Forecasting and mitigation of flooding in a Mediterranean karstic watershed

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Abstract Extreme rainfall on Mediterranean karstic watersheds can lead to flash floods that may cause serious human and material losses. The anticipation of these events and the risk management during flood events are at the core of society and financial stakes. Karstic aquifers should also be considered as valuable groundwater resources. An active management of these aquifers may allow for an optimal use of water resources, while regulating the influence of the karst during flood risk periods. This study was carried out in the framework of the "Multiple-Use Management of the Mediterranean Karstic Aquifer of the Lez River" project. It aimed at identifying the impact of the anthropic management of the water resource and floods under the present and future climate on the catchment. This project led to building a graphical method (toolbox for flood management presented as an abacus) for (i) a better understanding of the evolution of the water volume of the karstic system, the river discharge and the propagation of floods through constructed infrastructure of the river in urban areas, (ii) real-time flood forecasting, and (iii) analysing the impact of climate projections and active management scenarios with respect to the water in the karstic system as well as with respect to the flooding areas. The use of active management is thus shown to increase the availability of water resources while reducing flood risks.

Key words flood forecasting; active management of water resource; karstic system; climate change; Lez

THE KARSTIC MEDITERRANEAN CONTEXT AND THE LEZ PROJECT

Extreme rainfall on Mediterranean karstic catchments can lead to flash floods. Because these floods are unpredictable and rapid, they may lead to serious human and material losses. However, the presence of karstic aquifers leads to complex interactions between surface and groundwaters. The anticipation and mitigation of these flood effects and their evolution under changing climate represents a major challenge for nearby communities and public services. In order to improve the knowledge and thus the optimal management of the Mediterranean karstic Lez catchment water resources, the 4-year Multiple-use Management Lez project was initiated in 2009 (Fig. 1).

Because of the limited knowledge of the flux interactions between the surface and the subsurface, the project played a major role in obtaining a better optimization of water resources and flood risk management by the city of Montpellier. The first task aimed at enriching the

Fig. 1 The Lez project.

observation data base and allowing a better understanding of the physical processes. The following tasks consisted of: (i) developing the numerical models for the hydrogeological, hydrological and hydraulics physics, (ii) studying the vulnerability of the aquifer, (iii) improving flood risk management, and (iv) studying the impacts of climate change and pumping scenarios on water resource and floods.

This study aimed at developing models of the Lez karstic aquifer, catchment and river in order to have a better understanding of the hydrosystem. A graphical tool was derived from these models to improve real time flood forecasting. The impacts of climate projections and pumping scenarios were analysed with respect to the available water of the karst as well as with respect to the flood genesis.

The Lez catchment and its floods

The Lez spring and the temporary Lirou spring in southern France, are the main outlets of a karstic system developed in upper Jurassic limestone. These springs contribute to the discharge of the Lez River monitored at the station of Lavalette located upstream of the city of Montpellier (Fig. 2). The Lez at this station is a hydrological catchment of 114 km^2, the hydrogeological basin (including the area of the karstic springs) is estimated as 380 km^2. Several recharge zones can be identified within the catchment according to the nature of the exposed geological formation: (i) the Jurassic limestone (100 km^2) is the main area of recharge from effective rainfall; (ii) the Cretaceous marly-limestone formations (120 km^2), which are much less permeable than the Jurassic; and (iii) the Tertiary formations (160 km^2) that are generally impermeable and which do not significantly contribute to the karstic aquifer recharge. The watershed is covered in part with soil (forests or vineyards), and the other part has visible karstic outcrops (scrubland) with a poor urban cover.

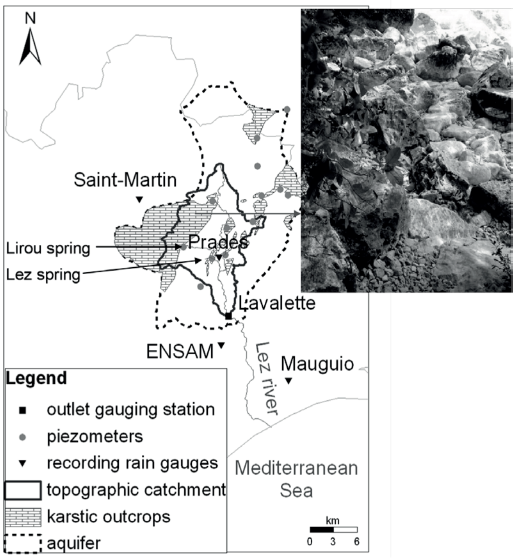

Fig. 2 The Lez catchment (Coustau, 2011).

