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The MEDYCYSS observatory, a Multi scale observatory of flood dYnamiCs and hYdrodynamicS in karSt (Mediterranean border Southern France)

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Abstract In karst hydrosystems, the heterogeneity and the complexity of the transfer processes within the different compartments (soil, epikarst, unsaturated zone, saturated zone) control the recharge-discharge relationship. The MEDYCYSS observatory (Multi scale observatory of flood dYnamiCs and hYdrodynamicS in karSt) has been set up to better understand these transfers in a Mediterranean context. This observatory consists in a large karst hydrosystem located between the Hérault River, the Vidourle River and the Mediterranean Sea (Southern France, north and west from Montpellier). It comprises two main hydrogeological sites and three main hydrological sites where karst/river interactions occur. The challenges of the MEDYCYSS observatory are i) to better characterize the karst/river interactions for the risk assessment of floods and water resource contamination; ii) to discriminate and quantify flow distribution (rapid and slow transfers) between the recharge catchment and the outlets of the hydrosystem; iii) to understand the role of the unsaturated zone on the long term storage of the aquifer and quantify the water storage variation with time; iv) to characterize groundwater hydrodynamics in karst watersheds under climatic and anthropogenic forcing at nested observation scales; and v) to quantify the recharge, which is a key variable for the assessment and management of groundwater resources in karsts. Accordingly, a continuous monitoring of the hydrochemistry and hydrodynamics (wells, karst network, permanent and

temporary springs), as well as of the river and spring discharges has been constructed to characterize transfer processes and parameterize local and regional scale models. Meteorological variables are also monitored at various points where measurements of soil humidity and evapotranspiration recently started.

1 Introduction

The number of damages related to flood has been increasing during the last years in the Mediterranean regions (Gaume et al., 2009). In these regions, most flood-prone streams and rivers flow on karstic rocks which are typical of the carbonates terrains of the Mediterranean circumference. Besides flood hazard, extreme rainfall events are also associated with the risk of groundwater resource contamination. Groundwater contamination can be related either to surface flow or groundwater flow because of the significant karst-river interactions. In all cases, a better assessment of these dynamics is a major stake for preserving the groundwater supply safety within the hydrosystem as groundwater management of these karsts is strongly dependent on the knowledge of their hydrodynamics. Moreover, because of the increased demand for water, the importance and awareness of karst aquifers in Mediterranean regions has grown.

For a better assessment of karst water resource, conceptual models are generally proposed to characterize the relationships between the recharge and the discharge at the outlets of the systems, based on hydrodynamics, hydrochemistry or isotopic studies (Bicalho et al., 2011 a,b,c; Fleury, 2010; Mazzilli, 2011; Borrell et al., 2008; Kong A Siou et al., 2011 c ; Coustau et al., 2011; Bailly-Comte et al., 2011). The quantification (on the basis of long term time series) of these recharge-discharge relationships is a key parameter to estimate the sustainable yield of aquifers and assess the impacts of climatic and anthropogenic changes on the long term groundwater resources. However, an important limit of these approaches is related to the fact that it does not take into account the heterogeneity and the complexity of the transfers within each compartment (soil, epikarst/perched aquifer, unsaturated zone, saturated zone) of the karst aquifer. It is thus crucial to characterize and then consider these transfers in distributed models that account for each compartment.

Therefore, various experimental sites have been constructed to better understand these transfer processes. On these pilot sites, the challenges are i) to better characterize the karst/river interactions for the risk assessment of floods and water resource contamination; ii) to discriminate and quantify the distribution of the hydric fluxes (rapid and slow transfers) between the surface and the spring; iii) to quantify the water storage variation with time and understand the role of the unsaturated zone on the long term storage of the aquifer; and iv) to quantify the recharge as a function of field and climatic parameters, as it is a key variable for the assessment and management of groundwater resources.

