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SNO KARST: a French network of observatories for the multidisciplinary study of critical zone processes in karst watersheds and aquifers

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Core ideas

• SNO KARST is a long-term critical zone observatory designed for a better understanding of flow and transport in karst aquifers and watersheds via a multi-disciplinary approach

• Complementary measurements of hydrodynamics, as well as physicochemical and geochemical variables are performed in the various compartments (epikarst, vadose zone, saturated zone) and outlets of karst systems located in a variety of climatic, geologic, geomorphologic and physiographic contexts

• Process sampling was set up over ten different sites with continuous monitoring of various variables for time scales ranging from ten to over fifty years on some sites

• New tools and new findings were acquired thanks to the complementarity of gathered data and conducted experiments on the individual sites of SNO KARST

Keywords (5): karst, hydrogeology, hydrodynamics, hydrochemistry, long-term monitoring

Abstract

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 an efficient management of karst groundwater resources. A comprehensive understanding of the various processes can be achieved only by studying karst systems over a wide range of spatio-temporal 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 hydro-geo-chemical variables in karst, and ii) promoting knowledge-sharing and developing cross-disciplinary research on karst.

The present paper provides an overview of the monitoring sites and of collective achievements such as the KarstMod modular modelling platform and the PaPRIKa toolbox. It also presents the

research questions addressed within the framework of SNO Karst, 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.

1. Introduction

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 % in the Mediterranean area, 22% of the European land 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 over a wide-range of spatio-temporal scales. As a result, they usually exhibit strongly non-linear responses to external forcings. Characterizing, modelling, 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 towards 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 are needed to understand and predict the hydrological behaviour 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 spatio-temporal 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 (see **Fig. 1**): Mediterranean, Mountainous (Pyrenees, Jura), Oceanic (West and North-West 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 modelling of hydrogeochemical fluxes within and at the outlets of karst hydrosystems and the relationships between global change and the physico-chemical 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 modelling 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 impacting 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.

The present paper describes 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. Section 2 gives an overview of the various sites and their characteristics. Section 3 presents the main research questions addressed by SNO KARST. Examples of recent findings achieved through the SNO KARST network are provided in Section 4. Section 5 is devoted to conclusions and perspectives.

2. Catchment properties and monitored parameters

SNO KARST gathers 9 observation sites located within various regions of France (**Fig. 1a**) and 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**).

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, geomorphological and geological conditions (surficial cover, lithology, tectonics, speleogenesis) on the hydrological behaviour and the transport of mass and energy in karstic aquifers and watersheds (**Fig. 1b**).

Not only is SNO KARST a monitoring network but 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 modelling of the response of water resources to short-, medium-, and long-term forcings.

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 in order 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 in all sites with a common, 15 minute base frequency. They are easily measurable using multiparametric probes. The 15 minute 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.

3. 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 the characterization of the role of the various internal compartments of each karst system and of the specific non-linearity 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 behaviour 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 zone and vulnerability of the groundwater resource and iii) karst geometry and its influence on hydrological functioning.

3.1 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 (Charlier et al., 2015a; Labat et al.,2000, 2001; Massei et al., 2006; Slimani et al., 2009; Valdes et al. 2007). Such changes may stem from both anthropogenic and climatic variations, and they occur either gradually (low-frequency inter-annual to multi-decadal 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 over 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 45-60 % of the global river dissolved load to oceans (Berner and Berner, 2012; Calmels et al., 2014; Ford and Williams, 2007; Amiotte Suchet et al., 2003; Gaillardet et al., 1999; Meybeck, 1987). It has been argued that CO_2 consumption by carbonate weathering on the continents is fully balanced by CO_2 release during calcite bio-precipitation 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 (approximately 10^5 years). Over shorter time periods, carbonate weathering is expected to play an important role in the global carbon balance (Amiotte Suchet et al., 2003; Calmels et al., 2014; Gaillardet and Calmels, 2012). During carbonate weathering, CO_2 from the atmosphere/soil is consumed and exported to the oceans in the form of dissolved inorganic carbon (mainly HCO_3^-). CO_2 uptake that occurs at the interface between the organic and inorganic carbon 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 to the conservation of parietal paintings.

Long term trends in water chemistry have been observed for various karst systems (Jeannin et al., 2016; Raymond et al., 2008). Within the SNO KARST sites, such trends are identified for Le Baget site and the Jura Mountains (Mudry et al., 2015; Charlier et al., 2016). Water mineralization being dominated by HCO_3^- concentration in carbonate aquifers, the long-term variations in electrical conductivity (EC) 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** that shows the EC variations over almost 40 years in the Jura Mountains. Springs (red curves) and rivers (blue curves) are classified according to the mean altitude of their recharge area (darker colours for lower elevations). Analysing 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 time scales. An increasing phase is observed from 1980 to 2000 and stabilizes afterwards. This behaviour 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 and quantifying the impact of the various anthropogenic processes on pCO_2 in soil and on carbonate weathering is still a pending issue. Isolating the respective contributions of these processes will allow for a re-interpretation of hydrochemical databases in terms of acid atmospheric pollution load and global warming impact on carbonate and surface water buffering response.