The Lez spring is pumped for water supply purposes of Montpellier city with an active management, at a higher rate than the low-water spring discharge in the summer periods, thus enabling the aquifer’s stored resources to be mobilized during the low-water period. This translates into a lowering of the piezometric head ($H < 65$ m amsl) in the karstic drain causing the dry up of the karstic spring. The aquifer is not being overexploited, the annual volume pumped is less than the recharge annual volume.

Rainfall data (raingauges and corrected weather radar), discharge at the spring and outlet, water elevations in the river and piezometric levels are available hourly. Geological and topographic data are also available and were supplied by the MEDYCYSS Observatory. The

Mediterranean region is prone to flash flood events due to intense rainfalls. Coustau (2011) studied flash floods of the Lez. The peak discharge of the Lez River (Lavalette) for the 21 studied floods events ranges from 40 to 467 m^3/s. The observed peak discharge at the Lez spring is less than 10% of the measured peak discharge. Furthermore, the peak of the piezometric elevation can occur after the peak of the surface discharge at the outlet, even if the piezometric elevation rise has already started. The spring discharge presents the same delay. The water flux interactions between surface and groundwater during the flood events are not well known, but they still have an impact on the flood genesis. The runoff coefficient ranges from 0.17 to 0.97. False alarms frequently occur (cumulative rain greater than 100 mm without over-flow at spring). The time response of the catchment can be very short (2 h) and the propagation of the flood through the city of Montpellier is influenced and controlled by numerous constructed infrastructures.

Numerical models for the Lez hydrosystem

Three numerical models were developed (Borrell-Estupina *et al.*, 2012) to simulate the hydrosystem:

- The hydrogeological model developed with the TEMPO code (Pinault *et al.*, 2001) simulates the daily evolution of the piezometric level in the karstic drain and the matrix and calculates the overflowing discharge of the spring (Ladouche *et al.*, 2013). The modelling approach, based on the transfer method (impulse response) allows for the characterization of the behaviour of the complex karstic systems (Ladouche *et al.*, 2006; Dörfliger *et al.*, 2009). This model was used to estimate the impact of climate change on the water resource and test the karst behaviour for pumping scenarios.
- The hydrological model, based on the SCS function, was modified to take into account the role of the underground karstic system on the surface flood genesis (Coustau *et al.*, 2012). The transfer function over the hillslopes up to the outlet of the catchment is a classical Lag and Routing function. The four parameters of the model were calibrated using discharge from flood events greater than 40 m^3/s. The Nash criterion ranges from 0.54 to 0.94, with a mean value of 0.86. The water deficit of the model reservoir is the initial condition and can be estimated at the beginning of each flood. It is shown that this state is correlated with the piezometric elevation inside the main drain of the karstic system a few hours before the beginning of the rainfall.
- The hydraulic model solves the Saint Venant equations. It takes into account the detailed topography of the river (cross-sections, longitudinal profile, 19 inline structures and bridges) defined from a topographic survey made using differential GPS. The cross-sections include a minor bed, a medium bed with higher friction coefficient and a major bed for the flood plain. The discretisation of the Saint-Venant equations is made using the implicit Preissmann scheme. The calibration of the model is done with 12 studied floods. The unknown lateral runoff from the city is estimated from collected discharge in the Lez River using data assimilation. The movement of the automatic weir at Pont de l'Eveque is simulated using a PID controller whose coefficients were tuned using local measurements available in the data base of the city of Montpellier. The free water surface simulations are very close to the observed ones (Nash = 0.96). A complete sensitivity analysis was performed in steady and unsteady flows in order to define the uncertainty on each water-discharge simulation.

