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Prediction of future interactions between karst and river regarding to climate change based on IPCC scenarios: application to a Mediterranean french river basin (Cèze)

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Abstract Groundwater in karst aquifers is a valuable resource in Mediterranean region which is particularly threatened by climate change. Climate change induces an increase in evapotranspiration and a decrease in rainfall available for groundwater resource. This impacts directly karst aquifer recharge and thus indirectly karst-river interactions. The study site is a karstic catchment located in the Mediterranean French river basin and known as the “Gorges of the Cèze River”. This site has been studied through interdisciplinary research since 2014 to improve understanding on hydrogeological functioning of this catchment. The river at different points and each of its karstic springs have been equipped with probes and studied by multiple metrics (geochemistry, biology, radioactivity...). As a continuation of these researches, this paper presents an attempt to model the interactions between the whole karstic catchment of the Gorges and the Cèze river and then to predict their evolution regarding to climate change scenarios. The model has been developed using Karst-Mod software, which consists in an adjustable modelling platform. Firstly, the model has been calibrated on one hydrological cycle and then validated on the following cycle. After that, future climate dataset was simulated by the ALADIN model, according to Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP) scenario data, including the study area in the above-named model in order to predict karst and river interactions and water production for the period 2030–2100. The results of this work are presented in terms of volume of water produced for three simulations corresponding to three RCP scenarios (2.6,4.5, and 8.5).

Keywords Climate change • groundwater resources • Mediterranean • karst aquifers • modeling • IPCC

1 Introduction

Groundwater in karst aquifers is a precious resource representing 25% of domestic water consumed in Mediterranean region (Margat 1998). Climate change is jeopardizing this resource by provoking more frequent and intense droughts (Cramer et al. 2018). Understanding groundwater flows, recharge, and discharge processes in karst aquifers is crucial to enable sustainable water management (Bakalowicz 2004). Groundwater flow modeling is recognized as a major tool for water management purpose. It can be achieved using lumped models which consist in a rather simple parameter-based approach to reproduce the hydrogeological functioning of an aquifer (Pascoletti 2018). The functioning of karstic springs has already been successfully simulated using lumped models (Fleury 2005). Nevertheless, modeling the water production of a whole and complex karstic catchment is still limited to few attempts. Furthermore, the hydrogeological modelling of a karstic catchment has still not been used to simulate the impacts of climate change. This paper presents an attempt to model the karstic water discharge along a whole section of the Cèze River and to predict its quantitative evolution according to IPCC's climate scenarios using

2 Material and methods

Study area

The study area (Fig. 1) belongs to a large karstic catchment located in the South of France. It consists in a calcareous plateau incised by the Cèze River, a tributary of the Rhône River, which length is 128.3 km and average flow 22 m³/s. This site is, since 2014, the subject of a multidisciplinary research (Chapuis 2017) which aims to characterize exchanges between Cèze River and its aquifer (Pascoletti and Chapuis 2022) and to meet a territorial policy promoting sustainable water management in Mediterranean context. Geological studies suggest interactions between river and Lower Cretaceous, Barremian and Lower Aptian (so called Urgonian) formations which constitute a highly karstified calcareous geological unit. This aquifer is mainly recharged by rainfall in spite of some inflows from river losses. Rainfall is characterized by a dry period from June to September with an average of 33

mm/month and a wet period from October to December with an average of 88 mm/month. The discharge areas correspond to the karstic springs located along the river and contributing to its flow.

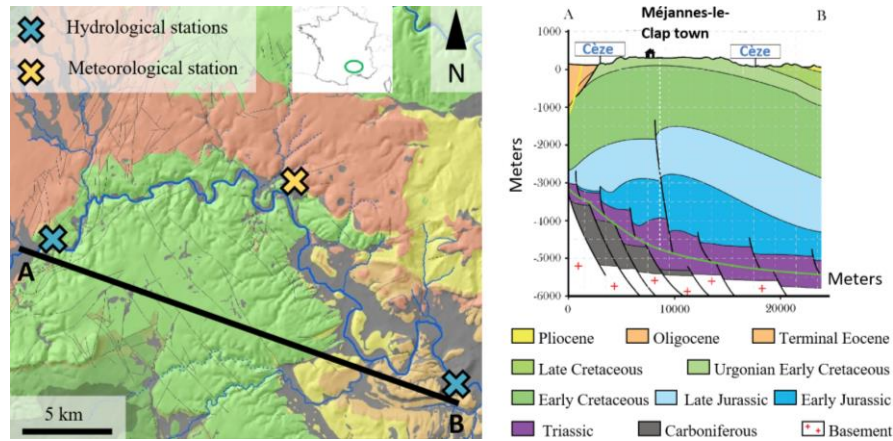


Fig. 1. Location map of the study area (modified from Chapuis 2017)