3.2 Biogeochemical functioning of the critical zone and vulnerability of the groundwater resource 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 (Bailly-Comte et al., 2008; 2009; Maréchal et al., 2008; Jourde et al., 2007, 2014; 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 carbon 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; Fournier et al., 2009; Valdes et al., 2006), respective contributions of mechanical and chemical erosion.

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

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 appears as a new possible way to identify flow paths with various residence time conditions in such heterogeneous systems, which is essential for a better assessment and management of ground water. 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.

3.3 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 modelling. In addition, karst systems are generally spatially poorly characterized and only monitored at their outlets. As a result, karst catchments are mostly analysed and modelled 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 modelling 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, saturated zone) and providing insights into the physical processes at stake within the sub-systems 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 3D karst networks (**Fig. 3**) to improve karst network modelling (Collon et al., 2017; Fournillon et al., 2012; Jouves et al., 2017) for karst hydrological behaviour understanding, but also as input for flow models.
– Exploring the links between systemic and physically-based approaches to improve the understanding and the modelling of karst hydrosystems: improvement of the efficiency of conceptual modelling (alternatives necessary to distributed modelling), 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).

4. New findings and achievements

4.1. The KarstMod modular modelling platform

Proposing a systematic and generic approach to karst hydrodynamic modelling was identified as a major challenge by SNO KARST. This generic assignment may be compared to what is being built at the meso-scale for the 3D 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. Inter-comparison of the extremely diverse sites of SNO KARST was thus used for testing the relevance of non-site-specific generic models. This has led to the development of the global conceptual, modular modelling 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 modelling of karst catchments. Such functions are not found in classical conceptual modelling platforms. KarstMod has been successfully applied to the SNO KARST network but also to other watersheds (Nerantzis et al., 2018, Poulain et al., 2018, Guinot et al., 2015). KarstMod provides a user-friendly tool to implement rainfall-discharge modelling 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-know and very common baseflow (BF) and quickflow (QF) hydrograph separation can be performed automatically over the whole time series (Baudement et al., 2017). Calibrated recession coefficients governing the proportion of BF and QF can then be conceptually related with the karst network connectivity inferred from geomorphologic and geologic observation. Conceptual modelling 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 multi-objective calibration approach, quasi Monte-Carlo procedure), ii) simulation analysis (cumulative probability plots, correlograms, spectral analysis), iii) sensitivity and equifinality analysis (mapping the objective function in the parameter space, sensitivity indexes). **Fig. 4** shows sample simulation results with their confidence interval, as generated from the KarstMod user interface.

4.2. Hydrological response of karst catchments to large scale atmospheric circulation patterns

Karst watersheds can display a strongly non-linear response to meteorological inputs. This is because the interactions between the internal watershed compartments change with the amplitude of climatic variations. In order 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 inter-annual (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). Firstly, the hydrological time series were decomposed as the superposition of large scale climate field time series and a local field using wavelet multiresolution analysis. Secondly, 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 over 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 years 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/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. 6 d-f**) clearly show dipole-like SLP patterns reminiscent of the North-Atlantic Oscillation 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 North Atlantic Oscillation (NAO) on hydrological conditions is well contrasted. This is not the case for the Radicatel site (**Fig. 6 g-i**), that is located in a transition zone regarding the expected impact of NAO over Western Europe. Although it is located in Southern France as the Lez site, Le Baget system clearly behaves differently, except for the two year oscillatory component (**Fig. 6 a-c**). 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.

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 years, 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 modelling using the KarstMod modelling 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. 6 f, was found to explain approximately 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 time scales. 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.

4.3. New tools for the assessment of the functioning and vulnerability of the karst aquifers

4.3.1 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 (Quiers et al., 2014; Durepaire 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 minute time step and a lower spectral resolution using a multispectral field fluorometer. **Fig. 9** shows the domain of Ex/Em matrixes that can be analysed by the fluorometer according to the optics systems: Turbidity (Rayleigh diffusion spectrum), Rhodamine, Uranine, AminoGacid 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 Ultra-Violet (UV, 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.

Besides, 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: is the tracer really present in the water?, and ii) quantification: 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.

4.3.2. 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 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.

4.4. Flow and transport properties with respect to karst geometry

4.4.1 Development of new transfer function approaches

A new tracer breakthrough interpretation in karst systems has been developed. It borrows from the modelling concepts in chemical engineering and control process (Labat and Mangin, 2015). Chemical reactors are modelled 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 semi-quantitative 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 characterised by a median altitude about 940 m and a recharge area around 13 km^2. The specific runoff is 36 $l.s^{-1}$.km-2with 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 characterised by the presence of sinkholes and temporary and permanent springs on a spatially restrained area of about 2 km^2.

Fig. 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 (TT1) and between Peyrere and Las Hountas (TT2) (**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 TT1 and TT2 respectively.