The analysis of the available recordings of pumping and piezometric elevations shows that on average over 1983–2010, the annual volume of pumping was 35 Mm^3 per year. For this study, the reference year was 2010 with 31.7 Mm^3. According to the INSEE and the Agglomeration of Montpellier, the population rate will increase by 0.9% per year by 2030, so that the pumping volume will increase to 40.4 Mm^3 by year.

Boé *et al.* (2006) developed a statistical dynamical scheme based on weather types and conditional resampling for climate. This methodology was implemented in the DSCLIM software (Pagé *et al.* 2009). The project SCRATCH2010 provides downscaled climate scenario. These scenarios included the improvements of Boé *et al.* (2007) and of the ANR-SCAMPEI project (Page & Terray, 2011). Nine of these scenarios were used here.

The simulations of floods required the coupling of these three models. They were then used to define a graphical tool dedicated to flash flood forecasting. It can be used to estimate the behaviour of the Lez catchment under climate projections or pumping scenarios.

RESULTS AND DISCUSSION

Analysis of the data set of flood events showed that the total amount of rainfall used by the hydro-system to fill up the kartsic system and also provided above a particular level, some surface runoff. It was observed in the numerical simulations, that above the threshold of 65 m amsl at the spring piezometer, it was the piezometric level in the main karstic drain that defined the runoff (Fig. 3).

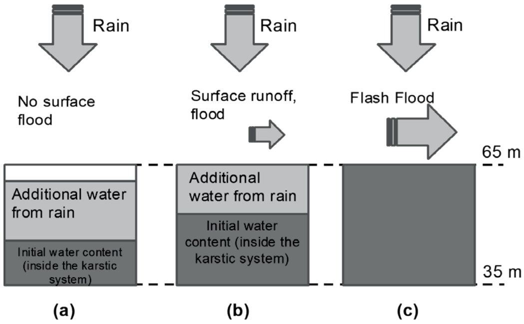

Fig. 3 The Lez karstic system behaviour during flood.

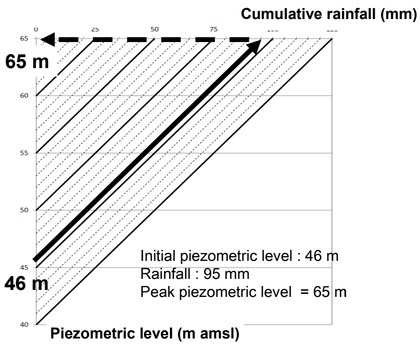

Fig. 4 Graphical simulation of the piezometric karst level under different rainfalls.

The graphical tool (Fig. 4, 5, 6) devoted to the flood risk relies on the proper description of:

- the hydrogeological behaviour that describes the response of the karstic system to a rainfall,
- the hydrological behaviour that allows the forecast of the surface flood upstream Montpellier, and
- the hydraulic behaviour that propagates the flood through the river and the engineering structures.

The use of this graphic tool is illustrated below in an example.

In September 2005, prior rainfall of 20 mm over a 10-day period saturated the soil of the watershed. With an initial piezometric level of 46 m amsl, the first 95 mm of rainfall filled the karstic system. The piezometric level increased to 65 m amsl, which is the threshold for overflow (Fig. 4). The 110 mm of rainfall during the next 3 h then contributed to the surface flood. The average rainfall intensity of 37 mm/h was high enough to be considered as extreme. The peak discharge estimated by the graphical tool was 460 m^3/s compared to the measured 467 m^3/s (Fig. 5).

Downstream, in the city of Montpellier, the river water level reached over 16 m amsl (Fig. 6). The system was considered as an orange vigilance level for the flood managers, very close to the red vigilance level.