Data and software

The model has been developed using KarstMod software which can reproduce the structure of conceptual lumped models of karst systems (Mazzilli et al. 2019). The hydrological data used to calibrate and verify the model presented below are provided by the French Ministry of Environment “Banque Hydro”. Two stations, in Tharoux and in La Roque-sur-Cèze were chosen to encompass the studied catchment (Fig. 1). The average daily flow measured by these stations during two hydrological cycles (14/10/2013 to 13/10/2015) were thus retrieved. Meteorological data produced by the French weather service “Météo France” have been used as inputs to drive the model. The station located in Montclus has been chosen because of its central geographic position (Fig. 1). To simulate future karst hydrology, data produced by the National Centre for Meteorological Research (CNRM) according to IPCC works’ (2014) were included in the model. These data proceed from meteorological simulations realized in 2014 from three RCP scenarios (2.6, 4.5 and 8.5). These data were produced at regional scale (12 km mesh). The coordinates of the chosen point on the grid (44.27090, 4.38973) corresponds precisely to our study site.

Model calibration and validation

From the above-described meteorological dataset, only the precipitation data has been injected into the model. The evapotranspiration served to determine a fitted sine function (regression coefficient: 0.84) to be used in the model (Fig. 2). Using a sine function rather than raw data seems to offer better results (Chapuis 2017).

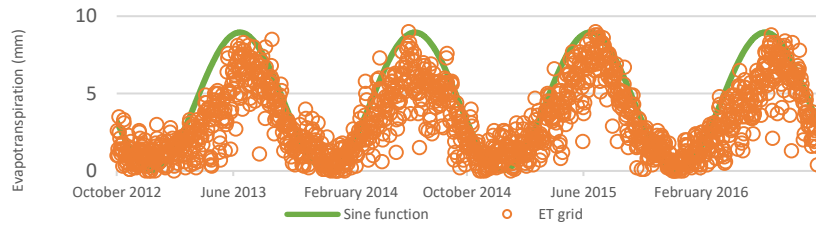


Fig. 2. Fitted sine function for evapotranspiration

The hydrological data were used to calibrate the model which aims to simulate karst water net production, that is to say the total inflow from karst left in the river in the end of the studied section. The method used to evaluate it, for each day, consists in subtracting downstream flows (measured at Tharoux) from upstream flows, (measured at La Roque-sur-Cèze). Flows thus obtained comprehend a proportion of superficial water considered as minimal because Cèze tributaries in the studied catchment are mainly intermittent. These flows also include a few negative values due to river losses or measurement errors. Those were replaced by “NOINTERP” in the input file so that KarstMod does not take them into account. Moreover, the obtained data contained an odd value briskly reaching 163 m³/s on the September 13, 2015 while the flow of the previous day was -104 m³/s. Both original flows (at Tharoux and at La-Roque-sur-Cèze) on that day were in fact estimated and not properly measured. Thus, this odd value has also been replaced by “NOINTERP”.

The model structure (Fig. 3) includes three compartments and seven discharges. QS is a sum of four outflows, two from the main compartment (E) and two others from two subcompartments (M and C). QEM and QEC are two different flows transferred from E to M and C, respectively. Qloss corresponds to lost outflows which not contribute to the final discharge.