4.4.2 Small- to meso-scale hydrodynamic processes

Inverse modelling 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 about 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). 22 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 to 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 data set (Wang et al., 2017). An important finding is that the success of inverse modelling 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 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 modelled hydraulic data. This results in transmissivity fields generated by a discrete conduit network embedded within the background matrix. The method allows the hierarchical flow behaviour observed in karst systems to be accounted for. Using the Terrieu data set, 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 (Fisher 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 minutes were 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 ten 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.

5. 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 LTER (Long-Term Ecosystem Research) and Critical Zone and Socio-Ecological Research observatories (eLTER RI).

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 modelling. 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/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 inter comparisons can be also addressed. Data analysis and modelling 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 in Section 4.2. 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 questions can be identified:

– Coupled modelling of hydrodynamic and geochemical processes. This question 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. antiobioresistance 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 question in particular is expected to benefit most from the complementary characteristics of the ten sites: comparing the response of sites with different sizes and characteristics but subjected to similar meteorological inputs (e.g. all Mediterranean 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 brought by 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 modelling 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 modelling issues raised by a number of SNO KARST sites.

Lastly, while 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.

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

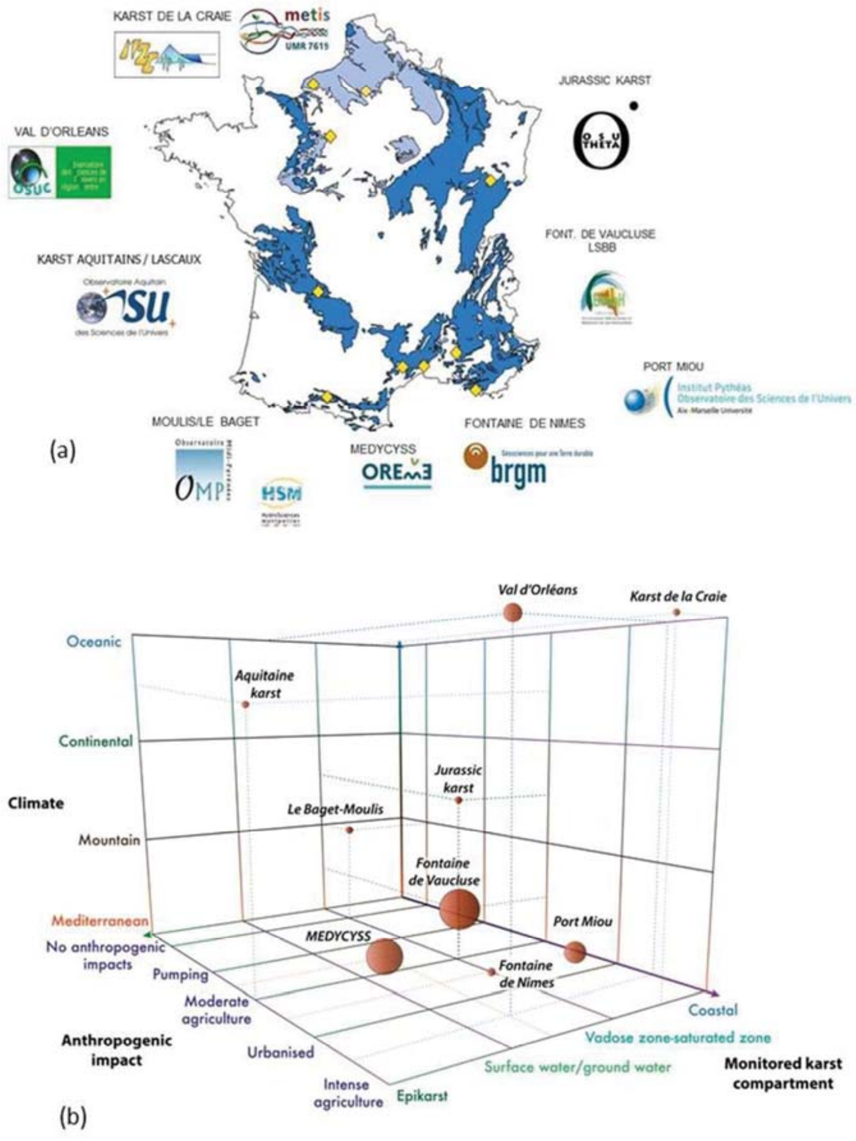

Figure 1: (a) Location of the observatory sites that compose the SNO KARST, and name of the OSUs and Lab in charge of their monitoring. (b) Diversity of hydrogeological, hydrological and hydrochemical settings of the various observatory sites; circle size is proportional to the catchment area (see Table 1 for more details)

