, INSU) of the French National Research Council (Centre National pour la Recherche Scientifique, CNRS) with the purpose of establishing an appropriate tool for the study of karst aquifers and watersheds. This is achieved through the synergy of several regional observatories all over France. The main objective is to acquire hydrological and physicochemical data by means of high frequency monitoring using common standards and procedures (data corpus, no resampling of raw data, etc.), and make them available to the international scientific community.

The various observatories of SNO KARST are located in different physiographic and climatic contexts (Fig. 1): Mediterranean, mountainous (Pyrenees, Jura), oceanic (west and northwest near the Atlantic), and continental regions. The SNO Karst network is therefore representative of a large diversity of environmental settings, allowing the development of comparative research projects.

Due to the complexity of karst hydrosystems, the assessment of their hydrogeological properties requires specific models and approaches. The emphasis is put on the modeling of hydrogeochemical fluxes within and at the outlets of karst hydrosystems and the relationships between global change and the physicochemical composition of water at the interface between the hydrologic and hydrogeologic compartments. Particular attention is paid to the data–model relationship so as to better understand the physics and chemistry of the medium and to enhance modeling capacity in reproducing variations of water and matter fluxes. Carbonate rocks that host karst systems are eminently prone to erosion and weathering, two processes that are highly dependent on the climatic, hydrologic, and meteorological regimes, but also on anthropogenic activities affecting the inputs to the karst system and/or the management of the land cover. Consequently, karst systems are more sensitive to environmental changes than most other hydrosystems.

Here we describe the structure of SNO KARST and its local observatories, the data acquired, and the research questions addressed. These concern mainly (i) the hydrological response of karst to climate variability and anthropogenic changes, (ii) the influence of karst on the geochemical mass balance of watersheds within the critical zone, and (iii) the relationships between the structure and hydrological functioning of karst aquifers and watersheds. Below, we give an overview of the various sites and their characteristics, present the main research questions addressed by SNO KARST, provide examples of recent findings achieved through the SNO KARST network, and present our conclusions and perspectives.

Catchment Properties and Monitored Parameters

The SNO KARST network encompasses nine observation sites located within various regions of France (Fig. 1a), sometimes comprising more than one unique field site. The corresponding field sites are maintained and supported by research teams from different universities and institutes (Fig. 1a).

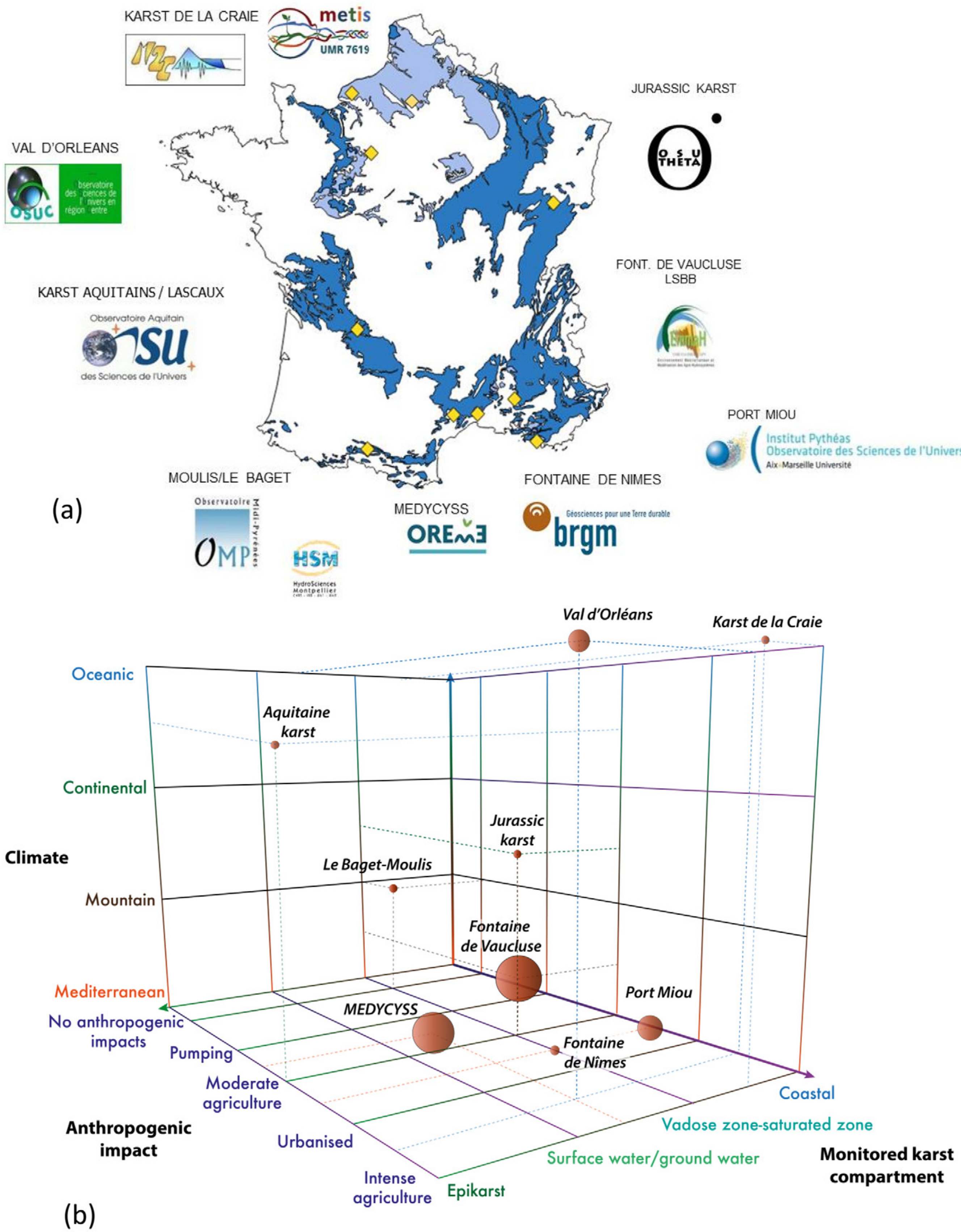

Fig. 1. (a) Location of the observatory sites that compose the French Karst National Observatory Service (SNO KARST), and name of the earth sciences and astronomy observatories (OSUs) and laboratories in charge of their monitoring. (b) Diversity of hydrogeological, hydrological, and hydrochemical settings of the various observatory sites; circle size is proportional to the catchment area (see Table 1 for more details).

These sites are located in areas with different climatic, geologic, geomorphologic, and physiographic contexts (Table 1). Such diversity brings a high added value in assessing the influence of meteorological and climatic conditions, land use, and geomorphological and geological conditions (surficial cover, lithology, tectonics, and speleogenesis) on the hydrological behavior and the transport of mass and energy in karstic aquifers and watersheds (Fig. 1b).

Not only is SNO KARST a monitoring network, but it is also a scientific community working on the development and standardization of approaches, tools, methods, and concepts based on the research developed in the individual observation sites. The SNO members develop tools for the characterization and modeling of the response of water resources to short-, medium-, and long-term forcing.

The various sites and supporting teams may develop specific research questions and, as a result, deploy specific monitoring procedures or surveys. However, a common, minimal set of parameters monitored in all sites has been defined to address research questions that require monitoring on several sites (Table 1). Two types of variables are distinguished: so-called basic variables, and site- or study-specific variables. The basic variables are sampled at all sites with a common, 15-min base frequency. They are easily measurable using multiparametric probes. The 15-min time step can be made temporarily smaller when required by specific objectives or experiments.

Site- or study-specific variables, such as geochemical measurements (major ions, trace elements, bacterial numeration, and isotopes including δ^2H, $\delta^{18}O$, $\delta^{13}C$, $^{87}Sr/^{86}Sr$, ^3H, $\delta^{15}N\text{-}NO_3^-$, and $\delta^{18}O\text{-}NO_3^-$) require more complex sampling and analytical procedures. For this reason, they are collected as a routine process for some parameters only and/or only during specific campaigns over periods defined using the basic hydrological measurements (flood, low waters) and seasonality.

Main Research Questions

A major challenge is to identify the intrinsic variability of water resources in karst hydrosystems as a response to climate variability and change. Addressing this challenge requires characterization of the role of the various internal compartments of each karst system and of the specific nonlinearity of its hydrodynamic and hydrochemical response. Long-term records of hydrological processes within various hydrological compartments are available at different observatories of the network (epikarst dynamics surveyed at some sites, covering surficial formation hydrology at other sites, etc.). Such monitoring, combined with the expertise of the SNO KARST research teams, makes it possible to characterize the role of the internal karst structure on the overall hydrodynamic behavior of the system. The diversity of the SNO KARST sites allows several research questions to be addressed. These include the characterization of karst aquifers and watersheds in terms of (i) hydrological and geochemical response to climate variability and anthropogenic pressure changes, (ii) biogeochemical functioning of the critical

Table 1. Main characteristics of the observatory sites (http://www.sokarst.org/).

Site	Location (France)	Recharge area	Climate	Karst specificity	Human impact and land cover	Continuous recording†
		km^2				
Fontaine de Vaucluse, Laboratoire Souterrain à Bas Bruit	Avignon	1115	Mediterranean, mountainous	thick unsaturated zone, deep karst network below the current base level	natural + agricultural land cover	*Q*, *H*, *P*, CE, *T*, Turb, Fluo
MEDYCYSS, Lez	Montpellier	>1000	Mediterranean	high karst–river interactions, multilayer karst system	high pumping rate for water supply (1.1 $m^3 s^{-1}$)	*Q*, *H*, *P*, EC, Cl^-, *T*, Turb, Fluo
Val d'Orléans	Orléans	284	continental	sinking stream in covered karst	urban + agricultural	*Q*, *H*, *P*, EC, *T*, Fluo
Le Baget, Moulis	Saint-Girons (Pyreneans)	13	mountainous	sinking stream	natural	*Q*, *H*, *P*, EC, *T*, Fluo
Karst de la Craie	Rouen, St Martin le Noeud	10	oceanic	sinking stream	natural + agricultural land cover	*Q*, *H*, *P*, EC, *T*, Fluo
Jurassic karst	Besançon	3 sites, 30–40 km^2 each	continental, mountainous	sinking stream, diffuse infiltration	natural + agricultural land cover	*Q*, *H*, *P*, EC, *T*, Turb, NO_3^-, DOC, TOC, Fluo
Fontaine de Nimes	Nimes	55	Mediterranean	flash flood	high anthropogenic pressure (urban area)	*Q*, *H*, *P*, EC, *T*, Fluo
Port-Miou Provence	Marseille	400	Mediterranean	coastal, deep karst network below the current base level, multilayer karst system	natural + agricultural + industrial land cover	*Q*, *H*, *P*, EC, *T*, Turb, Fluo
Karst Aquitains Lascaux Cave, Toulon Springs	Bordeaux	<1, 100	continental, oceanic	measurements in epikarst, multilayer karst system	natural + agricultural land cover	*Q*, *H*, *P*, CE, *T*, Turb, Fluo, pH, NO_3^-, DOC, TOC, DO

† *Q*, discharge; *H*, water level; *P*, rainfall; CE, electric conductivity; *T*, temperature; Turb, turbidity; Fluo, fluorescence; DOC, dissolved organic C; TOC, total organic C; DO, dissolved O_2.

zone and vulnerability of the groundwater resource, and (iii) karst geometry and its influence on hydrological functioning.

Hydrological and Geochemical Response of Karst Watersheds to Climate Variability and Anthropogenic Changes

The strong heterogeneity of karst systems makes their hydrological response and the spatiotemporal evolution of their physicochemical characteristics particularly sensitive to local and/or large-scale environmental changes (Labat et al., 2000, 2001; Massei et al., 2006; Slimani et al., 2009; Valdes et al., 2007; Charlier et al., 2015a). Such changes may stem from both anthropogenic and climatic variations, and they occur either gradually (low-frequency interannual to multidecadal oscillation and/or trends) or abruptly (e.g., step change, in the case of threshold exceedance). Studying long-term hydrological variability is needed to characterize hydrodynamic and physicochemical responses across a wide range of hydroclimatic conditions and filter out exceptional events and changes in boundary conditions (Duran et al., 2016), but also to land cover evolution and anthropogenic activity influences.