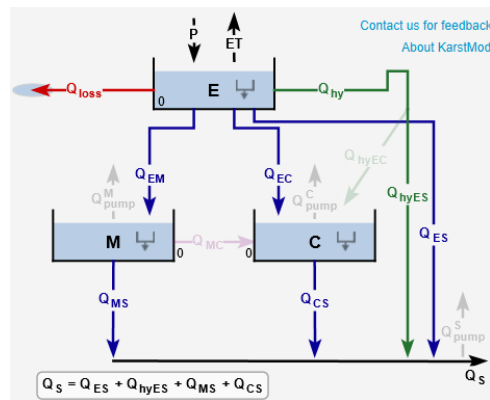


Fig. 3. Model structure

The Nash–Sutcliffe Efficiency coefficient (NSE) has been set at 0.8 directly in the software, so that KarstMod only seeks for models above 0.8. The calibration period has been defined to span the first 365 days and the validation period the next 365 days. A maximal value of 600 km² for the recharge area has been defined and the other parameters have been left unsettled. KarstMod has then been launched and successfully determined a set of parameters allowing the model to meet the predefined performance objective.

Simulation of future karst-river interactions

The calibrated and validated model has then been used to simulate net water production of the Gorges of the Cèze for 2030–2100 period considering three RCP scenarios. Three input files containing precipitation and evapotranspiration data for each scenario were constituted. While precipitation data (rain added up to snow) can be found directly in the CNRM dataset, evapotranspiration has to be calculated. It was done using the other available parameters and with Abtew (1996) method:

$$ET0 = K \cdot \frac{R_s}{\lambda}$$

- R_s : solar radiation expressed in MJ.m⁻².d⁻¹
- λ : latent heat of vaporization equals to 2.45 MJ.kg⁻¹
- K : dimensionless coefficient

In comparison with other methods, Abtew equation gives satisfying results (Xu and Singh 2000; Ndiaye et al. 2017). Besides, it only uses few meteorological parameters. Solar radiation (R_s) is also known as global radiation, which is the sum of direct shortwave radiation from the sun and diffuse radiation (Oudin 2004). Thus, the so called surface downwelling shortwave radiation in CNRM dataset can be used. Fig. 2 Fitted sine function for evapotranspiration Fig. 3 Model structure Prediction of Future Interactions Between Karst and River ... 109 The latent heat of

vaporization (kP is the energy required to change water from liquid to vapor in a constant pressure and constant temperature process. The value of the latent heat varies as a function of temperature. As k varies only slightly over normal temperature ranges, a single value of 2.45 MJ kg^{-1} can be used, which corresponds to the latent heat for an air temperature of about $20 \text{ }^\circ\text{C}$. Finally, K has to be determined in order to calibrate evapotranspiration to the data presented in Fig. 3. To make the calculation of the evapotranspiration closer to reality and to be coherent with CNRM simulations, solar radiation parameter proceeding from these has been used. Data from RCP 8.5 scenario have been chosen, because it seems to correspond to the late climate evolution (Schwalm et al. 2020). The calculated evapotranspiration fits the sine function when $K = 0.65$ (regression coefficient: 0.78).

3 Results

The model offers a rather close reproduction of karst net water production for two hydrological cycles (Fig. 4). It reaches an NSE value of 0.812 and 0.804 for calibration and validation periods and estimates a 593 km^2 recharge area.

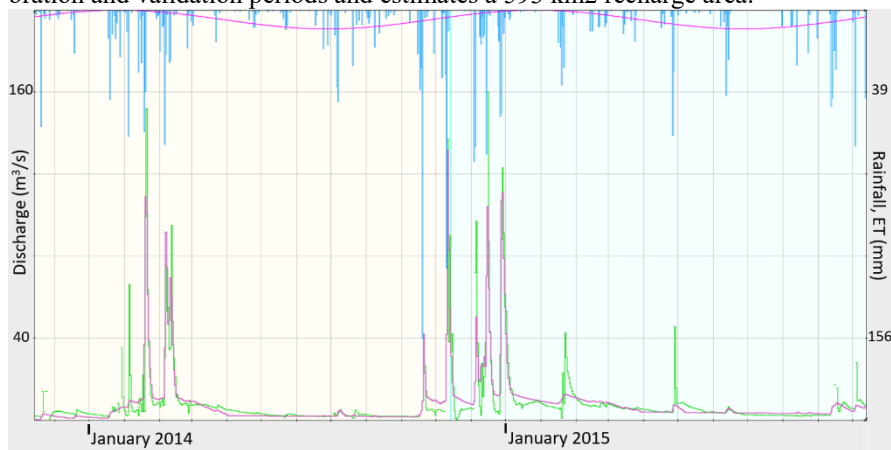


Fig. 4. Observed flow in green versus simulated flow in pink

Then, this model has been used to simulate karst net water production for the years to come. To analyze the data produced by the simulations, a graph comparing the cumulative volumes of water produced by the studied catchment according to the three different RCP scenarios has been drawn (Fig. 5).