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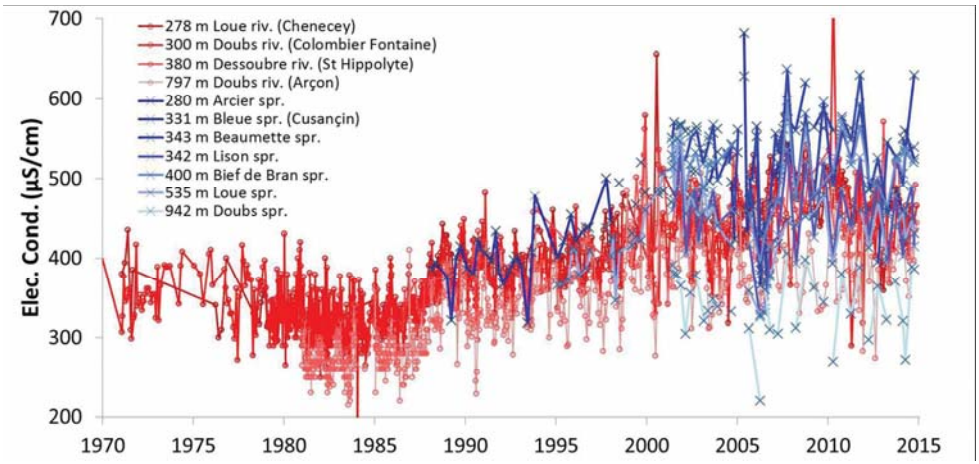

Figure 2 : Evolution of electrical conductivity in springs and rivers in the Jura Mountains (Charlier et al., 2016)

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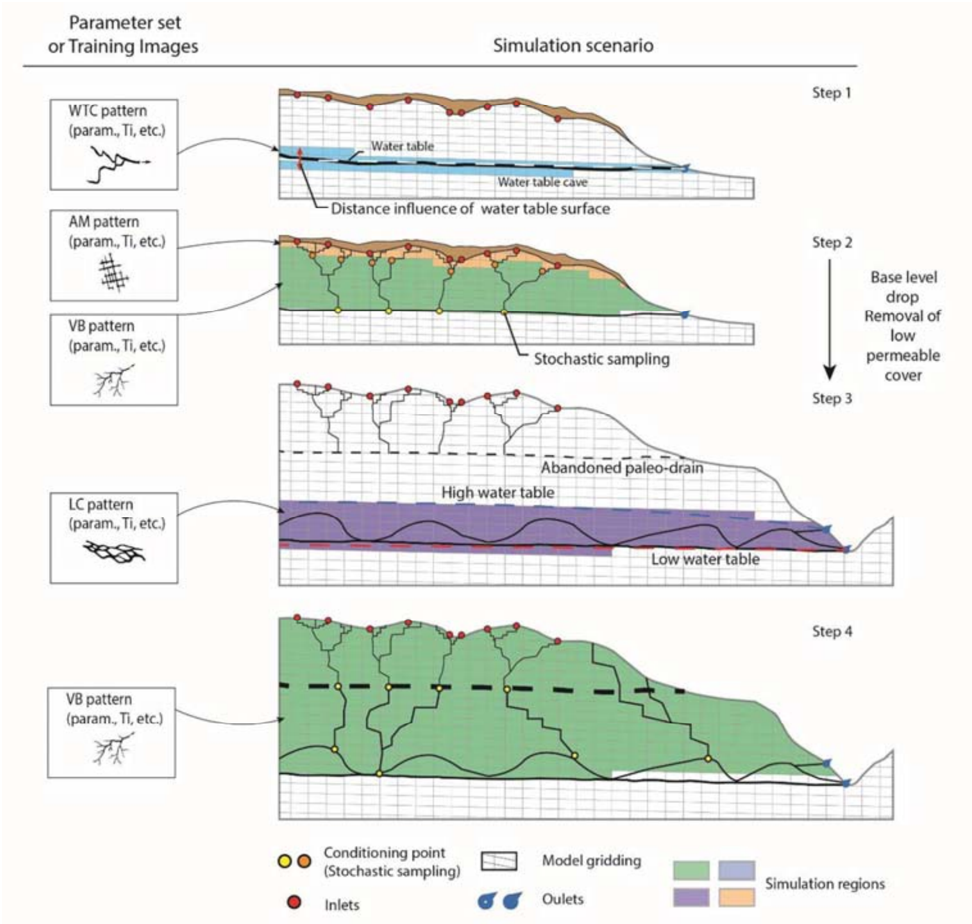

Figure 3 - Conceptual cross-section of a carbonate massif with karst generation in four steps (polygenic karst network). For each step, a karst pattern (deducted from field geomorphological observation) is associated and can be simulated as 3D karst network using geometric and topologic parameters or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

293x279mm (120 x 120 DPI)

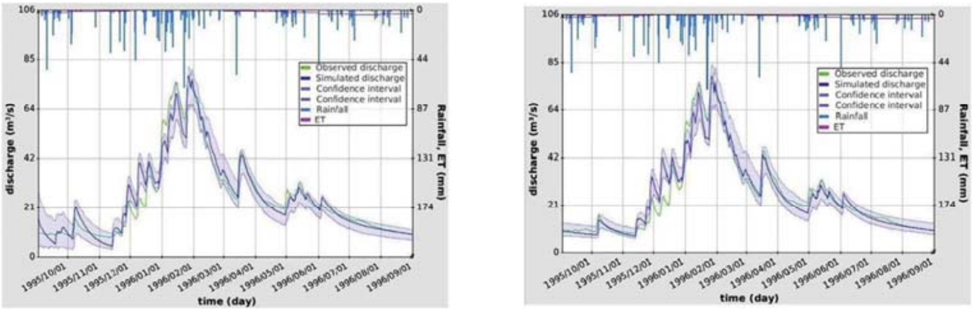

Figure 4: KarstMod provides a variety of tools for simulation analysis and equifinality assessment. Here, simulation results are provided together with their confidence intervalfor the behavioural parameter set (Nash Sutcliffe efficiency higher than 0.9) during calibration stage: (left) no warm-up period, (right) a one-year warmup (after Mazzilli et al., 2017)