Owing to the high solubility of calcite, carbonate weathering contributes to 45 to 60% of the global river dissolved load to oceans (Meybeck, 1987; Gaillardet et al., 1999; Amiotte Suchet et al., 2003; Ford and Williams, 2007; Berner and Berner, 2012; Calmels et al., 2014). It has been argued that CO_2 consumption by carbonate weathering on the continents is fully balanced by CO_2 release during calcite bioprecipitation in the oceans (Berner, 1992). However, this is probably true only for time periods longer than the residence time of HCO_3^- in the oceans (~10^5 yr). During shorter time periods, carbonate weathering is expected to play an important role in the global C balance (Amiotte Suchet et al., 2003; Calmels et al., 2014; Gaillardet and Calmels, 2012). During carbonate weathering, CO_2 from the atmosphere and soil is consumed and exported to the oceans in the form of dissolved inorganic C (mainly HCO_3^-). Carbon dioxide uptake that occurs at the interface between the organic and inorganic C cycles is sensitive to global warming, soil cover, and agricultural practices. It also drives the concentration of CO_2 in caves (Peyraube et al., 2012, Houillon et al., 2017), a key factor in the conservation of parietal paintings.

Long-term trends in water chemistry have been observed for various karst systems (Raymond et al., 2008; Jeannin et al., 2016; Lorette et al., 2016). Within the SNO KARST sites, such trends are identified for the Le Baget site and the Jura Mountains (Mudry et al., 2015; Charlier et al., 2016). With water mineralization being dominated by HCO_3^- concentration in carbonate aquifers, the long-term variations in electrical conductivity in springs and rivers in karstic catchments give an interesting overview of their geochemical response to global change (Charlier et al., 2016). This is illustrated by Fig. 2, which shows the variations in electrical conductivity during almost 40 yr in the Jura Mountains. Springs (red curves) and rivers (blue curves) are classified according to the mean altitude of their recharge area (darker colors for lower elevations). Analyzing the effect of recharge area elevation indicates that the higher the altitude of the recharge area, the higher the mineralization level. However, the time series shows no monotonic trends, but large-scale oscillations associated with high infra-annual variations due to recharge events.

Overall, these large-temporal-scale evolutions are similar for all monitoring points. This indicates that the response of the carbonate aquifers is not site dependent and that the dissolution rate of carbonates varies over long timescales. An increasing phase is observed from 1980 to 2000 that stabilizes afterward. This behavior may be attributed to various anthropogenic processes, but the individual contributions are difficult to identify. Alternatively, it might be explained by the feedback of global warming or by acid contamination originating from atmospheric and/or agricultural inputs (Probst et al., 1990; Amiotte Suchet et al., 1995; Perrin et al., 2008). Identifying

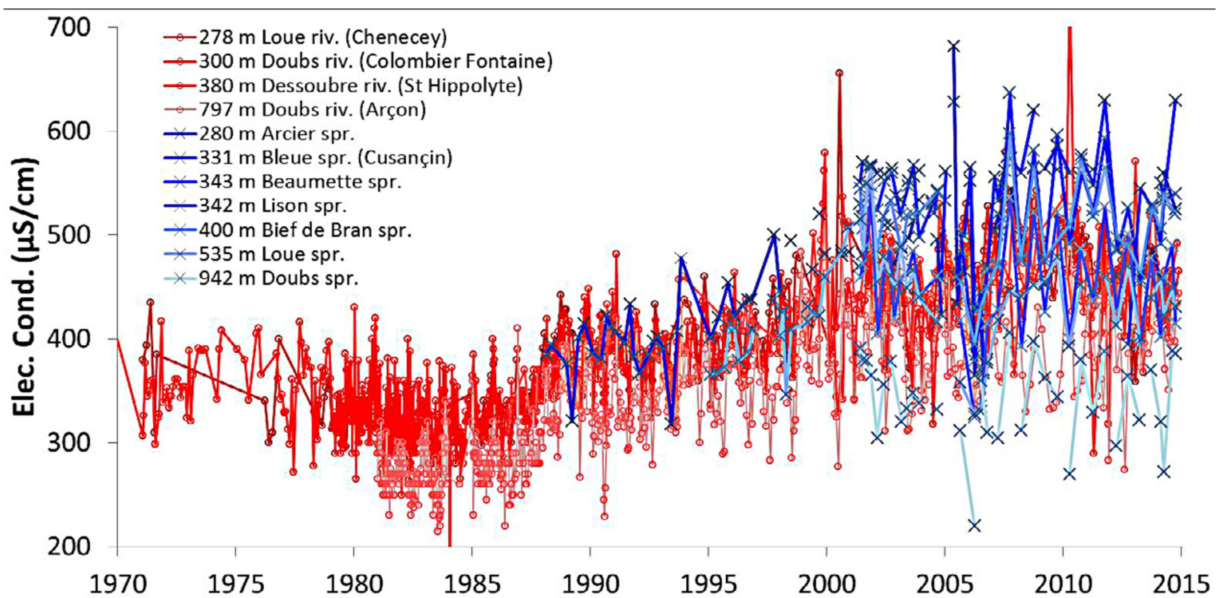

Fig. 2. Evolution of electrical conductivity (elec. cond.) in springs (spr.) and rivers (riv.) in the Jura Mountains (Charlier et al., 2016).

and quantifying the impact of the various anthropogenic processes on CO_2 partial pressure in soil and on carbonate weathering is still a pending issue. Isolating the respective contributions of these processes will allow for a reinterpretation of hydrochemical databases in terms of acid atmospheric pollution load and global warming impact on carbonate and surface water buffering response.

Biogeochemical Functioning of the Critical Zone and Vulnerability of the Groundwater Resources in Karst Aquifers and Watersheds

Research fostered within SNO KARST addresses the following points:

- The hydrological balance and event dynamics of watersheds with a strong karstic component. In particular, what is the role played by the karst compartment in sustaining low water levels, allowing for flood mitigation or triggering flood amplification (Jourde et al., 2007, 2014; Bailly-Comte et al., 2008; 2009; Maréchal et al., 2008; Charlier et al., 2015b)? Should the presence of karst be taken into account in stochastic approaches for the predetermination of hydrological extremes?
- The influence of karst on the mass balance of transported elements on the continental surface: mineral and organic C cycle (Batiot et al., 2003; Binet et al., 2006; Blondel et al., 2010; Quiers et al., 2014), transfer, storage, and release of suspended sediments (Massei et al., 2006; Valdes et al., 2006; Fournier et al., 2009), and the respective contributions of mechanical and chemical erosion.

Specific attention is paid to the influence of karst on chemical and microbial fluxes during recharge events (Caetano Bicalho et al., 2012; Charlier et al., 2012; Hery et al., 2016; Cholet, 2017), because such events regulate major geochemical cycles (such as the C cycle) and the propagation of chemical and microbial pollution in karst aquifers (Laroche et al., 2010; Khaldi et al., 2011; Fournier et al., 2017).

The development of recent tracers such as rare earth elements (Cholet et al., 2018), or radon and radium isotopes (Molina-Porras et al., 2017), as well as $^{88}Sr/^{86}Sr$ to identify the origin of water, is a new possible way to identify flow paths with various residence time conditions in such heterogeneous systems, which is essential for better assessment and management of groundwater. The interactions between surface water and groundwater make karst systems subterranean hyporheic zones, where mixing between circumneutral to slightly acidic and well oxygenated surface waters with buffered groundwater create highly reactive zones, with possible impacts on river chemistry.

Karst Geometry and Its Implication on Hydrological Functioning

Understanding the physical structure of karst systems (the location and geometry of conduit networks and their interactions with the surrounding fractured medium) is a difficult task. This is a major obstacle to building appropriate geological models that are necessary to flow, mass transport, and water–rock interaction modeling. In addition, karst systems are generally spatially poorly characterized and only monitored at their outlets. As a result, karst catchments are mostly analyzed and modeled using conceptual approaches designed to understand, interpret, and reproduce the variability of flow rates and/or water level at karst outlets (Tritz et al., 2011; Ladouche et al., 2014; Guinot et al., 2015; Arfib and Charlier, 2016; Baudement et al., 2017; Mazzilli et al., 2017). Such approaches remain a widespread and relevant means of characterizing the hydrological functioning of karst systems. However, supplementation with process-based modeling of flow and transport when spatialized information is available offers challenging but promising perspectives. The research effort in terms of monitoring the karst structure and geometry focuses on

- Improving the quantification of geometric indicators within the various compartments (soil, epikarst, vadose zone, and saturated zone) and providing insights into the physical processes at stake within the subsystems via hydrodynamic and hydrochemical monitoring (Barhoum et al., 2014; Binet et al., 2017; Cholet et al., 2017).
- Conducting geophysical investigations to improve the characterization of the structure and flows on the sites and proposing methodological developments in geophysical imagery.
- Studying speleogenesis, geometric, and topologic parameters of three-dimensional karst networks (Fig. 3) to improve karst network modeling (Fournillon et al., 2012; Collon et al., 2017; Jouves et al., 2017) for karst hydrological behavior understanding, but also as input for flow models.
- Exploring the links between systemic and physically based approaches to improve the understanding and the modeling of karst hydrosystems, including improvement of the efficiency of conceptual modeling (alternatives necessary to distributed modeling), and improvement of the interpreting capabilities of time series analysis and signal processing approaches (physical meaning of the components and statistical properties of the hydrological signal).

New Findings and Achievements

The KarstMod Modular Modeling Platform

Proposing a systematic and generic approach to karst hydrodynamic modeling was identified as a major challenge by SNO KARST. This generic assignment may be compared with what is being built at the mesoscale for the three-dimensional surface underground integration of fluid dynamics and matter fluxes in drainage basins (Rousset et al., 2004). In the specific case of karst, the lack of knowledge on flow geometry and channelization precludes the use of distributed models. For this reason, it seems advisable that the rainfall–discharge relationship of karst systems be understood in a compartment-based form. The diversity of the SNO KARST sites makes it possible to provide information on the functioning of the various internal compartments of karst systems. Such information allows improving the parameterization of either conceptual or physics-based models. Intercomparison of the extremely diverse sites of SNO KARST was thus used for testing the relevance of

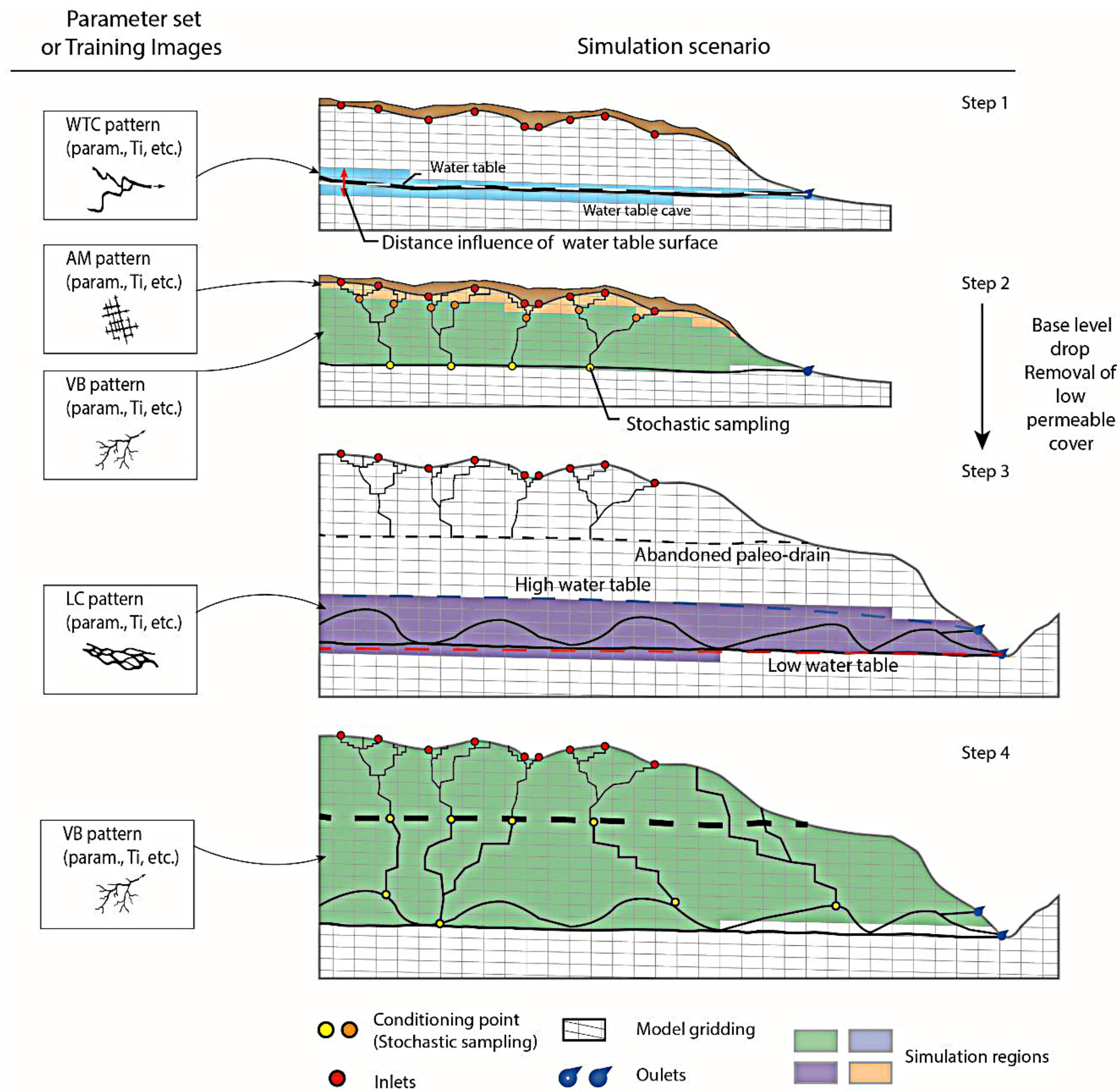

Fig. 3. Conceptual cross-section of a carbonate massif with karst generation in four steps (polygenic karst network). For each step, a karst pattern (deducted from field geomorphological observation) is associated and can be simulated as three-dimensional karst network using geometric and topologic parameters or training images. Water table cave (WTC), angular maze (AM), vadose branchwork (VB), and looping cave (LC) patterns refer to Jouves et al. (2017) classification. Modified from Jouves (2018).