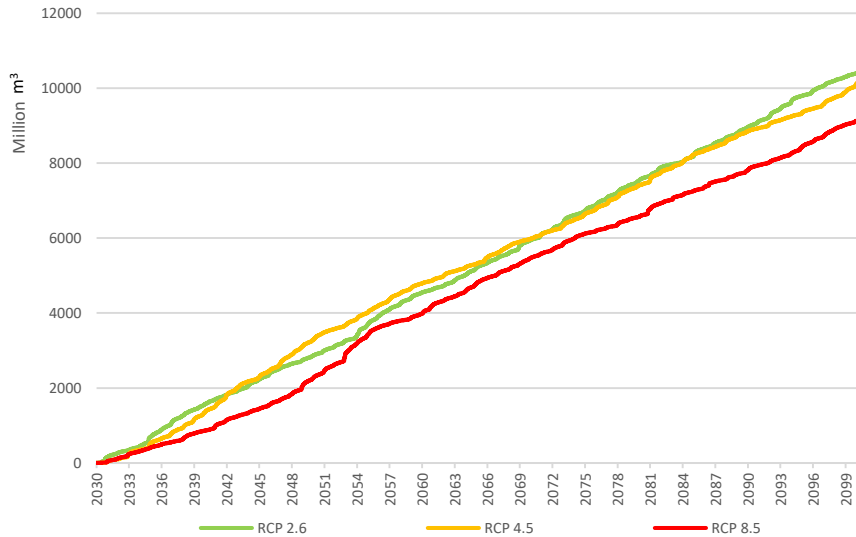


Fig. 5. Cumulative volumes for each RCP scenarios

4 Discussion

Interpretation

The model reproduces karstic net water production in a satisfying way. However, the model seems to have difficulties to emulate all peaks discharges, which is a very common flaw in hydrological modeling. As an example, in January 2014, when two peaks, both followed by a brisk recession, occurred, the model only simulates a concentration curve growing progressively. But in general, whilst simulated peaks are lower, the recession occurs more slowly. So, KarstMod smooths the curves and stretches the flows, probably to fit statistical laws. KarstMod also tends to give a regular aspect to the curves, whereas some curves' shapes proceeding from the original data seems odd, like the one in November 2014 which consists in a sudden growth and decrease.

Simulating future karstic hydrology with KarstMod produces results in terms of flows and volumes. For interpretation purposes, cumulative volumes are more relevant as they help to cast light on possible trends regarding to climate change. It seems that the curves presented in Fig. 5 are in correlation with RCP trends, because the more the scenario is pessimistic the less the karst produces water. Whilst water production curves for RCP 2.6 and RCP 4.5 scenarios are close, the one correspond-

ing to RCP 8.5 scenario appears to be very distinct. RCP 8.5 is indeed a very pessimistic scenario for climate evolution and considering Fig. 5, it also seems to be very pessimistic for future karstic groundwater production and interactions between karst and river in terms of flow. At the end of the simulation period, around 1 billion m³ of water less has been produced by the catchment in the case of RCP 8.5 scenario compared to RCP 2.6 scenario. This is, on average, somewhat equivalent to an annual loss of about 14 million m³ of water, which represents around 7% of the amount of water produced by the studied catchment during the hydrological cycle used for calibration step (2013–2014).

Limits

Such a modeling attempt necessarily implies some limits which have to be mentioned. Firstly, calibrating the model helps determine the best way to simulate the hydrological functioning of the studied catchment for a limited period of time, then, this functioning is used for the whole period 2030–2100, but really karst hydrological functioning may evolve because it's a dynamic process. Another common pit-fall when modeling is the calculation of the recharge area. To meet the performance objectives, the calibration step may lead to an overestimated recharge area. Here it has been estimated at 593 km², a reasonable value although somewhat elevated. KarstMod determines this value during calibration step within a range of value set by the user. But, it is noticeable that the more the range is low, the less the performance objectives are easily met. Hydrological and meteorological data used to develop the model also encourage to be cautious because of uncertainty in measurement. Obviously, there are among hydrological data some surprising values that may be due to measurement errors.