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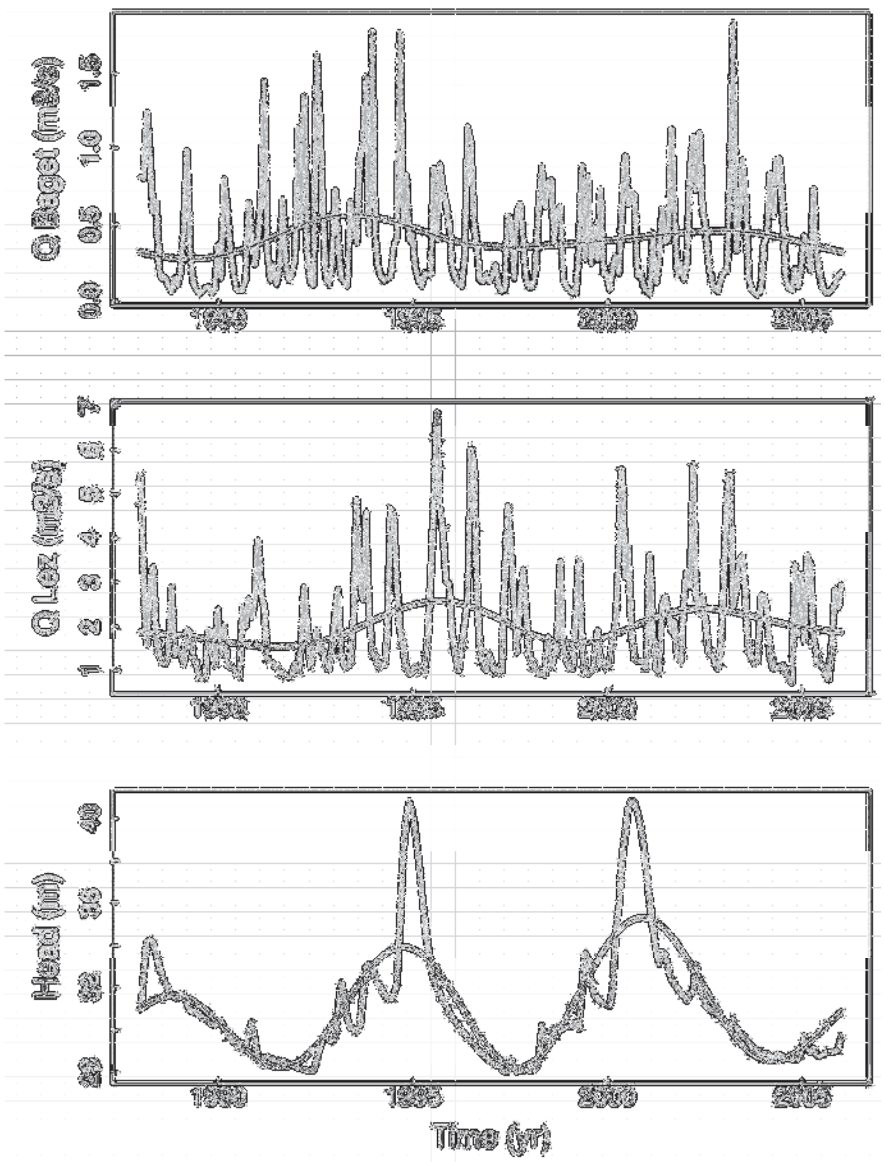

Figure 5: Monthly-aggregated time-series of springflow at Le Baget and Lez sites, and hydraulic head at outlet of Radicatel site. Blue lines are the wavelet details obtained from multiresolution analysis corresponding to interannual low-frequency components within each time-series.