non-site-specific generic models. This has led to the development of the global conceptual, modular modeling KarstMod platform (Mazzilli et al., 2017) that allows for simulating, predicting and interpreting karst hydrological functioning. This platform incorporates a variety of transfer functions (Tritz et al., 2011; Guinot et al., 2015) that were developed specifically for the modeling of karst catchments. Such functions are not found in classical conceptual modeling platforms. KarstMod has been successfully applied to the SNO KARST network but also to other watersheds (Guinot et al., 2015; Kazakis et al., 2018; Poulain et al., 2018). KarstMod provides a user-friendly tool to implement rainfall–discharge modeling and can be widely applied for water resources management. It facilitates the systematic use of quantitative simulation in the water management process. For example, the well-known and very common baseflow and quickflow hydrograph separation can be performed automatically over the whole time series (Baudement et al., 2017). Calibrated recession coefficients governing the proportion of baseflow and quickflow can then be conceptually related with the karst network connectivity inferred from geomorphologic and geologic observation. Conceptual modeling should then be seen as complementary to the more classical time series analysis and speleogenesis-derived information.

KarstMod has been developed to offer an up-to-date tool for (i) model calibration (single or multiobjective calibration approach, quasi Monte-Carlo procedure), (ii) simulation analysis (cumulative probability plots, correlograms, and spectral analysis), (iii) sensitivity and equifinality analysis (mapping the objective function in the parameter space, sensitivity indices). Figure 4 shows sample simulation results with their confidence interval, as generated from the KarstMod user interface.

Hydrological Response of Karst Catchments to Large-Scale Atmospheric Circulation Patterns

Karst watersheds can display a strongly nonlinear response to meteorological inputs. This is because the interactions between the internal watershed compartments change with the amplitude of climatic variations. To assess the sensitivity of karst systems to climate variability and changes, the relationships between karst hydrological variations and large-scale climate variability was studied using the SNO KARST database. The climatic determinism of long-term interannual (hereafter referred to as low-frequency) karst hydrological variations was investigated. Three sites were used: the Radicatel Chalk karst observatory in Northern France, the Lez/MEDYCYSS observatory in Southern France, and the Moulis/Le Baget observatory in the Pyrenees. The climatic conditions are thus highly contrasted.

The approach was based on that proposed by Massei et al. (2017). First, the hydrological time series were decomposed as the superposition of large-scale climate field time series and a local field using wavelet multiresolution analysis. Second, the correlations between large-scale and local-scale components were assessed by generating composite maps for the various wavelet scales. The large-scale variable was the sea level pressure (SLP) field time series across the North Atlantic area obtained from reanalysis products (NOAA 20th century or ERA Interim reanalyses). It was selected because it represents a good proxy for atmospheric circulation that has a major influence on precipitation variability. Different site-dependent, local-scale variables were defined: precipitation, flow, or water level time series. Since the focus was put on long-term variability, the series were aggregated on a monthly time step. Wavelet multiresolution analysis allowed low-frequency components to be identified in the hydrological signal (Fig. 5). For instance, low-frequency oscillations with periods of 6 yr were detected at the three sites. The fraction of variance explained by such oscillations was found to be site dependent. In the Chalk karst, the high-amplitude of the low-frequency components is attributed to the regional dynamics of the large porous or fractured chalk aquifer (El Janyani et al., 2012).

The results show that the local-scale, low-frequency spring flow and water level variations are systematically related to a rather well-defined SLP pattern for each component of the hydrological signal (Fig. 6). It is worth noting that similar low-frequency components and corresponding spatial SLP patterns as spring flow or water level were obtained for precipitation (not shown) at all sites. This confirms that the oscillations in the flow and/or water levels originate from the climate input and are not due to site-dependent physical characteristics or human-driven changes in the hydrosystems. The Mediterranean Lez system composite maps (Fig. 6d–6f) clearly show dipole-like SLP patterns reminiscent of the North Atlantic Oscillation (NAO) climate regime (Hurrell and Deser, 2009). This result was expected in that the Lez site is located in a region where the effect of the NAO on hydrological conditions is well contrasted. This is not the case for the Radicatel site (Fig. 6g–6i), which is located in a transition zone regarding the expected impact of NAO across Western Europe. Although it is located in Southern France as the Lez site, the Le Baget system clearly behaves differently, except for the 2-yr oscillatory component (Fig. 6a–6c). This is attributed to Le Baget's specific mountainous location. These results show that low-frequency climate forcing is filtered in a similar fashion regardless of site location.

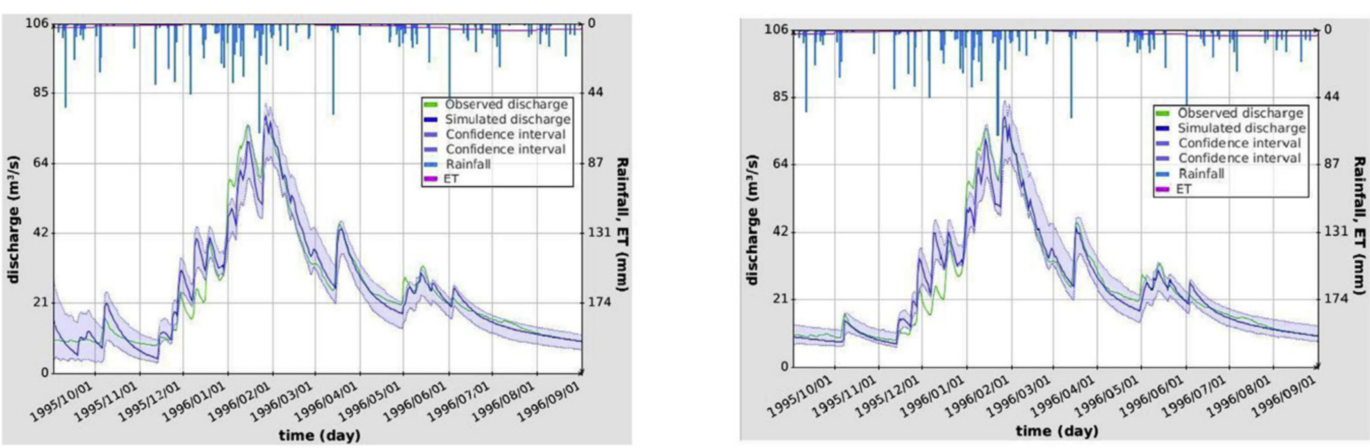

Fig. 4. KarstMod provides a variety of tools for simulation analysis and equifinality assessment. Here, simulation results are provided together with their confidence interval for the behavioral parameter set (Nash Sutcliffe efficiency > 0.9) during the calibration stage: (left) no warmup period, (right) a 1-yr warmup (per Mazzilli et al., 2017). ET stands for evapotranspiration.

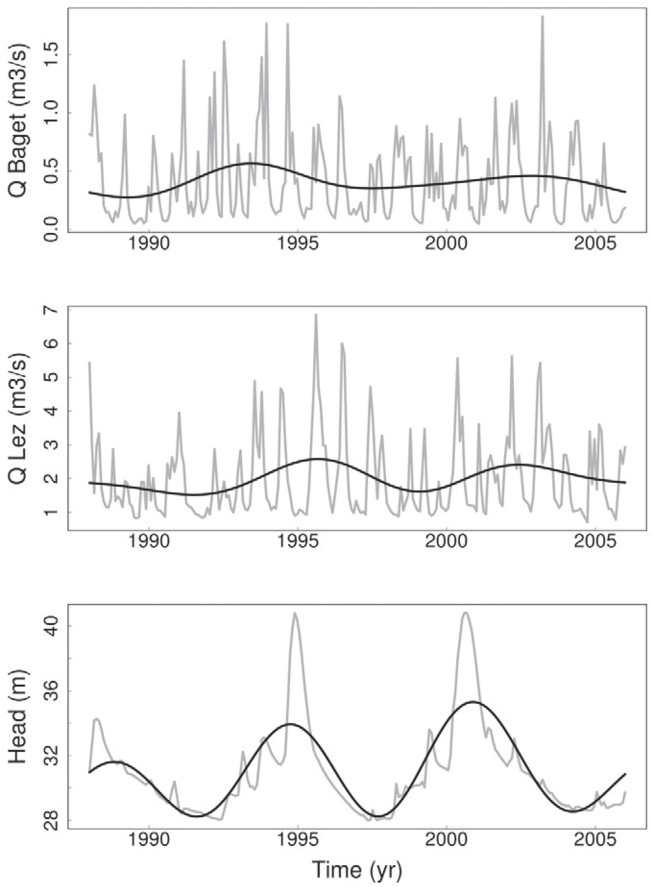

Fig. 5. Monthly aggregated time series of spring discharge (Q) at Le Baget and Lez sites, and hydraulic head at the outlet of the Radicatel site. Blue lines are the wavelet details obtained from multiresolution analysis corresponding to interannual low-frequency components within each time series.

The variability of such climate drivers has a clear impact on the dynamics of the karst system. For instance, high-turbidity events (that are typical of karst-conduit drainage) recorded at the Radicatel site are obviously associated with a ∼6-yr interannual oscillation (Chedeville et al., 2016). They occur mostly during rising water level over time periods of ∼3 yr, as shown in Fig. 7.

This emphasizes the crucial role played by low-frequency large-scale atmospheric dynamics on karst response in a regional aquifer. At the Lez site, precipitation–streamflow modeling using the KarstMod modeling platform (Mazzilli et al., 2017) allowed the matrix–conduit network exchange flow rates to be assessed. The same ∼6-yr oscillating component, corresponding to the NAO-like large-scale pattern of Fig. 6f, was found to explain ∼30% of the total variance in the annual matrix drainage (Fig. 8). This oscillatory component thus exerts a strong large-scale atmospheric control on the drainage flow from the matrix to the conduit network.

These results help to improve the understanding of the relationships between atmospheric circulation patterns and hydrological variations at multiple timescales. They are an essential prerequisite to the understanding and, ultimately, simulating and predicting the impact of future climate variations on the hydrodynamics of karst aquifers and watersheds.

New Tools for Assessment of the Functioning and Vulnerability of the Karst Aquifers

New Approaches in Natural Tracing

Long-term natural fluorescence monitoring has been active at the Lez spring (MEDYCYSS observatory) since 2010 and at the Fontaine de Nîmes spring since 2012. This monitoring contributes to a better understanding of the dynamics of fast infiltration fluxes that carry suspended materials and dissolved organic matter. These fluxes can be identified from the wavelength of the scattered light due to suspended materials and fluorescence of natural organic fluorophores. Among these fluorophores, humic-like compounds naturally originate from soil leachates (Batiot-Guilhe et al., 2008; Blondel et al., 2010). Proteic-like compounds stem from fresh organic matter or microbial production that may come from organic effluents (Lapworth et al., 2009; Mudarra et al., 2011). For the Lez karst system, distinguishing between humic- and proteic-like compounds is important in that the proteic-like peak has been shown to be related to fast infiltration waters that carry bacterial contamination pulses (Durepaire et al., 2014; Quiers et al., 2014; Erostate et al., 2016).