The quick overview of the potential level of risk of the forecasted hydrological situation provided by this tool is of great interest. Still, it remains limited as it does not provide information

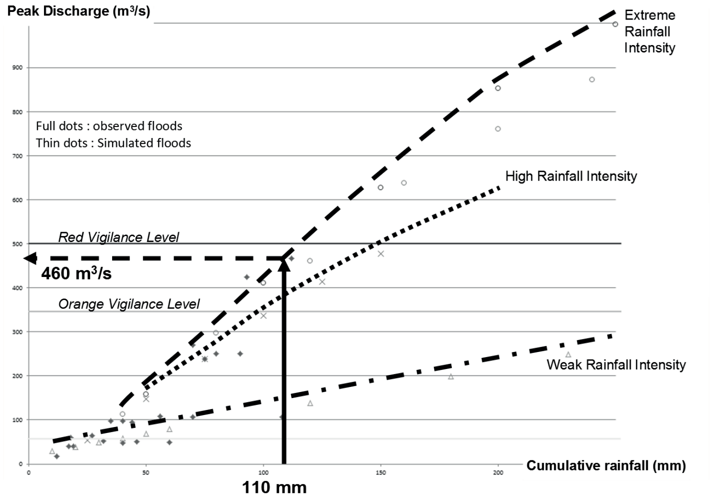

Fig. 5 Graphical simulation of the peak discharge according to the intensity and amount of rainfall.

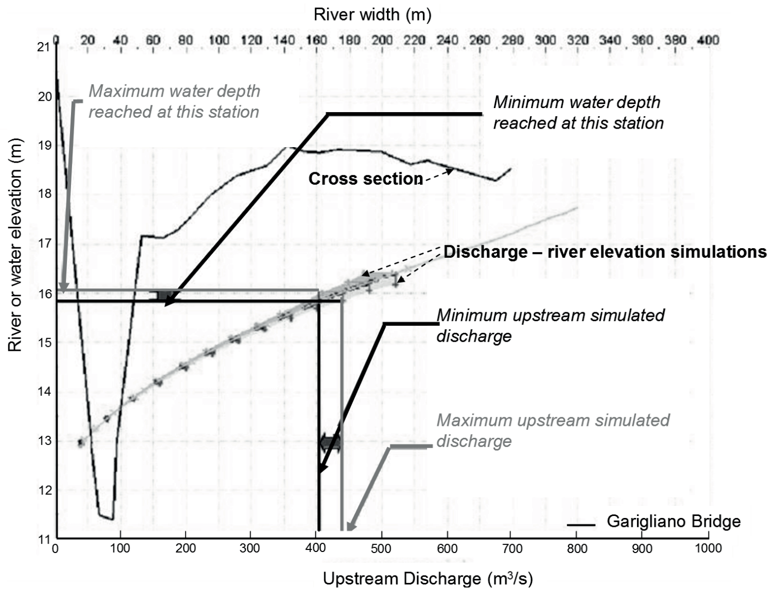

Fig. 6 Graphical simulation of water elevation at Garigliano station for different peak discharges upstream.

about the temporal evolution of the flood. Indeed, the correlation between cumulative rainfall, piezometric level and peak discharge is observed while analysing the flood water balance. Heterogeneities in the rainfall over the catchment are not integrated into this approach. While distributed rainfall could be treated with different graphical tools, this approach was not implemented in the Lez project prototype for the sake of simplicity. Additionally, it should be noted that the intensity of the rainfall strongly influences the flood genesis, so that a higher temporal resolution and accuracy in the weather forecasts is needed.

Finally, the water elevation forecast is computed from the Lavalette discharge, without any lateral inflows from the city. Heterogeneous rainfall could lead to high runoff from the city of Montpellier up to the Lez River. Therefore the free water surface elevation perhaps could be underestimated.

PROJECTIONS: CLIMATE CHANGE AND IMPACTS

The analysis of the past 30-year series of five raingauges and temperature observing stations of the region shows a Mediterranean behaviour with high cumulative rainfalls during autumn, that tends to increase over time, and an increase of the mean temperature in summer and spring (Maréchal *et* *al.*, 2013). These results are in agreement with recent works by Chaouche *et al.* (2010) and Lespinas *et al.* (2010).

The analysis of the future climate (2045–2065) is achieved by Maréchal *et al.* (2013) over nine disaggregated climatic scenarios (greenhouse gases mean emission A1B according to the IPCC (Nakicenovic & Swart, 2000)). It shows an increase of the average monthly temperature between +1.5°C and +2.3°C (±1°C). Still, there is no significant trend in the future simulated rainfalls. The multi-model analysis shows that the forecasted average of the monthly rainfall decreases by –5 to –10% over the year. The accuracy of these results has yet to be discussed because of a very strong variability between the scenarios (mean variations of ±50% in comparison with the present). Even if this future trend is in contradiction with what was concluded over the past 30-year period, the very high variability of the simulated rainfalls shows how inaccurate the future cumulative rainfall is.