2 Experimental sites of the MEDYCYSS Observatory

The MEDYCYSS observatory (Fig. 1) comprises three main watersheds where karst/river interactions occur: the Lez, the Mosson and the Coulazou river catchments. The major objectives of MEDYCYSS are:

- The observation and characterisation at local and regional scale of groundwater hydrodynamics in karst watersheds, under climatic and anthropogenic forcing;
- The observation and characterisation of the rapid hydrological processes during extreme flood events in Mediterranean watersheds, where interactions occurs between the river network and the karst aquifer;
- The observation and characterisation of groundwater resource contamination hazard, based on the coupled hydrochemistry /hydrodynamic monitoring;
- The assessment of the links between karst evolution over time (geology and geomorphology) and its current hydrodynamic behaviour.
- The characterisation and coupled modelling of the groundwater and surface water hydrodynamics in karst watersheds;
- The characterisation and modelling of the global change impact on the recharge/discharge relationships over long time period.

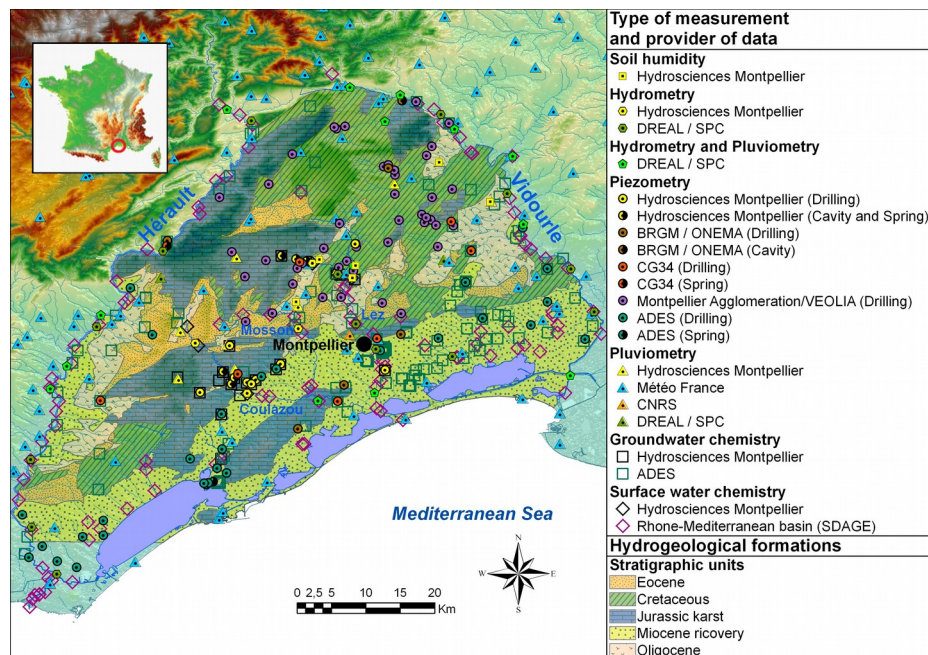


Fig.1: Hydrogeological and hydrological contexts of the MEDYCYSS observatory (44° 00'N, 4°00'E - 43°17'N 3° 26'E)

Long term time series (more than 40 years) of rain, water table level and discharge exist on the three experimental sites, which is a major asset for long term modelling and the characterization of global change impact on the long term groundwater resource.

2.1 Karst watersheds of the Coulazou and Mosson rivers

Since 2004, the experimental site of the Coulazou River allowed to study the modality of surface floods genesis (Jourde et al. 2007) and transfer (Bailly-Comte et al. 2008, Bailly-Comte et al. 2009) in karst terrains, at the scale of a well monitored small catchment. This site comprises a karst catchment, the Causse d'Aumelas, which is a Jurassic calcareous plateau crossed by the intermittent Coulazou River. This area is a binary karst system developed within the calcareous Jurassic plateau, in contact with an Oligocene impermeable basin in the North and a Miocene impermeable basin in the South.

In order to better understand the groundwater contribution to flash floods in the Coulazou river the water table in the karst aquifer is monitored in various locations (wells, karstic network, permanent and temporary springs), as well as the Coulazou river discharge at the entry and the exit of the karst system.