Our approach is based on the combination of (i) natural organic matter (NOM) characterization using a laboratory spectrofluorometer and (ii) long-term monitoring at a 15-min time step and a lower spectral resolution using a multispectral field fluorometer. Figure 9 shows the domain of Ex/Em (excitation/emission) matrices that can be analyzed by the fluorometer according to the optics systems: turbidity (Rayleigh diffusion spectrum), rhodamine, uranine, amino G acid, or “proteic” optics system. The latter is a customized optics system specifically designed for the monitoring of proteic compounds. The Ex/Em matrix (Fig. 9) shows the fluorescence intensity for a given excitation and emission wavelength, with NOM compounds ranging from the mid ultraviolet (250 nm) to indigo light (450 nm).

The methodology was applied to the Lez and Fontaine de Nîmes sites. It was used at the Lez Spring to better understand the dynamics of bacterial contamination (Erostate et al., 2016). It is to be applied to other sites of the SNO network where long-term fluorescent time series are available. Since anthropogenic inputs may modify the dynamics and spectrum of the natural fluorescent organic matter, this will allow the sensitivity of this approach to other climate and anthropogenic inputs to be assessed.

Understanding the origin and dynamics of natural fluorescence provides important information when conducting a fluorescent tracer test because natural fluorescence can be interpreted as a tracer recovery. It may also disturb the quantification of the tracer recovery. Accordingly, a new method of tracer test correction called multioptics correction has been developed for a multispectral field fluorometer (Bailly-Comte et al., 2018). It has been successfully applied to the Lez and Fontaine de Nîmes karst systems to address the following questions in terms of (i) detection and (ii)

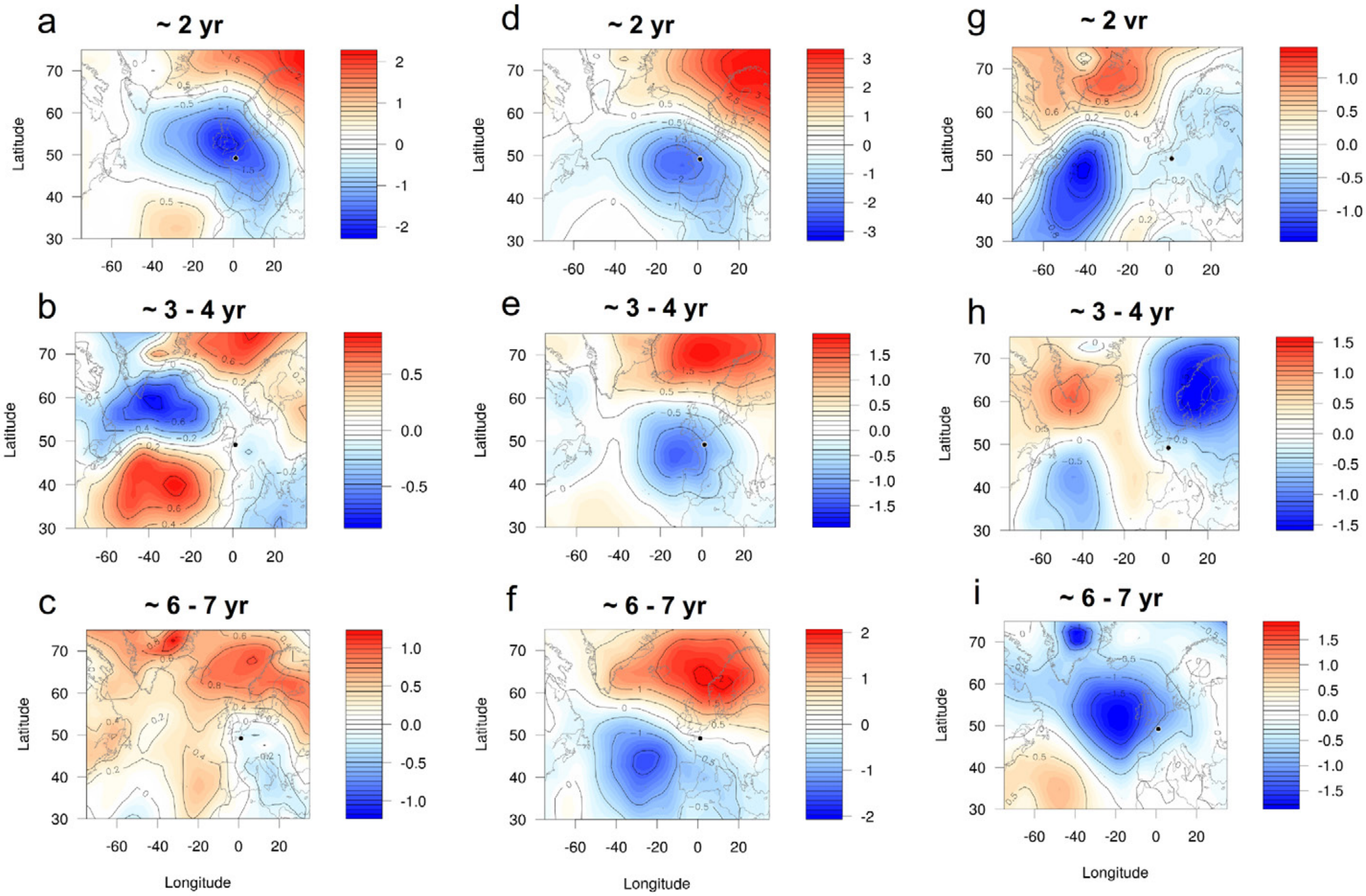

Fig. 6. Sea level pressure (SLP) composite maps based on ~2-, ~ 3- to 4-, and ~6- to 7-yr low-frequency components of spring flow (or water level) at karst outlets: (a, b, and c) Le Baget site, (d, e, and f) Lez site, (g, h, and i) Radicatel site. Blue and red shaded areas highlight the zones of below-average and above-average SLP, respectively, when spring flow or water level is high.

quantification: (i) is the tracer really present in the water, and (ii) to what extent does natural fluorescence influence the measurements?

The results show that fluorescent tracer tests can yield accurate measurements, even in areas of high natural fluorescence and high turbidity. This greatly improves artificial tracing results during flood events in the presence of highly variable NOM and suspended matter.

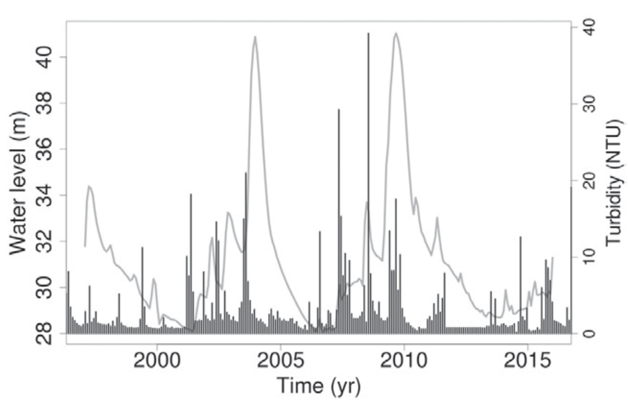

Fig. 7. Daily turbidity (in nephelometric turbidity units [NTU]) and water level at Radicatel site between 1997 and 2017. The highest amplitude turbid events occur during interannual rising water level within the karst system, showing a clear interannual atmospheric-driven control of karst response.

Development of a Plugin for the PaPRIKa Vulnerability Assessment Methodology Implementation in QGIS

Multi-criteria methods are indispensable to intrinsic vulnerability assessment in karst. The standardized European method

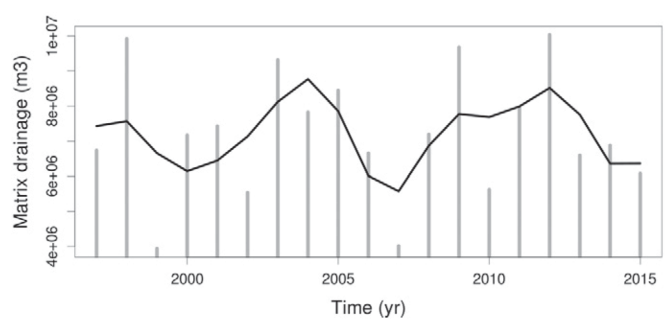

Fig. 8. Annual volume of simulated matrix drainage to conduit network (vertical gray bars) at the Lez site and its low-frequency ~6-yr oscillatory component (solid black line) extracted by wavelet multiresolution decomposition.

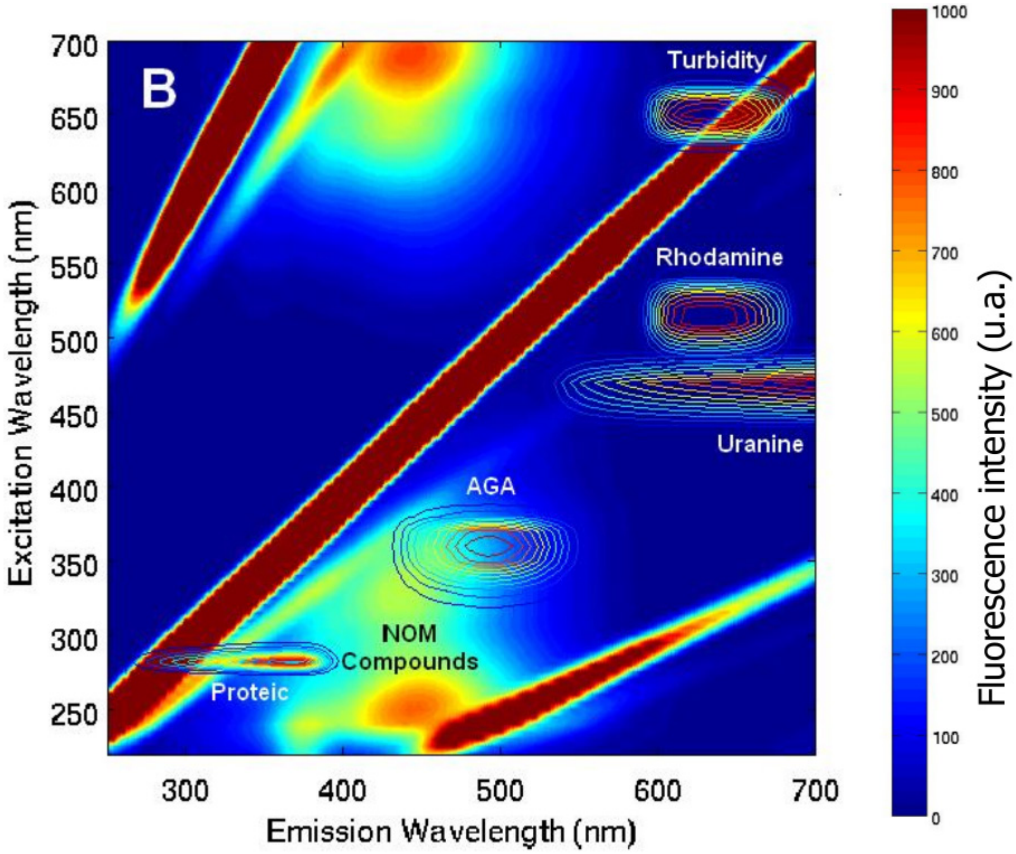

Fig. 9. Normalized spectral responses of the five optics system of the GGUN multispectral fluorometer plotted on an excitation/emission matrix obtained at the Lez Spring on 21 Sept. 2015 (Bailly-Comte et al., 2018). NOM refers to natural organic matter and AGA to amino G acid.

for multi-criteria vulnerability assessment is called PaPRIKa (Dörfliger and Plagnes, 2009). This is the acronym of Protection of aquifers from the assessment of four criteria: P for protection (considering the most protective aspects among parameters related to soil cover, unsaturated zone, and epikarst behavior), R for rock type, I for infiltration and Ka for karstification degree (Kavouri et al., 2011).