Considering both climate and pumping changes, the tested scenarios do not induce over-exploitation of the karstic system (because the pumped volume remains under the refill volume). The average of the minimum piezometric level is predicted to decrease with a monthly variability (Fig. 7) and the expected change in the storage capacity of the karst during the flood that can reach 75 mm (equivalent rainfall) in August and September (Fig. 7).

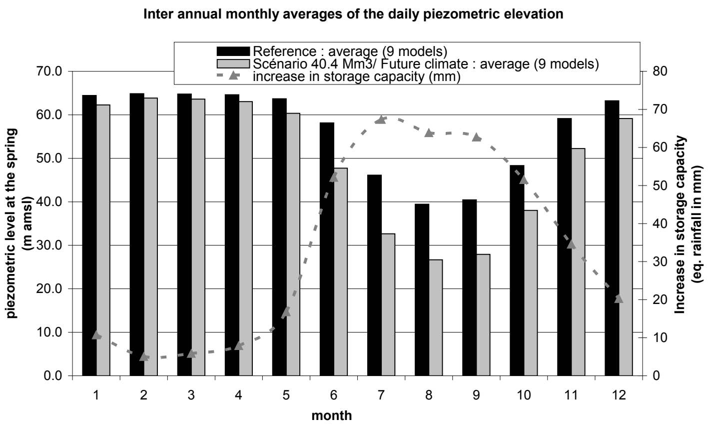

Fig. 7 Comparison of the inter annual monthly averages of the daily piezometric elevation. In black the present climate(1971–2000) with a median pumping (33 Mm^3/year). In grey the future climate (2046–2065) with a pumping of 40.4 Mm^3/year, the averages are calculated with the nine climate models. Standard deviation is of 0.2 for the present series and 4.1 for the future series.

Considering the graphical tools and the simulated scenarios, it appears that the effect of a decrease in the initial piezometric level on the flood genesis is significant for any climate change. For an initially saturated karstic system (65 m amsl at the spring), the orange vigilance level is reached for a rainfall of 100 mm (with a weak rainfall intensity). If the initial karst level is at 20 m amsl, the same rainfall will not produce any discharge. To summarize, the higher the initial karst level, the greater the rainfall influences the flood discharge. Thus an increase in the pumping in the karst can improve the reliability of the flood forecast, while reducing the flood risk.

Nevertheless, one strong hypothesis was made: even if these simulations are out of the calibration range (20–35 m abs against 35–65 m amsl), the behaviour of the hydrosystem is supposed to be the same. Thus the flood intensities could decrease because of a possible mitigation by the karst storage. The impact of this active management under an increase in temperature (and as a consequence in evapotranspiration) in terms of flood peaks varies according to the initial water content of the karst and to the rainfall intensity and can be evaluated with the graphical tool for any rainfall predictions.

CONCLUSION AND PERSPECTIVES

By the active management of the Lez karstic system, it is possible to increase the availability of water resources, even under climate change, in order to satisfy the growing water needs of the city of Montpellier. As a consequence of the greater pumping of the groundwater, flood risk on the city of Montpellier can also be reduced.

The graphical method developed in the framework of the Lez project is useful for (i) flood forecasting, (ii) the free water surface evolution through the river and its constructed infrastructure and (iii) the estimation of the impact of different pumping scenarios on flood genesis.

It is currently being tested by the regional flood forecasting service (SPC and SCHAPI). The impact of active management on water resources is also analysed by the Montpellier water managers (Agglomeration of Montpellier).

Further research should be carried out on the false alarm cases. Future studies should also focus on the coupling of the three numerical models and their real-time runs (Coustau *et al.*, 2012), (Harader *et al.*, 2013), as well as on the impact of non stationarity of timing of the karstic system and its watershed behaviours.

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