More than 15 karstic events, which can function alternately as sinkholes or springs, have been observed in this hydrosystem. In order to understand the interactions between surface water and groundwater, hydrodynamic monitoring is enriched with various chemical tracers monitoring (Major and trace elements, TOC: Total Organic Carbon, stable isotopes of water and Carbon) on springs, boreholes, swallow holes, and on the *Coulazou* river. This “multiparameters” approach allows identifying the various types of water that contribute to flow, but also flow inversions between the karst system and the river. The understanding of these specific links between surface water and groundwater are fundamental to estimate the vulnerability of the aquifer and to protect water resources in this Mediterranean context (Batiot et al., 2005; Selles et al., 2011). Moreover, a regular monitoring (twice a month during two hydrological cycles) of CO₂ and ²²²Rn allowed explaining the temporal variability of these elements (Batiot et al., 2007).

One of the major interest of this site is that, from upstream to downstream, the watershed evolution is characteristic of many Mediterranean rivers like Cèze, Hérault, Vidourle or Gardon in southern France, i.e: i) an upstream impervious watershed; ii) an intermediate watershed where karst/river interactions occur, with consequences on floods but also on groundwater contamination; iii) a downstream watershed in a alluvial plain, where flood hazard is generally more important.

This system thus constitutes a local scale experimental site to study karst/river interactions before focusing on larger systems where flood hazards have larger human and economic consequences.

On this site, some important experimental results characteristics of most Mediterranean karst watersheds and concerning hydrodynamics, groundwater/surface water interactions and transport have been highlighted:

- A hydrodynamic analysis coupled with a hydrological modelling showed that groundwater contribution from the karst to surface flood can reach one third of the total flood volume, and increase the flood peak discharge by a factor of two (Jourde et al., 2007).
- Times series analysis in time (correlation) and frequency (power spectral density) domains coupled with recession curves analysis showed that:
 - karst groundwater flows may either attenuate or amplify the rapid surface flow transfers depending on the initial state (groundwater level) of the system (Bailly-Comte et al., 2008a, b).
 - the initial groundwater level may be used to forecast the type of hydraulic connection between the river and the saturated zone during flood. This level is found to be also controlled by the limited discharge capacity of karst conduits. A conceptual model of karst/river interactions during flood has been proposed (Bailly-Comte et al., 2009).
 - water exchange between matrix and conduits control the spring hydrograph (Bailly-Comte et al., 2010)
- A dye tracing experiment conducted in a small but highly transient tracing system interacting with the Coulazou River has shown that plurimodal tracer breakthrough curves only result from surface water/groundwater interactions, each flood pulse of the sinking stream inducing a tracer pulse at the outlet with low dilution and dispersion (Selles et al., 2011).

2.2 Karst watershed of the Lez river

The hydrological and hydrogeological catchments of the Lez River (North-West of the city of Montpellier) are remarkable as regards both their vulnerability to pollutions or flood hazards, and the active management of the groundwater resource. The objectives of the hydrodynamics monitoring are: (i) a better understanding of flash floods and contaminant transfers during extreme rain events, (ii) the characterization of the recharge and the transfer processes within each compartment of the karst system. To improve the understanding of the groundwater origins and its circulation dynamics within this karst system, regular sampling for hydrochemical and isotopical analysis is also carried out on the main springs and wells of the karst system. The application of a multi-tracer approach based on major ions, trace elements, isotopes and emerging tracers, helped determining water origins, water mixing proportions and levels of anthropogenic contaminations. Those results also allowed proposing a conceptual model of groundwater circulation for this aquifer (Batiot et al., 2008; Bicalho et al. 2009; Bicalho et al. 2010; Bicalho et al. submitted). High flow rate pumping (up to 6000 m³/h) performed at the Lez spring for Montpellier water supply allows

investigating the hydrodynamic properties of the karst aquifer at a regional scale. Besides, a small experimental site (Terrieu site) with 18 boreholes and 3 wells on a 500 m² area allows the characterisation of the hydrodynamic properties of the karst aquifer at a local scale (pumping up to 60 m³/h). This configuration allows identifying the hydrodynamic behaviour of the karst system at nested observation scale and thus characterizing the scale effects in the assessment of hydrodynamic properties from pumping test analysis at local and regional scales (Jazayeri et al., 2011). Recent works focused on the karst drainage network development as a function of the hydrological, geodynamical and structural changes over time (Leonardi et al., 2011)

Recent studies also allowed proposing new results regarding hydrological modelling in karst watershed. For example, a distributed parsimonious event-based rainfall-runoff model was developed and applied on the Lez watershed upstream Montpellier (Coustau et al., 2011). On one hand, the model produces very satisfactory flash flood simulations, and on the other hand, its initialization is relatively easy thanks to a powerful relationship between the initial condition of the model and either the Hu2 index from the Meteo-France SIM model (soil humidity), or the piezometric levels. The interpretation of the model suggests that groundwater does not affect the first peaks of the flood, but can strongly impact subsequent peaks in the case of a multi-storm event. Because this kind of model is based on a limited amount of readily available data, it could be a crucial tool for flash floods real-time forecasting.