In the framework of SNO KARST, a QGIS plugin was developed for a standardized PaPRIKa implementation under QGIS. The toolbox provides a clear workflow allowing a consistent vulnerability map to be produced in an open-source environment. The PaPRIKa plugin for QGIS was used for pollution risk assessment in the karst aquifer of Damasi-Titanos in Thessaly, Central Greece. (Kazakis et al., 2018).

Flow and Transport Properties with Respect to Karst Geometry

Development of New Transfer Function Approaches

A new tracer breakthrough interpretation in karst systems has been developed. It borrows from the modeling concepts in chemical engineering and control process (Labat and Mangin, 2015). Chemical reactors are modeled as a cascade of ideally mixed reservoirs connected by pipes. The tracer (and then mass transfer) is assumed to follow the movement of water through a series of reservoirs. A transfer function approach is applied to reconstruct artificial tracer tests in the karstic system. The seven-parameter transfer function is based on the assumption of a rapid flow component and a slow flow component acting simultaneously. The rapid component corresponds roughly to the flow processes in the drainage network and the highly transmissive fracture network. The slow component roughly corresponds to the delayed response in relationship to flow process in less transmissive fractured or fissured zones. Model calibration is deemed to provide semiquantitative information about the respective contributions of quick-flow components and slow-flow transfer processes. Quantifying the two pathways is of salient importance with respect to contaminant dispersion since a predominating rapid flow generally implies limited attenuation of the pollutant concentration. Conversely, predominating slow flows induce pollutant dilution and the subsequent decrease in the peak pollutant concentration at the outlet. The quick component corresponds roughly to flow processes in the drainage network and the highly transmissive fracture network, whereas the slow component roughly corresponds to the delayed response in relationship with flow process in less transmissive fractured or fissured zone.

These functions are applied to several tracer tests experiments at Le Baget. This basin located in the Pyreneans Mountains (Ariège, France) is characterized by a median altitude ~940 m and a recharge area of ~13 km^2. The specific runoff is 36 L s^{-1} km^{-2} with a mean daily runoff about 450 L s^{-1}. The injections and recovery site are located on the downstream part of the aquifer (Fig. 10). In this zone, the system is characterized by the presence of sinkholes and temporary and permanent springs on a spatially restrained area of ~2 km^2.

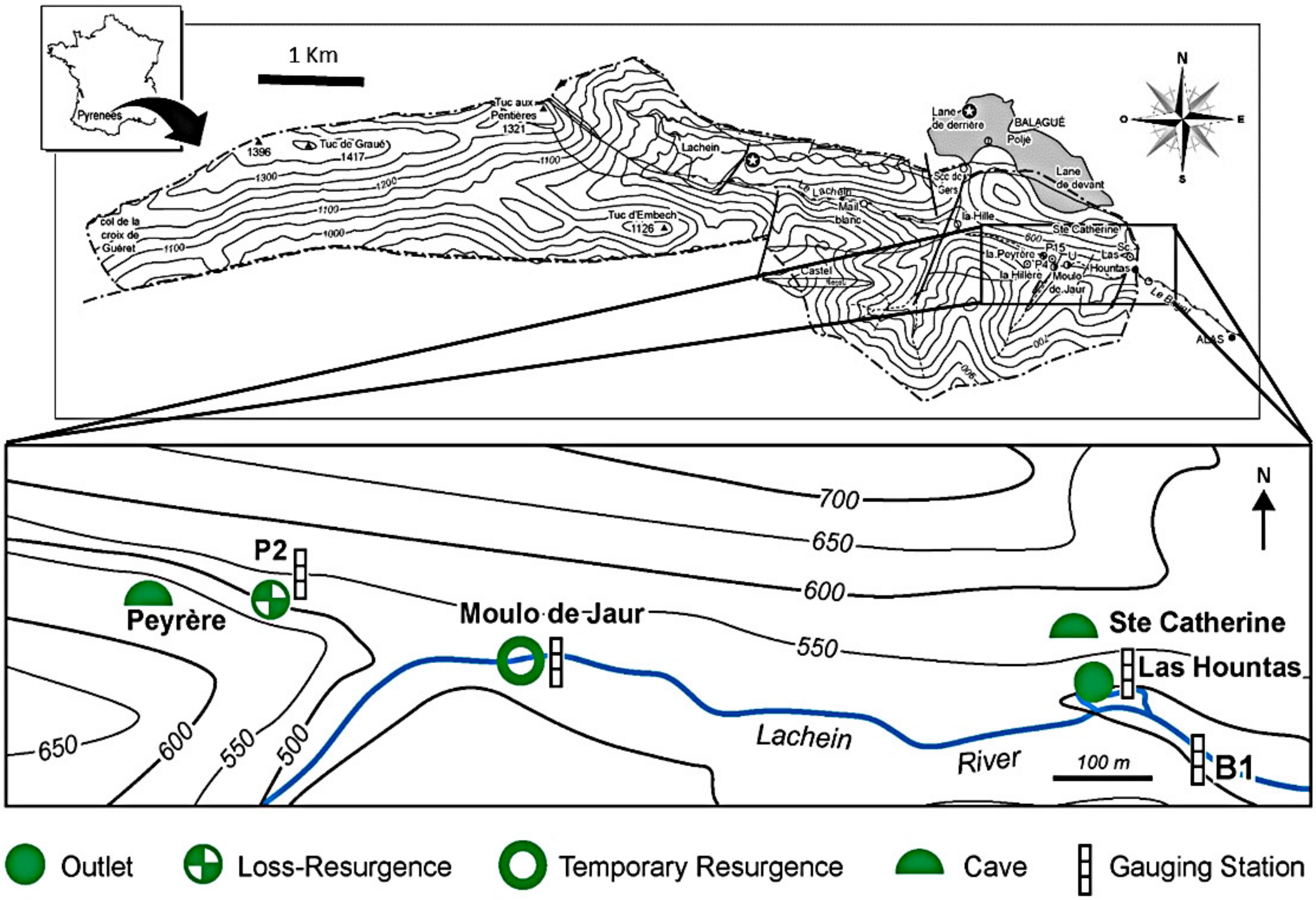

Fig. 10. Localization of the Baget karstic system and description of the watershed, in which limits are represented by the dashed line. The inlet and outlet tracer injection and recovery are located in the upstream part of the basin (black rectangle).

Figure 11 shows the experimental and simulated residence time distribution results of two tracer tests based on fluorescein injection. Periods without rainfall were selected so that the variations of the spring outflow were minimal during the tracer test. The advective and diffusive components of the model transfer function are also plotted. The recovery of tracer tests between P2 loss and Las Hountas (Tracer Test 1) and between Peyrere and Las Hountas (Tracer Test 2) (Fig. 10) allowed possible discrepancies between low and medium water levels to be identified for a given inlet–outlet system. When the water levels increase, the contribution of the advective component to the integral of the simulated RTD is 30 and 55% for Tracer Tests 1 and 2, respectively.

Small- to Mesoscale Hydrodynamic Processes

Inverse modeling appears as one of the most efficient ways of characterizing the complex connectivity and architecture of heterogeneous systems. So far, several inverse methods have been proposed for the assessment of flow properties heterogeneity in karst. They have been tested at the Terrieu experimental site (MEDYCYSS) within SNO KARST. The field site is located in the Lez karst basin ∼20 km north of Montpellier, Southern France. The carbonate rocks consist mainly of Jurassic to Cretaceous limestones. A well-developed karstic conduit network is found at the interface between the rock units (Jazayeri Noushabadi et al., 2011). Twenty-two boreholes are drilled within a 30-m × 50-m area (Fig. 12), thus allowing for high-resolution hydraulic tomography operations.

A quasi-Newton inverse method was first applied to test the capability of tomographic pumping test data to identify the structure of hydraulic connectivity in karst aquifers (Wang et al., 2016). Although the inverted transmissivity field is highly dependent on a priori information provided on the inversions, the approach allows the connectivity between the major karst conduits to be identified correctly.

To address the issue of uniqueness of inversion solutions and quantify the uncertainty in the inversed transmissivity fields, a stochastic Newton inverse method was proposed and applied to the same field dataset (Wang et al., 2017). An important finding is that the success of inverse modeling in karst systems strongly depends on whether the connectivity between the boreholes used in the tomographic hydraulic tests is preserved in the a priori model. In addition, the number and locations of observation boreholes with respect to the karst network control the resolution

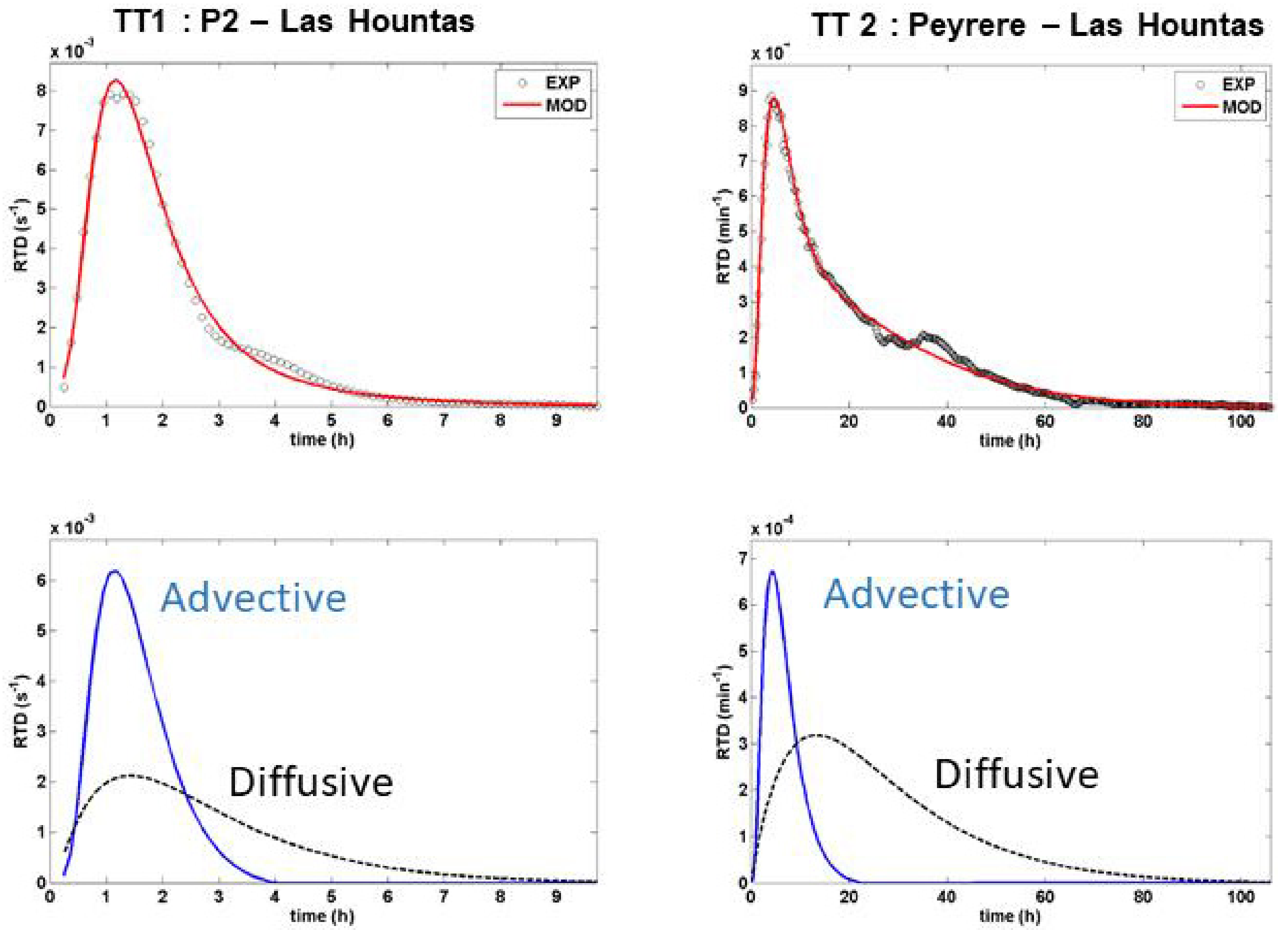

Fig. 11. Deconvolution of the simulated residence time distribution (RTD) curve between advective and diffusive flow components. TT1 and TT2 refer to Tracer Tests 1 and 2, respectively.

of the tomograms. The issue of the complex spatial organization of karst conduits was addressed by proposing an inverse method based on the parameterization of discrete features (Fischer et al., 2017). This method, called cellular automata-based deterministic inversion (CADI), distributes the hydraulic properties along linear structures and iteratively modifies the structural geometry of this conduit network to minimize the difference between the observed and modeled hydraulic data. This results in transmissivity fields generated by a discrete conduit network embedded within the background matrix. The method allows the hierarchical flow behavior observed in karst systems to be accounted for. Using the Terrieu dataset, the CADI method generates a variety of possible karst networks, the geometrical characteristics of which are in a close agreement with those derived from previous inversions and direct field observations.