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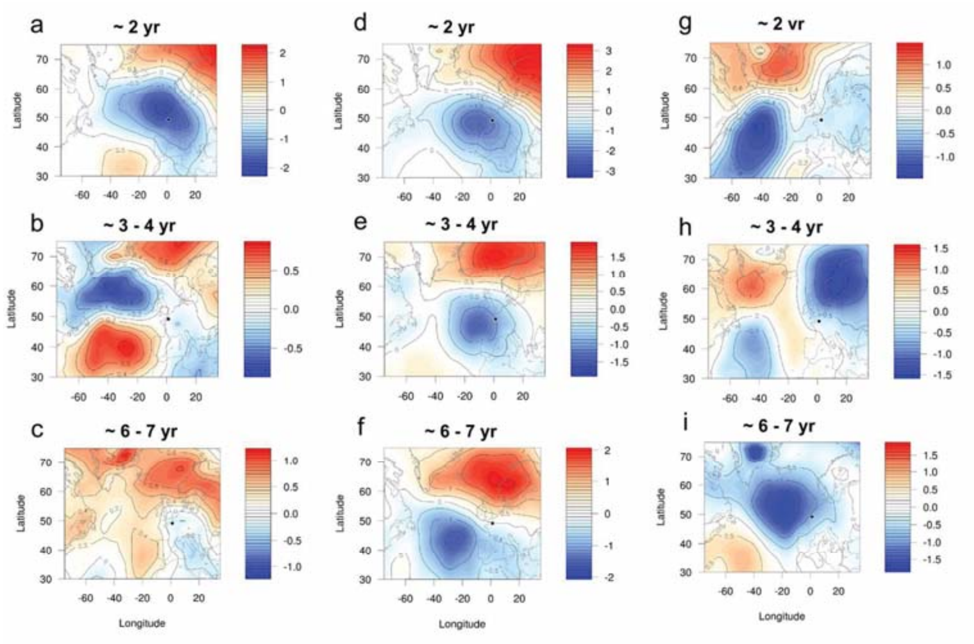

Figure 6: Sea Level Pressure (SLP) composite maps based on ~2-yr, ~ 3-4-yr and ~6-7-yr low-frequency components of springflow (or water level) at karst outlets (a, b, c : Le Baget site; d, e, f: Lez site; g, h, i: Radicatel site). Blue (resp. red) shaded areas highlight the zones of below-average SLP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

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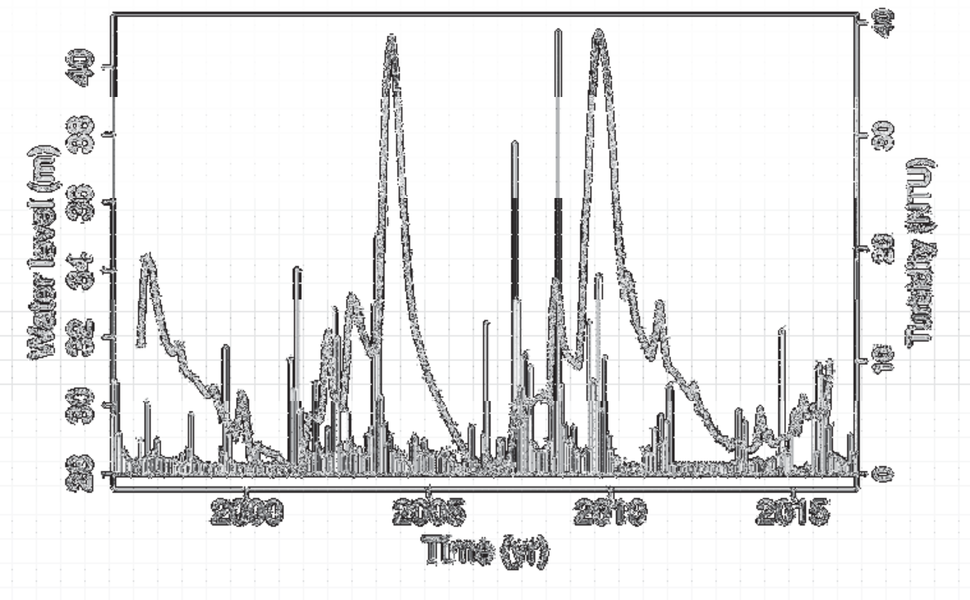
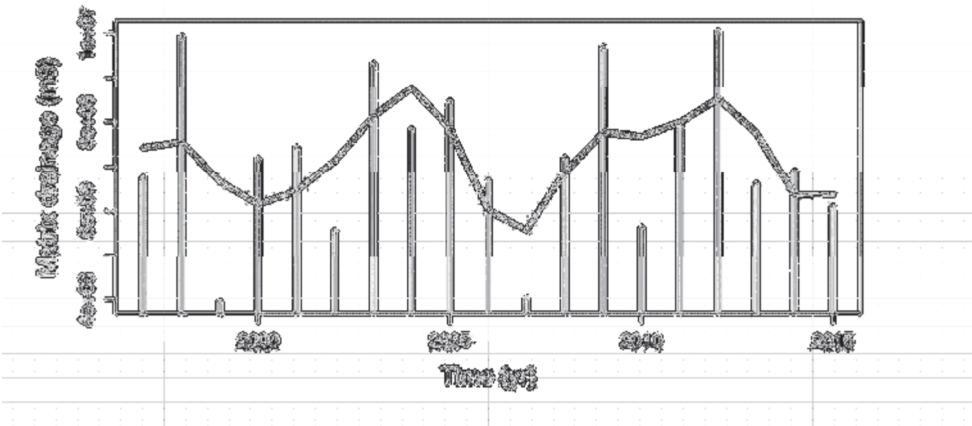


Figure 7 – Daily turbidity and water level at Radicatel site between 1997 and 2017. The highest-amplitude turbid events occur during interannual rising water level within the karst system, showing a clear interannual atmospheric-driven control of karst response.