An original methodology based on neural networks was also developed to better understand the hydrodynamical behaviour of karst (Kong A Siou et al., 2011 a,b,c). A dedicated architecture allows to describe the recharge of the system according to its geological heterogeneity. This model allows refining knowledge on the behaviour and the delimitation of its alimentation basin (Kong A Siou et al., 2011 c). Global modelling based on reservoir model that takes into account flow through both the saturated zone and the unsaturated infiltration zone was developed to characterize the functioning of this aquifer under active water management (Fleury et al. 2009; Mazzilli et al., 2011)

The Lez hydrosystem was also studied to assess the role of karst in flood dynamics, with a specific focus on the consequences of the active management of the groundwater resource, which offers some new insights in the integrated water resource/flood management on these hydrosystems with a high karstic component (Jourde et al., 2011)

3. Conclusion and perspectives in terms of modelling and observation strategies

Flow modelling in karst hydrosystems implies various approaches to capture the spatio-temporal complexity of the studied site. Indeed groundwater

hydrodynamics differs from surface water hydrodynamics, which involve referring to different conceptual models. Furthermore, depending on the considered temporal scale, the dominant processes within the hydrosystem will not be the same. For example, at the temporal scale of a flash flood, the processes will notably differ from the processes at the scale of one or more hydrological cycles.

The distributed measurement of humidity and evapotranspiration, together with piezometric monitoring in different compartments of the hydrosystems will enhance both hydrological modelling for flash floods forecasting and recharge estimation for hydrogeological modeling and water resource evolution with time.

Developing a multi-tracer approach based on major and trace elements and emerging tracers (isotopes, Rare Earth Elements, fluorescence of Dissolved Organic Matter), a better characterisation of the water origins, water mixing and of potential anthropogenic contaminations has been achieved (Batiot et al., 2008; Bicalho et al. 2009, Bicalho et al. 2010; Bicalho et al. submitted). The hydrochemical monitoring already shows that the chemical signatures vary all along the hydrological cycle but also during a flood event. This change will enhance a better understanding of the various processes occurring in different compartments of the karst system.

It will be useful to distinguish different types of pedological and landscape units, where infiltration and evapotranspiration will be determined. Defining a mean soil permeability and evapotranspiration for each units and characterizing the variability of these parameters within one unit will be possible. Based on these results, a GIS analysis taking into account landscape use, pedology and geology, will facilitate the drawing of a map with these distributed parameters.

The different perspectives in terms of modelling and observation strategies can be listed as follows:

- Couple distinct models for the integrated and distributed simulation of the hydrological, hydrogeological and hydraulic processes in karst hydrosystems at different time scales (flood event, hydrological cycle) .
- Analyse the sensitivity and assess the uncertainty of the hydrological and hydrogeological models with regards to the main parameters (e.g. contrast between the hydrodynamic parameters of the different compartments, initial state of the system, soil humidity, recharge),
- Discriminate and quantify the distribution of the hydric fluxes (rapid and slow transfers) in each compartment of the hydrosystem.
- Characterize the transfer within each subsystem and develop distributed models taking into account the transfer within each compartment of the hydrosystem.
- Quantify the water storage variation with time and understand the role of the unsaturated zone on the long term storage of the aquifer.
- Quantify the recharge, which is a key variable for the assessment and management of groundwater resources in karsts

- Quantify the recharge-discharge relationships to estimate the sustainable yield of aquifers and determine the impacts of climatic change on the long term groundwater resources.
- Quantify the impact of anthropogenic forcing (pumping, active management) on the global water balance and hydrodynamic behaviour of the karst system.

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