Further research focuses on better identifying cross-borehole connectivity and representing the spatial arrangement of karst conduit networks. A harmonic pumping technique was applied. Numerical harmonic pumping tests with various pumping locations, amplitudes, and frequencies were first simulated in a synthetic hierarchical network formed by interconnected fractures and karst conduits embedded in a background matrix (Fischer et al., 2018). A sensitivity analysis showed that the phase offset of the monitored responses in observation wells allows the degree of connectivity between source and measurement points to be identified. The amplitude of the response provides information about the conductivity of the major flow conduits (Fig. 13). High frequency pumping tends to identify boreholes directly connected to the pumping points through connections provided by karst conduits. Low-frequency pumping tends to identify boreholes with dual connectivity (part of propagation occurring in the networks, part in the matrix) to the pumping point. Harmonic pumping tests using a wide range of frequencies is thus helpful in mapping the hierarchical arrangement of flow features of various types (i.e., karst conduit, fracture, and matrix). The method was applied to the Terrieu site to infer the spatial distribution of the main karst channels (Fig. 13). The results were consistent with those derived from an integrated analysis of geology, borehole logging, and tomographic hydraulic tests. However, they were obtained at a much lower cost. Only 30 min was needed to perform the harmonic test. The approach was coupled to the newly developed CADI method and applied to the Terrieu data. Compared to tomographic inversions using constant pumping rates, the harmonic pumping approach requires at least two times as few tests. Besides, these tests are at least 10 times as short as constant rate tests. The resolution of the so obtained tomograms is similar to that of constant rate tests. The harmonic approach can thus be expected to enhance the interpretation of karst system features.

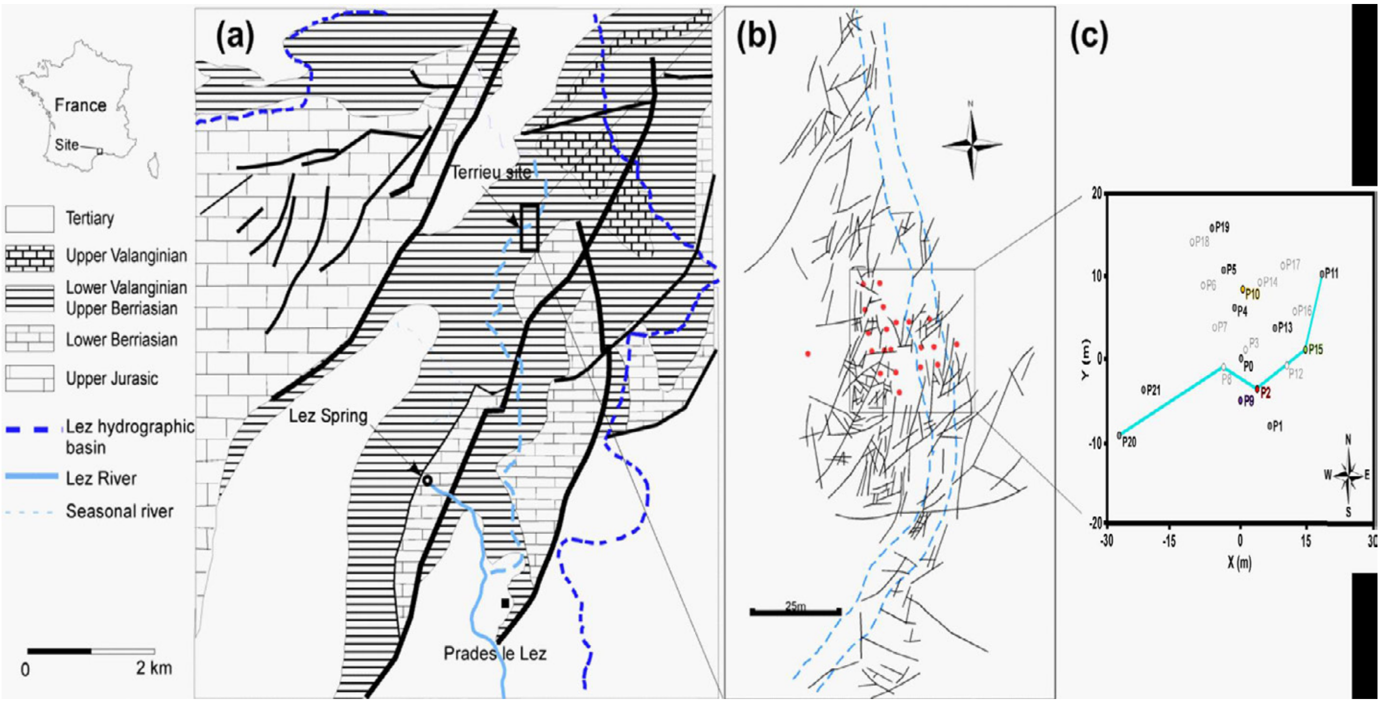

Fig. 12. (a) The Lez spring and the fractured karstic aquifer referred to as the Lez aquifer (MEDYCYSS Observatory), (b) an aerial fracture map of the Terrieu experimental field site (local scale), and (c) borehole locations on the Terrieu site. The colors for P2, P9, P10, and P15 refer to the colors used to designate these boreholes in Fig. 13. The blue line indicates conduit connectivity assessed from previous investigations (Wang et al., 2016). The boreholes in light gray were not measured during the harmonic pumping test (modified from Jazayeri Noushabadi et al., 2011).

Conclusion

SNO KARST is a national network of observatories created in 2014 by the National Institute for Earth Sciences and Astronomy (INSU) of the French National Research Council (CNRS). This network belongs to the national distributed research infrastructure OZCAR (Critical Zone Observatories: Research and Application) that associates most of the French observation sites dedicated to the observation and monitoring of the critical zone and actively contributes to a pan-European infrastructure integrating Long-Term Ecosystem Research (LTER) and Critical Zone and socio-ecological research observatories.

The SNO KARST network gathers the main monitored karst sites in Metropolitan France where long-term measurements are available. Its purpose is to make data, experimental sites, and methods available to the scientific community, and to develop a networking expertise in karst monitoring and modeling. The various sites are well-suited to specific field experiments (i.e., small, well-constrained sites with known major point-source recharge and outlets, heavily instrumented karst and fractured sites comprising several boreholes, sites with preferential access to intensively monitor vadose and epikarstic zones, etc.). Measurements are available in various hydrological compartments: soils, superficial cover formations, epikarst, vadose zone of distinct thicknesses, drilling in ducts, fractures, and within cracked blocks. These compartments exert a key influence on the hydrodynamic and transport properties of karst systems.

Owing to the wide range of geological, geomorphological, and climatic conditions found on the SNO KARST sites, specific research questions can be addressed. The SNO features collaborations between and support by the local operating teams. Research questions involving site and data intercomparisons can be also addressed. Data analysis and modeling approaches can be tested and developed thanks to the data collected at the SNO KARST sites.

The added value of using different sites with complementary characteristics is illustrated by the study of the NAO reported above. The recharge areas of the Radicatel, Moulis/Le Baget, and Lez catchments are respectively around 10, 55, and 130 km^2. However, the filtering of the climatic component is similar for the three sites.

A number of emerging research issues can be identified:

- Coupled modeling of hydrodynamic and geochemical processes. This issue may be addressed in a first step by developing the KarstMod structure, although this is not a compulsory step.
- Assessment of mineral–bacteria interactions. Thanks to already available expertise, data, and analytical setups of some operating teams, the issues of rock weathering, water quality, and sanitary issues (e.g., antibioresistance transfer in karst waters) can be addressed.
- Improving knowledge of the relationships between the statistical and spectral information content of hydrological time series and the flow properties in karst watersheds.

This latter issue in particular is expected to benefit most from the complementary characteristics of the 10 sites through comparing the response of sites with different sizes and characteristics but subjected to similar meteorological inputs (e.g., all Mediterranean

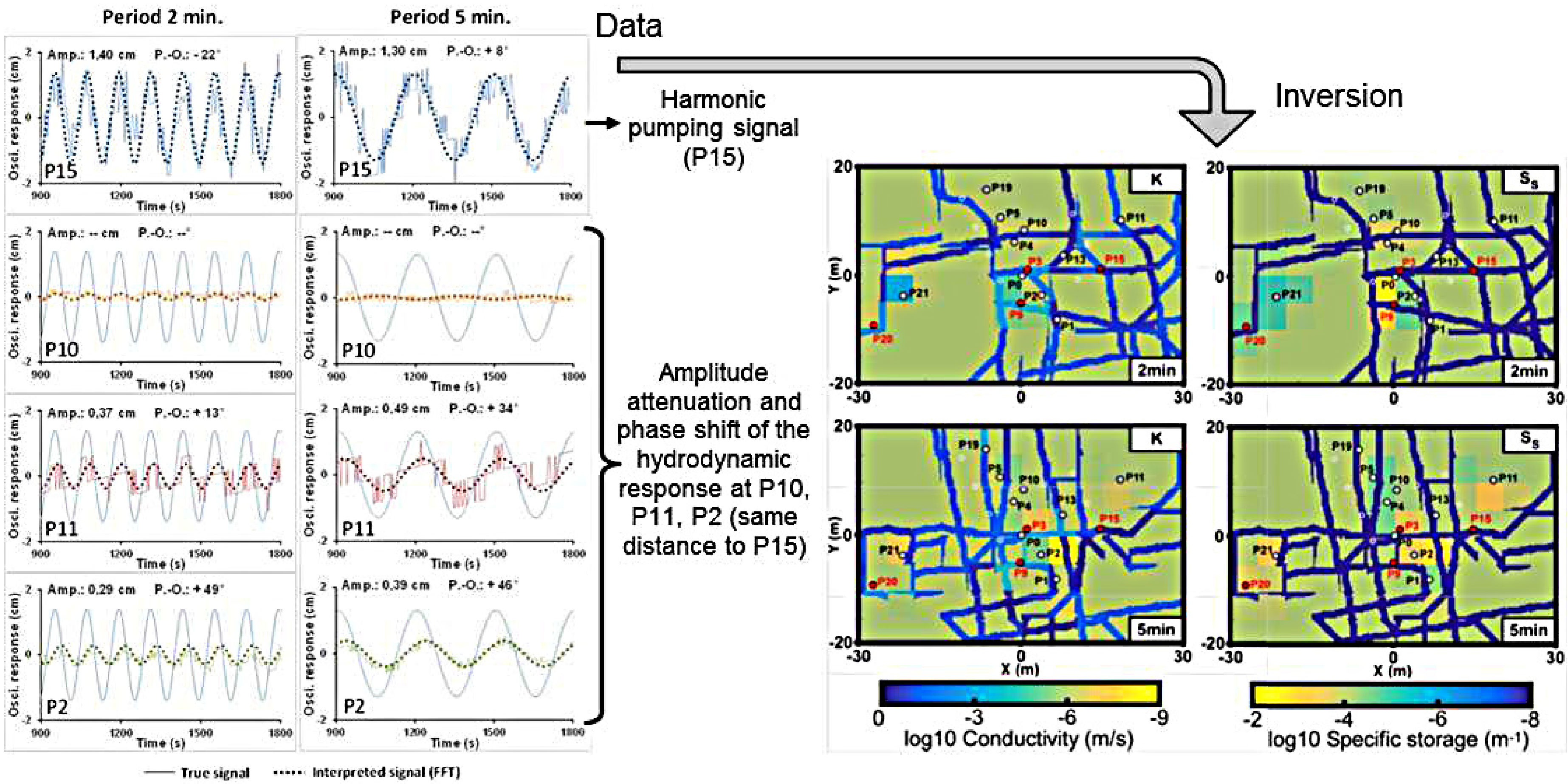

Fig. 13. Registered oscillatory (osci.) responses for each measurement borehole for the $T = 5$ min and $T = 2$ min period of pumping borehole signals (full lines) with variable amplitude and phase offset values in P10, P11, and P2 (dotted lines).Modified from Fischer et al. (2017).

sites, or all continental or oceanic sites), or catchments with similar sizes and structure but subjected to different hydrological regimes. It is expected to be a key step toward a better understanding of the functioning of karst systems. The added value from the synergy between the various sites is also reflected in the development of the KarstMod platform that was developed with the objective of achieving a generic platform applicable to all the sites of the SNO KARST network. Some of the modeling functionalities proposed in the modular platform (e.g., the hysteretic discharge law [Tritz et al., 2011] and the infinite characteristic time transfer function [Guinot et al., 2015]) were developed specifically to address the modeling issues raised by a number of SNO KARST sites.