Furthermore, some of them are not measured but estimated. The proposed methodology to determine karstic water production also implies limits, especially through the existence of negative flows, which can proceed from measurement errors or from important losses in the river that can occur "randomly". This makes the modeling approach even more complicated. The presented methodology also implies that karstic net water production contains a part of surface water, here considered as minimal but still existing. Concerning the meteorological data, evapotranspiration calculation is a frequent factor of uncertainty because it depends on a lot of other meteorological parameters. For the prediction part of this work, Abteu method has been selected because it seems trustworthy regarding to other works and can be applied even if few meteorological parameters are available for evapotranspiration calculation. But, this method is one among other existing methods. This work is also based on IPCC and CNRM climate models. But, it is noticeable that uncertainty also exists in climate projections, which clearly appears when comparing different models (Ly et al. 2019).

In sum, trying to predict future contribution of karstic flows remains an ambitious undertaking exposed to several uncertainties, even if the methodology presented

here is coherent and even if the model proves to be reliable considering its performances.

Perspectives

The work presented here enables several perspectives to gain more in-depth knowledge of the subject. It would be interesting to observe how the karstic water production of the catchment evolves during the years to come to compare this evolution to the projections made in this paper and to adjust the model if necessary. It would also be interesting to improve the knowledge of the functioning of the studied catchment by extending the calibration period of the model. This would be an opportunity to understand karstic hydrological processes in a more dynamic way. For that purpose, it would be useful to evaluate the part of superficial water in the karstic net water production calculated here and to subtract it in order to gain a better appreciation of the exact groundwater outflows.

Furthermore, the methodology that has been followed throughout the study can easily be applied to another karstic catchment. As an example, it could easily be used for a study site like the Ardèche River and its karstic catchment that shares the same climate regime and the same geological context, even if its hydrological scale is larger.

Finally, the model constructed for the research presented here rest upon a triplet of models: RCP/GCM/RCM (respectively: Representative Concentration Pathway, General Circulation Model, and Regional Circulation Model). But different types of GCM and RCM models are available. As an example, simulations obtained from climate models developed by the Pierre-Simon-Laplace Institute (IPSL) or by the Swedish Meteorological and Hydrological Institute are also available. Using these simulations as input data and comparing the results with those presented here could be interesting. Moreover, climate models are constantly updated. New simulations, provided by French laboratories of climate simulations are available since 2020. The latest IPCC report is also available and will probably be translated soon in new climate simulations adapted to French regional scales.

Conclusion

The model developed with KarstMod is reproducing karstic water net production of the studied area, which is the sum of flows provided by the karst to the Cèze River and remaining in it at the end of the studied section. The structure of the model is rather simple, because it comprehends only a few compartments and flow exchanges. But its performance is satisfying as a NSE value of 0.812 and 0.804 is

reached for calibration and validation periods each spanning one hydrological cycles. Then the model has been used to simulate the future karstic water net production by using CNRM meteorological simulations at regional scale which rest upon three RCP scenarios from the IPCC. It appears that the hydrological trends presented in this paper are in correlation with RCP trends. In fact, the more the scenario is pessimistic, climate wise, the less the karst produces water. Whilst water production evolution for RCP 2.6 and RCP 4.5 scenarios looks similar, the one corresponding to RCP 8.5 scenario is very distinct. RCP 8.5 appears to be very pessimistic for future karstic groundwater production and interactions between karst and river in terms of flow. RCP 8.5 scenario represents around 1 billion m³ of water less in comparison with RCP 2.6 scenario for the whole simulation period. That being said, one should focus on trends rather than such an estimation because trying to number the evolution of karstic production of water remains very challenging and submitted to uncertainties.

Still, the knowledge acquired through this study aroused the interest of water stakeholder. Thereby, the model developed is also expected to be a pedagogical tool to help water management policy, considering that the model presented here has the advantage of focusing on a regional scale. Climate projections and observation of hydrological trends could be a way to anticipate and adapt to change, which could be decisive in a sensitive area like the Mediterranean region.

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