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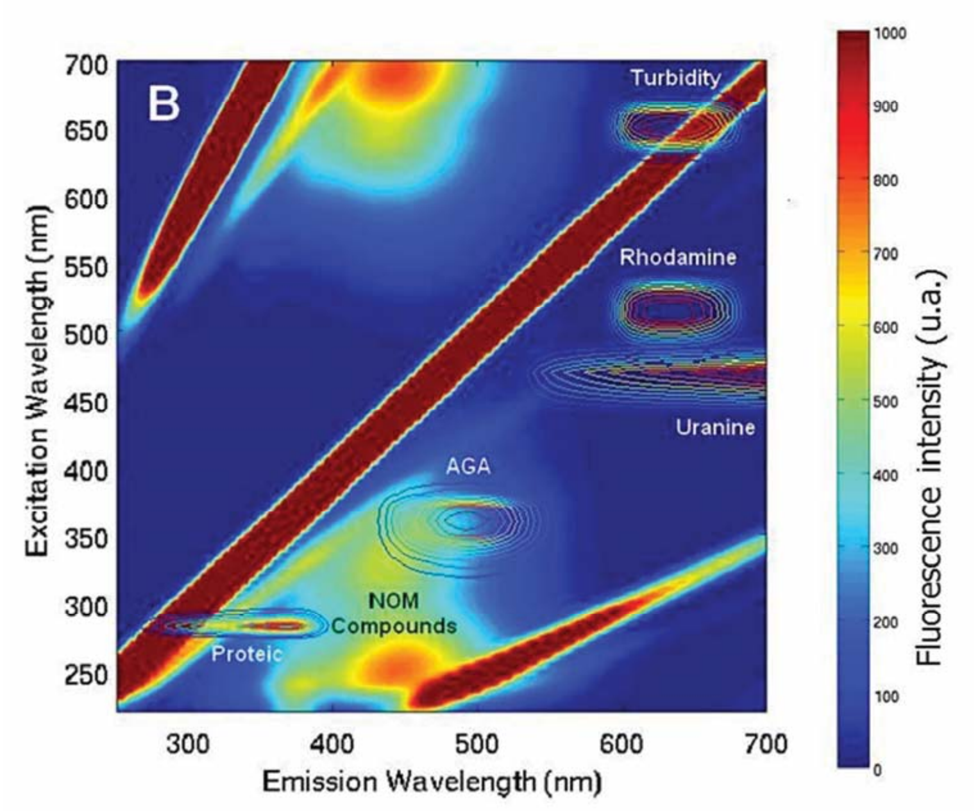

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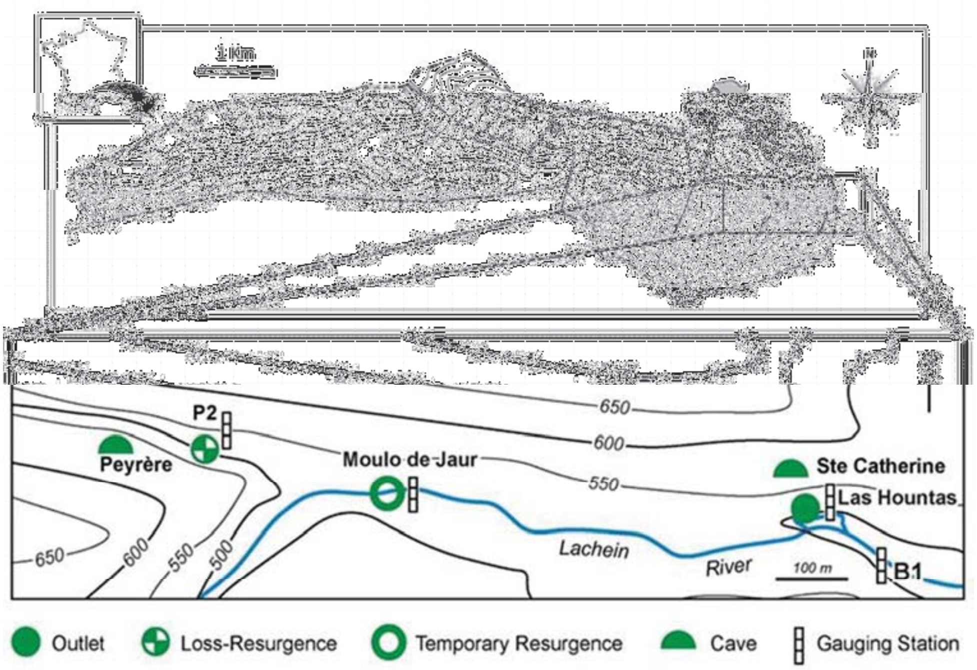