Lastly, although a number of analytical techniques and protocols have been developed on a local basis at specific sites, it is expected that their implementation and use will be made more systematic on the scale of the entire SNO in the future. The authors should like to encourage the scientific community to use the SNO KARST data and sites when addressing new research questions or developing new experimental designs.

References

Arfib, B., and J.-B. Charlier. 2016. Insights into saline intrusion and freshwater resources in coastal karstic aquifers using a lumped rainfall–discharge–salinity model (the Port-Miou brackish spring, SE France). J. Hydrol. 540:148–161. doi:10.1016/j.jhydrol.2016.06.010

Amiotte Suchet, P., J.-L. Probst, and W. Ludwig. 2003. Worldwide distribution of continental rock lithology: Implications for the atmospheric/soil CO_2 uptake by continental weathering and alkalinity river transport to the oceans. Global Biogeochem. Cycles 17(2). doi:10.1029/2002GB001891

Amiotte Suchet, P., A. Probst, and J.L. Probst. 1995. Influence of acid rain in CO_2 consumption by rock weathering: Local and global scales. Water Air Soil Pollut. 85:1563–1568. doi:10.1007/BF00477203

Bailly-Comte, V., X. Durepaire, C. Batiot-Guilhe, and P.-A. Schnegg. 2018. In situ monitoring of tracer tests: How to distinguish tracer recovery from natural background. Hydrogeol. J. 26:2057–2069. doi:10.1007/s10040-018-1748-8

Bailly-Comte, V., H. Jourde, A. Roesch, S. Pistre, and C. Batiot-Guilhe. 2008. Time series analyses for karst/river interactions assessment: Case of the Coulazou River (southern France). J. Hydrol. 349:98–114. doi:10.1016/j.jhydrol.2007.10.028

Bailly-Comte, V., H. Jourde, and S. Pistre. 2009. Conceptualization and classification of groundwater–surface water hydrodynamic interactions in karst watersheds: Case of the karst watershed of the Coulazou River (southern France). J. Hydrol. 376:456–462. doi:10.1016/j.jhydrol.2009.07.053

Barhoum, S., D. Valdès, R. Guérin, C. Marlin, Q. Vitale, J. Benmamar, and P. Gombert. 2014. Spatial heterogeneity of high-resolution Chalk groundwater geochemistry: Underground quarry at Saint Martin-le-Noeud, France. J. Hydrol. 519:756–768. doi:10.1016/j.jhydrol.2014.08.001

Batiot, C., C. Linan, B. Andreo, C. Emblanch, F. Carrasco, and B. Blavoux. 2003. Use of total organic carbon (TOC) as tracer of diffuse infiltration in a dolomitic karstic system: The Nerja Cave (Andalusia, southern Spain). Geophys. Res. Lett. 30:2179. doi:10.1029/2003GL018546

Batiot-Guilhe, C., J.L. Seidel, M.A. Cordier, S. Van-Exter, C. Bicalho, A. Lafare, et al. 2008. Characterization of underground flows in karstic aquifers by studying DOM fluorescence example of two Mediterranean systems (Lez and Causse d'Aumelas, Southeastern France). Paper presented at the 13th International Water Resources Association World Water Congress, Montpellier, France. 1–4 Sept. 2008.

Baudement, C., B. Arfib, N. Mazzilli, J. Jouves, T. Lamarque, and Y. Guglielmi. 2017. Groundwater management of a highly dynamic karst by assessing baseflow and quickflow with a rainfall-discharge model (Dardennes springs, SE France). Bull. Soc. Geol. Fr. 188:40. doi:10.1051/bsgf/2017203

Berner, E.K., and R.A. Berner. 2012. Global environment: Water, air, and geochemical cycles. 2nd ed. Princeton Univ. Press, Princeton, NJ.

Berner, R.A. 1992. Weathering, plants, and the long-term carbon cycle. Geochim. Cosmochim. Acta 56:3225–3231. doi:10.1016/0016-7037(92)90300-8

Binet, S., E. Joigneaux, H. Pauwels, P. Albéric, C. Fléhoc, and A. Bruand. 2017. Water exchange, mixing and transient storage between a saturated karstic conduit and the surrounding aquifer: Groundwater flow modelling and inputs from stable water isotopes. J. Hydrol. 544:278–289. doi:10.1016/j.jhydrol.2016.11.042

Binet, S., J. Mudry, C. Bertrand, Y. Guglielmi, and R. Cova. 2006. Estimation of quantitative descriptors of northeastern Mediterranean karst behavior: Multiparametric study and local validation of the Siou-Blanc massif (Toulon, France). Hydrogeol. J. 14:1107–1121. doi:10.1007/s10040-006-0044-1

Blondel, T., C. Emblanch, Y. Dudal, C. Batiot-Guilhe, Y. Travi, and S. Gaffet. 2010. Transit time environmental tracing from dissolved organic matter fluorescence properties in karstic aquifers. Application to different flows of Fontaine de Vaucluse experimental basin (SE France). In: B. Andreo, et al., editors, Advances in research in karst media. Springer, Berlin. p. 143–149. doi:10.1007/978-3-642-12486-0_22

Caetano Bicalho, C., C. Batiot-Guilhe, J.L. Seidel, S. Van Exter, and H. Jourde. 2012. Geochemical evidence of water source characterization and hydrodynamic responses in a karst aquifer. J. Hydrol. 450–451:206–218. doi:10.1016/j.jhydrol.2012.04.059

Calmels, D., J. Gaillardet, and L. François. 2014. Sensitivity of carbonate weathering to soil CO_2 production by biological activity along a temperate climate transect. Chem. Geol. 390:74–86. doi:10.1016/j.chemgeo.2014.10.010

Charlier, J.-B., C. Bertrand, and J. Mudry. 2012. Conceptual hydrogeological model of flow and transport of dissolved organic carbon in a small Jura karst system. J. Hydrol. 460–461:52–64. doi:10.1016/j.jhydrol.2012.06.043

Charlier J.-B., Y. Caballero, B. Ladouche, E. Lucas. 2016. What drives the long-term evolution of water quality in the Jura Mountains? A combined analysis of global change impacts. Paper presented at Eurokarst 2016, Neuchâtel, Switzerland. 5–7 Sept. 2016.

Charlier, J.-B., B. Ladouche, and J.-C. Maréchal. 2015a. Identifying the impact of climate and anthropic pressures on karst aquifers using wavelet analysis. J. Hydrol. 523:610–623. doi:10.1016/j.jhydrol.2015.02.003

Charlier, J.-B., R. Moussa, V. Bailly-Comte, L. Danneville, J.-F. Desprats, B. Ladouche, and A. Marchandise. 2015b. Use of a flood-routing model to assess lateral flows in a karstic stream: Implications to the hydrogeological functioning of the Grands Causses area (Tarn River, Southern France). Environ. Earth Sci. 74:7605–7616. doi:10.1007/s12665-015-4704-0

Chedeville S., B. Laignel, N. Massei, E. Hauchard, V. Ladhui, D. Todisco, G. Hanin, and J. Rodet. 2016. Study of hydro-sedimentary variability of the Radicatel karst system influenced by climate signal fluctuations (Normandy, France). Hydrol. Sci. J. 61:732–740. doi:10.1080/02626667.2014.965171

Chen, Z., A. Auler, M. Bakalowicz, D. Drew, F. Griger, J. Hartmann, et al. 2017. The world karst aquifer mapping project: Concept, mapping procedure and map of Europe. Hydrogeol. J. 25:771–785. doi:10.1007/s10040-016-1519-3

Cholet, C. 2017. Fonctionnement hydrogéologique et processus de transport dans les aquifères karstiques du Massif du Jura. Ph.D. diss. Besançon Univ., Besançon, France.

Cholet, C., J.-B. Charlier, R. Moussa, M. Steinmann, and S. Denimal. 2017. Assessing lateral flows and solute transport during floods in a conduit-flow-dominated karst system using the inverse problem for the advection–diffusion equation. Hydrol. Earth Syst. Sci. 21:3635–3653. doi:10.5194/hess-21-3635-2017

Cholet, C., M. Steinmann, J.-B. Charlier, and S. Denimal. 2018. Characterizing fluxes of trace metals related to dissolved and suspended matter during a storm event: Application to a karst aquifer using trace metals and rare earth elements as provenance indicators. Hydrogeol. J. doi:10.1007/s10040-018-1859-2 (in press).

Collon, P., D. Bernasconi, C. Vuilleumier, and P. Renard. 2017. Statistical metrics for the characterization of karst network geometry and topology. Geomorphology 283:122–142. doi:10.1016/j.geomorph.2017.01.034

Dörfliger, N., and V. Plagnes. 2009. Cartographie de la vulnérabilité intrinsèque des aquifères karstiques: Guide méthodologique de la méthode PaPRIKa. Rep. BRGM RP-57527-FR. Bureau Rech. Géol. Minières, Orléans, France.

Duran, L., M. Fournier, N. Massei, and J.P. Dupont. 2016. Assessing the nonlinearity of karst response function under variable boundary conditions. Ground Water 54:46–54. doi:10.1111/gwat.12337

Durepaire, X., C. Batiot-Guilhe, V. Bailly-Comte, and P. Brunet. 2014. Suivi en continu de la MON fluorescente à l'aide d'un fluorimètre de terrain: Implications pour le suivi des traçages artificiels. In: Résumés de la 24ème Réunion des Sciences de la Terre (RST), Pau, France. 27–31 Oct. 2014. Soc. Géol. France. p. 466. https://rst2014-pau.sciencesconf.org/conference/rst2014-pau/rstabstractsnum.pdf (accessed 27 Nov. 2018).

El Janyani, S., N. Massei, J.-P. Dupont, M. Fournier, and N. Dörfliger. 2012. Hydrological responses of the chalk aquifer to the regional climatic signal. J. Hydrol. 464–465:485–493. doi:10.1016/j.jhydrol.2012.07.040

Erostate, M., V. Bailly-Comte, C. Batiot-Guilhe, and X. Durepaire. 2016. Relationships between natural fluorescence and organic matter content based on sampling and in-situ monitoring of groundwater. Application to the karst systems of the Lez and Fontaine de Nîmes springs. Paper presented at the 43rd International Association of Hydrogeologists Congress, Montpellier, France. 25–29 Sept. 2016.

Fischer, P., A. Jardani, H. Jourde, M. Cardiff, X. Wang, S. Chedeville, and N. Lecoq. 2018. Harmonic pumping tomography applied to image the hydraulic properties and interpret the connectivity of a karstic and fractured aquifer (Lez aquifer, France). Adv. Water Resour. 119:227–244. doi:10.1016/j.advwatres.2018.07.002

Fischer, P., A. Jardani, X. Wang, H. Jourde, and N. Lecoq. 2017. Identifying flow networks in a karstified aquifer by application of the cellular automata-based deterministic inversion method (Lez Aquifer, France). Water Resour. Res. 53:10508–10522. doi:10.1002/2017WR020921

Ford, D., and P.D. Williams. 2007. Karst hydrogeology and geomorphology. John Wiley & Sons, New York. doi:10.1002/9781118684986

Fournier, M., A. Motelay-Massei, N. Massei, M. Aubert, M. Bakalowicz, and J.P. Dupont. 2009. Investigation of transport processes inside karst aquifer by means of STATIS. Ground Water 47:391–400. doi:10.1111/j.1745-6584.2008.00532.x

Fournier M., N. Massei, J.P. Dupont, T. Berthe, and F. Petit. 2017, Modelling of bacteria-contaminated particles transfer in a karst aquifer by means of multivariate analysis. Paper presented at the American Geophysical Union Fall Meeting, New Orleans, LA. 11–15 Dec. 2017. Abstract no. H54B-07.

Fournillon, A., S. Abelard, S. Viseur, B. Arfib, and J. Borgomano. 2012. Characterization of karstic networks by automatic extraction of geometrical and topological parameters: Comparison between observations and stochastic simulations. In: J. Garland, et al., editors, Advances in carbonate exploration and reservoir analysis. Spec. Publ. 370. Geol. Soc., London.

Gaillardet, J., and D. Calmels. 2012. Les carbonates, ces oubliés... Géochronique 124:43–45.

Gaillardet, J., B. Dupré, and C.J. Allègre. 1999. Geochemistry of large river suspended sediments: Silicate weathering or recycling tracer? Geochim. Cosmochim. Acta 63:4037–4051. doi:10.1016/S0016-7037(99)00307-5

Guinot, V., M. Savean, H. Jourde, and L. Neppel. 2015. Conceptual rainfall–runoff model with a two-parameter, infinite characteristic time transfer function. Hydrol. Processes 29:4756–4778. doi:10.1002/hyp.10523

Hery, M., V. de Montety, C. Batiot-Guilhe, A. Masnou, J.-L. Seidel, A. Almakki, et al. 2016. Characterization of antibioresistance of bacterial communities in a Mediterranean karst system: Impact of hydrogeological functioning during the hydrological cycle. Paper presented at the 43rd International Association of Hydrogeologists Congress, Montpellier, France. 25–29 Sept. 2016.

Houillon, N., R. Lastennet, A. Denis, P. Malaurent, S. Minvielle, and N. Peyraube. 2017. Assessing cave internal aerology in understanding carbon dioxide (CO_2) dynamics: Implications on calcite mass variation on the wall of Lascaux cave (France). Environ. Earth Sci. 76:170. doi:10.1007/s12665-017-6498-8

Hurrell, J.W., and C. Deser. 2009. North Atlantic climate variability: The role of the North Atlantic Oscillation. J. Mar. Syst. 78:28–41. doi:10.1016/j.jmarsys.2008.11.026

Jazayeri Noushabadi, M.R., H. Jourde, and G. Massonnat. 2011. Influence of the observation scale on permeability estimation at local and regional scales through well tests in a fractured and karstic aquifer (Lez aquifer, southern France). J. Hydrol. 403:321–336. doi:10.1016/j.jhydrol.2011.04.013

Jeannin, P.-Y., M. Hessenauer, A. Malard, and V. Chapuis. 2016. Impact of global change on karst groundwater mineralization in the Jura Mountains. Sci. Total Environ. 541:1208–1221. doi:10.1016/j.scitotenv.2015.10.008

Jourde, H., A. Lafare, N. Mazzilli, G. Belaud, L. Neppel, N. Doerfliger, and F. Cernesson. 2014. Flash flood mitigation as a positive consequence of anthropogenic forcing on the groundwater resource in a karst catchment. Environ. Earth Sci. 71:573–583. doi:10.1007/s12665-013-2678-3

Jourde, H., A. Roesch, V. Guinot, and V. Bailly-Comte. 2007. Dynamics and contribution of karst groundwater to surface flow during Mediterranean flood. Environ. Geol. 51:725–730. doi:10.1007/s00254-006-0386-y

Jouves, J. 2018. Origine, caractérisation et distribution prédictive des structures karstiques. De la karstologie aux modèles numériques 3D. Ph.D. diss. Aix-Marseille Univ., Marseille, France.

Jouves, J., S. Viseur, B. Arfib, C. Baudement, H. Camus, P. Collon, and Y. Guglielmi. 2017. Speleogenesis, geometry and topology of caves: A quantitative study of 3D karst conduits. Geomorphology 298:86–106. doi:10.1016/j.geomorph.2017.09.019

Kavouri, K., V. Plagnes, N. Dörfliger, J. Trémoulet, F. Rejiba, and P. Marchet. 2011. PaPRIKa: A method for estimating karst resource and source vulnerability—Application to the Ouysse karst system (southwest France). Hydrogeol. J. 19:339–353. doi:10.1007/s10040-010-0688-8

Kazakis, N., K. Chalikakis, N. Mazzilli, C. Ollivier, A. Manakos, and K. Voudouris. 2018. Management and research strategies of karst aquifers in Greece: Literature overview and exemplification based on hydrodynamic modelling and vulnerability assessment of a strategic karst aquifer. Sci. Total Environ. 643:592–609. doi:10.1016/j.scitotenv.2018.06.184

Khaldi, S., M. Ratajczak, G. Gargala, M. Fournier, T. Berthe, L. Favennec, and J.P. Dupont. 2011. Intensive exploitation of a karst aquifer leads to Cryptosporidium water supply contamination. Water Res. 45:2906–2914. doi:10.1016/j.watres.2011.03.010

Labat, D., R. Ababou, and A. Mangin. 2000. Rainfall–runoff relations for karstic springs. Part II: Continuous wavelet and discrete orthogonal multiresolution analyses. J. Hydrol. 238:149–178. doi:10.1016/S0022-1694(00)00322-X

Labat, D., R. Ababou, and A. Mangin. 2001. Introduction of wavelet analyses to rainfall–runoffs relationship for karstic basins: The case of Licq-Atherey karstic system (France). Groundwater 39:605–615.

Labat, D., and A. Mangin. 2015. Transfer function approach for artificial tracer test interpretation in karstic systems. J. Hydrol. 529:866–871. doi:10.1016/j.jhydrol.2015.09.011

Ladouche, B., J.-C. Maréchal, and N. Dörfliger. 2014. Semi-distributed lumped model of a karst system under active management. J. Hydrol. 509:215–230. doi:10.1016/j.jhydrol.2013.11.017

Lapworth, D.J., D.C. Gooddy, D. Allen, and G.H. Old. 2009. Understanding groundwater, surface water and hyporheic zone biogeochemical processes in a Chalk catchment using fluorescence properties of dissolved and colloidal organic matter. J. Geophys. Res. 114:456–462. doi:10.1029/2009JG000921

Laroche, E., F. Petit, M. Fournier, and B. Pawlak. 2010. Transport of antibiotic-resistant *Escherichia coli* in a public rural karst water supply. J. Hydrol. 392:12–21. doi:10.1016/j.jhydrol.2010.07.022

Lorette, G., R. Lastennet, N. Peyraube, and A. Denis. 2016. High-Resolution hydrochemical monitoring in a mulitlayer karst aquifer: The example of Toulon Springs. Paper presented at the 43rd International Association of Hydrogeologists Congress, Montpellier, France. 25–29 Sept. 2016.

Maréchal, J.C., B. Ladouche, and N. Dörfliger. 2008. Karst flash flooding in a Mediterranean karst, the example of Fontaine de Nîmes. Eng. Geol. 99:138–146. doi:10.1016/j.enggeo.2007.11.013

Massei, N., B. Dieppois, D.M. Hannah, D.A. Lavers, M. Fossa, B. Laignel, and M. Debret. 2017. Multi-time-scale hydroclimate dynamics of a regional watershed and links to large-scale atmospheric circulation: Application to the Seine river catchment, France. J. Hydrol. 546:262–275. doi:10.1016/j.jhydrol.2017.01.008

Massei, N., J.P. Dupont, B.J. Mahler, B. Laignel, M. Fournier, D. Valdes, and S. Ogier. 2006. Investigating transport properties and turbidity dynamics of a karst aquifer using correlation, spectral, and wavelet analyses. J. Hydrol. 329:244–257. doi:10.1016/j.jhydrol.2006.02.021

Mazzilli, N., V. Guinot, H. Jourde, N. Lecoq, D. Labat, B. Arfib, et al. 2017. KarstMod: A modelling platform for rainfall–discharge analysis and modelling dedicated to karst systems. Environ. Model. Softw. doi:10.1016/j.envsoft.2017.03.015

Meybeck, M. 1987. Global chemical weathering of surficial rocks estimated from river dissolved loads. Am. J. Sci. 287:401–428. doi:10.2475/ajs.287.5.401

Molina-Porras, A., M. Condomines, and J.-L. Seidel. 2017. Radium isotopes, radon and 210Pb in karstic waters: Example of the Lez system (South of France). Chem. Geol. 466:327–340. doi:10.1016/j.chemgeo.2017.06.022

Mudarra, M., B. Andreo, and A. Baker. 2011. Characterization of dissolved organic matter in karst spring waters using intrinsic fluorescence: Relationship with infiltration processes. Sci. Total Environ. 409:3448–3462. doi:10.1016/j.scitotenv.2011.05.026

Mudry, J.-M., F. Degiorgi, E. Lucot, and P.-M. Badot. 2015. Middle term evolution of water chemistry in a karst river: Example from the Loue River (Jura Mountains, Eastern France). In: B. Andreo, et al., editors, Hydrogeological and environmental investigations in karst systems. Springer, Berlin. p. 147–151. doi:10.1007/978-3-642-17435-3_17

Perrin, A.S., A. Probst, and J.L. Probst. 2008. Impact of nitrogenous fertilizers on carbonate dissolution in small agricultural catchments: Implications for weathering CO_2 uptake at regional and global scales. Geochim. Cosmochim. Acta 72:3105–3123. doi:10.1016/j.gca.2008.04.011

Peyraube, N., R. Lastennet, and A. Denis. 2012. Geochemical evolution of groundwater in the unsaturated zone of a karstic massif, using the PCO_2–SIc relationship. J. Hydrol. 430–431:13–24. doi:10.1016/j.jhydrol.2012.01.033

Poulain, A., A. Watlet, O. Kaufmann, M. Van Camp, H. Jourde, N. Mazzilli, et al. 2018. Assessment of groundwater recharge processes through karst vadose zone by cave percolation monitoring. Vadose Zone J. 32:2069–2083. doi:10.1002/hyp.13138

Probst, A., E. Dambrine, D. Viville, and B. Fritz. 1990. Influence of acid atmospheric inputs on surface water chemistry and mineral fluxes in a declining spruce stand within a small granitic catchment (Vosges Massif, France). J. Hydrol. 116:101–124. doi:10.1016/0022-1694(90)90118-H

Quiers, M., C. Batiot-Guilhe, C. Bicalho, Y. Perette, J.L. Seidel, and S. Van-Exter. 2014. Characterization of rapid infiltration flows and vulnerability in karst aquifer using a decomposed fluorescence signal of dissolved organic matter. Environ. Earth Sci. 71:553–561. doi:10.1007/s12665-013-2731-2

Raymond, P.A., N.-H. Oh, R.E. Turner, and W. Broussard. 2008. Anthropogenically enhanced fluxes of water and carbon from the Mississippi River. Nature 451:449–452. doi:10.1038/nature06505

Rousset, F., F. Habets, E. Gomez, P. Le Moigne, S. Morel, J. Noilhan, and E. Ledoux. 2004. Hydrometeorological modeling of the Seine basin using the SAFRAN-ISBA-MODCOU system. J. Geophys. Res. 109:D14105. doi:10.1029/2003JD004403

Slimani, S., N. Massei, J. Mesquita, D. Valdés, M. Fournier, B. Laignel, and J.P. Dupont. 2009. Combined climatic and geological forcings on the spatio-temporal variability of piezometric levels in the chalk aquifer of Upper Normandy (France) at pluridecennal scale. Hydrogeol. J. 17:1823–1832. doi:10.1007/s10040-009-0488-1

Tritz, S., V. Guinot, and H. Jourde. 2011. Modelling the behaviour of a karst system catchment using non-linear hysteretic conceptual model. J. Hydrol. 397:250–262. doi:10.1016/j.jhydrol.2010.12.001

Valdes, D., J.P. Dupont, B. Laignel, S. Ogier, and T. Leboulanger. 2007. A spatial analysis of structural controls on karst ground-water geochemistry at a regional scale. J. Hydrol. 340:244–255. doi:10.1016/j.jhydrol.2007.04.014

Valdes, D., J.-P. Dupont, N. Massei, B.t. Laignel, and J. Rodet. 2006. Investigation of karst hydrodynamics and organization using autocorrelations and T-DC *curves*. J. Hydrol. 329:432–443. doi:10.1016/j.jhydrol.2006.02.030

Wang, X., A. Jardani, and H. Jourde. 2017. A hybrid inverse method for hydraulic tomography in fractured and karstic media. J. Hydrol. 551:29–46. doi:10.1016/j.jhydrol.2017.05.051

Wang, X., A. Jardani, H. Jourde, L. Lonergan, J. Cosgrove, O. Gosselin, and G. Massonat. 2016. Characterization of the transmissivity field of a fractured and karstic aquifer, Southern France. Adv. Water Resour. 87:106–121. doi:10.1016/j.advwatres.2015.10.014