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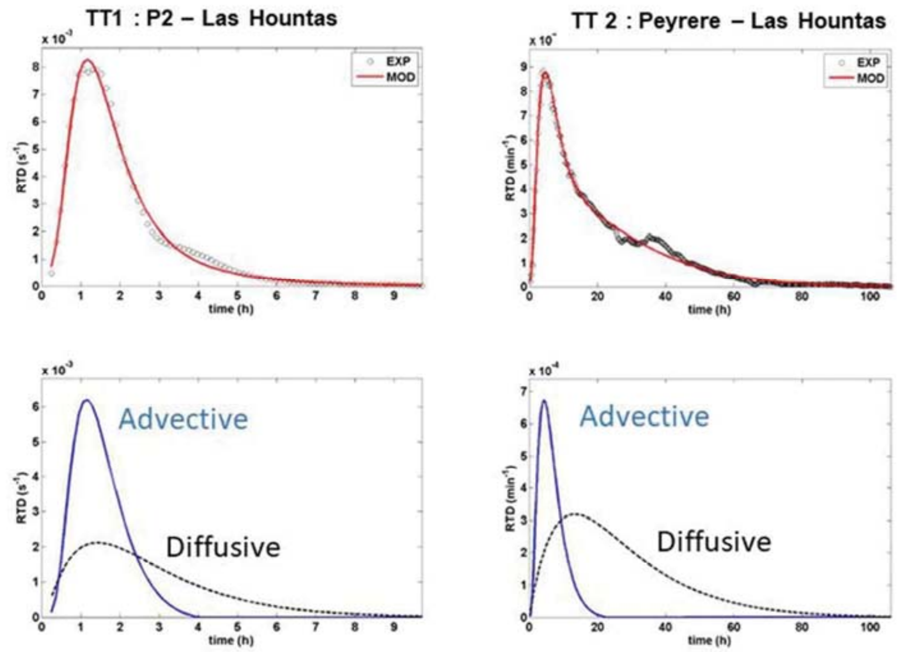

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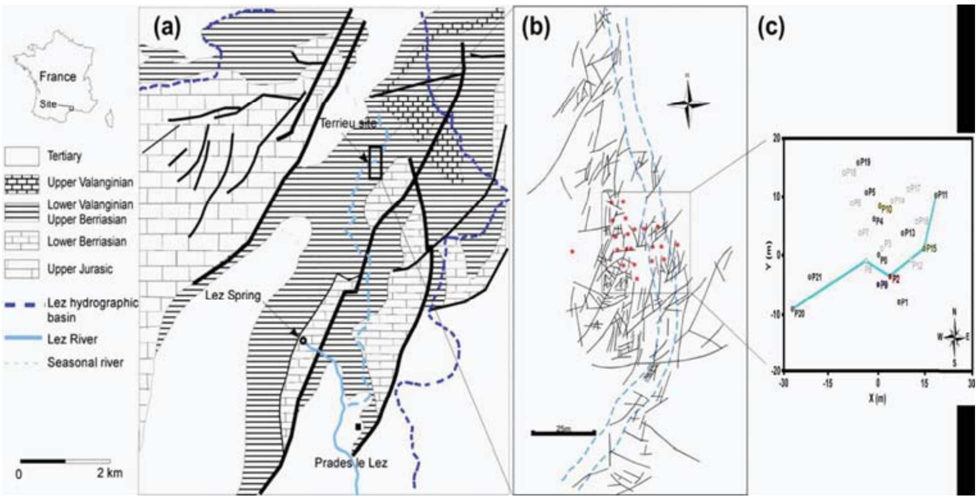

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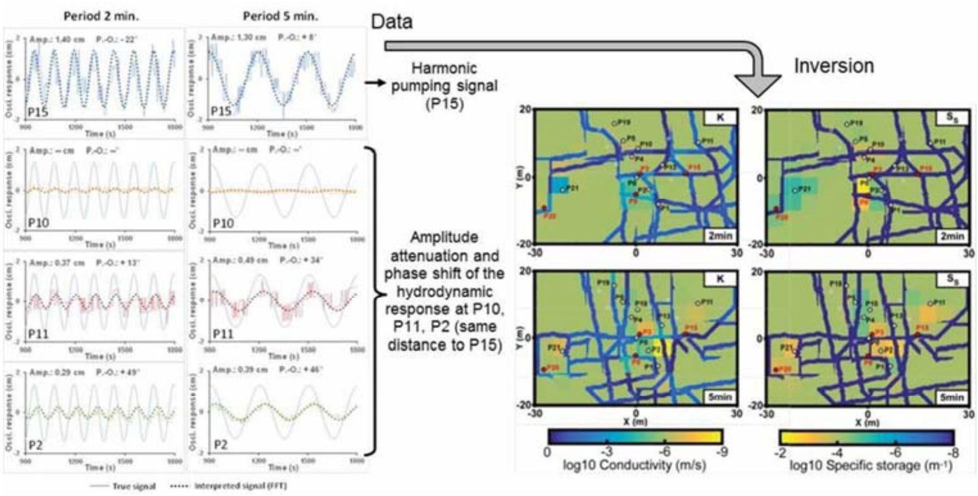

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Site	Location (France)	Recharge area (km²)	Climate	Karst specificity	Human impact and land cover	Continuous recording
Fontaine de Vaucluse - LSBB	Avignon	1115	Mediterranean, Mountainous	Thick unsaturated zone Deep karst network below the current base-level	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)	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 ; pH: pH ; Cl^-: chloride, NO3-: nitrate ; DOC: dissolved organic carbon ; TOC: total organic carbon ; DO: dissolved oxygen