Journal of Hydrology 519 (2014) 3178–3192

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Performance and complementarity of two systemic models (reservoir and neural networks) used to simulate spring discharge and piezometry for a karst aquifer

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ARTICLE INFO

Article history:
Received 9 January 2014
Received in revised form 10 October 2014
Accepted 14 October 2014
Available online 23 October 2014
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Barbara Mahler, Associate Editor

Keywords:
Karst
Modeling
Neural networks
Reservoir model
Water management

SUMMARY

Karst aquifers can provide previously untapped freshwater resources and have thus generated considerable interest among stakeholders involved in the water supply sector. Here we compare the capacity of two systemic models to simulate the discharge and piezometry of a karst aquifer. Systemic models have the advantage of allowing the study of heterogeneous, complex karst systems without relying on extensive geographical and meteorological datasets. The effectiveness and complementarity of the two models are evaluated for a range of hydrologic conditions and for three methods to estimate evapotranspiration (*Monteith*, *a priori* ET, and effective rainfall). The first model is a reservoir model (referred to as VENSIM, after the software used), which is designed with just one reservoir so as to be as parsimonious as possible. The second model is a neural network (NN) model. The models are designed to simulate the rainfall–runoff and rainfall–water level relations in a karst conduit. The *Lez* aquifer, a karst aquifer located near the city of *Montpellier* in southern France and a critical water resource, was chosen to compare the two models. Simulated discharge and water level were compared after completing model design and calibration. The results suggest that the NN model is more effective at incorporating the nonlinearity of the karst spring for extreme events (extreme low and high water levels), whereas VENSIM provides a better representation of intermediate-amplitude water level fluctuations. VENSIM is sensitive to the method used to estimate evapotranspiration, whereas the NN model is not. Given that the NN model performs better for extreme events, it is better for operational applications (predicting floods or determining water pumping height). VENSIM, on the other hand, seems more appropriate for representing the hydrologic state of the basin during intermediate periods, when several effects are at work: rain, evapotranspiration, development of vegetation, etc. A proposal for improving both models is also provided.

1. Introduction

Karst aquifers are well known for the large quantity of freshwater they supply to the world's population, currently estimated at some 25% (Ford and Williams, 2007). Karst systems are characterized by a highly heterogeneous structure, leading to complex underground stream flows that are neither fully observable nor accurately measurable. It is therefore difficult to develop a realistic model that includes physical assessments of the operation of karst systems. Moreover, structural heterogeneity introduces additional nonlinearities and thresholds into the relation between rainfall and the overflow discharge of the spring (hereafter referred to as the "rainfall–discharge relation"), thus complicating the identification of the rainfall–discharge relation without precise knowledge of the karst structure. For this reason, since the 1970s models have become much more elaborate (especially the rainfall–discharge model) (Mangin, 1975; Thiery and Bérard, 1984; Najib et al., 2008; Jukić and Denić-Jukić, 2009; Tritz et al., 2011). Conceptual or systemic models have been developed to provide an approach that does not require accurate assumptions about the physics and detailed geometry of the karst system. Nevertheless, few comparative evaluations of these two approaches have been conducted, and only rarely by specialists familiar with both. The aim

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http://dx.doi.org/10.1016/j.jhydrol.2014.10.041
0022-1694/

of the present study is to compare the performances and complementarity of two systemic models applied to the hydrodynamic modeling of karst aquifers: a neural network (or NN) model, and a reservoir model developed using the VENSIM® software.[1] The NN model involves a statistical approach using no *a priori* information about the system. VENSIM, on the other hand, relies on a more classical procedure that considers the aquifer behavior as one or several reservoirs. Even though both models have already been presented in the literature; the present study includes specific experiments and arrangements of both models to be compared. In addition, several evapotransporation (ET) estimations are tested in order to assess the sensitivity of the two models to this non-measurable quantity. The two models are compared in terms of a series of criteria: parsimony, calibration and performance relative to hydrological conditions (flood, low water level, intermediate floods ...). We should also point out that each model was used by a specialist team in order to generate the best possible calibrations and simulations.

In addition to the introduction and conclusion, this paper consists of four parts. The first will focus on presenting the two models, VENSIM and NN, within their respective system frameworks. The second part will describe the basin targeted for this comparative assessment, the *Lez* karst aquifer, as regards its complex geological structure, climatic characteristics and relevant available data. The *Lez* aquifer performs a critical function in supplying freshwater to the city of *Montpellier*, France (400,000 inhabitants). In addition, this aquifer is exposed to a Mediterranean climate, renowned for major rainfall events during the autumn and hot, dry summers. In this climatic context, it is extremely important to develop models that include evapotranspiration; however since evapotranspiration cannot be accurately measured or estimated and given the level of dryness observed in Mediterranean climate zones, special attention has been paid to the way such information is fed into the models.

The third part will provide each model's specific design and results for the *Lez* Spring discharge and water level simulations; this output is dependent on the specific model and evapotranspiration introduced. The fourth and final section will discuss the results obtained and propose interpretations and potential improvements for both models.

The conclusion will summarize the approach adopted and assess the effectiveness and of these two models relative to hydrological conditions and the type of evapotranspiration.

2. Conceptual and systemic modeling of karst aquifers

As highlighted in the introduction, karst systems are well known for their physical heterogeneity, which stems from both the karstification process (i.e. enlargement of fractures and faults, Bakalowicz, 2005) and their geology (Ford and Williams, 2007). Such complexity can be incorporated into hydrodynamic modeling through the use of stochastic approaches, e.g. in simulating virtual karst networks consistent with the overall physical knowledge available for the target basin (Collon-Drouaillet et al., 2012). Other approaches are deterministic; for instance, conceptual approaches rely on global concepts, with saturated or unsaturated zones as the underlying operating hypothesis (Fleury et al., 2009). Ultimately, when no physical constraints or hypotheses are provided regarding behavior, then purely data-driven models must identify both the "concepts" and parameters that fit the observed behavior (Kurtulus and Razack, 2007).

As regards data availability, the ideal physical model requires field measurements in order to assign parametric values; a conceptual reservoir model makes use of a calibration phase to calculate its parameters, which generally offer realistic, though not physical, values. Models of the third type themselves determine both the "concepts" and parameters. Machine learning models (e.g. neural networks or support vector machines) fall into this type; they require a training phase to simultaneously calculate both the functions and their parameters during the same training step. Hence, the greater the knowledge of the process being modeled, the greater the reason for choosing physical models. Conversely, with less knowledge of the process being modeled, data series become more essential and need to be longer and more accurately sampled. Representing the goal of the modeling approach, the dataset must represent the targeted behavior. The calibrated systemic model is then representative of the hydrosystem behavior under the conditions encountered in the database. Taking the above considerations into account, the modeling of a complex karst aquifer should entail the use of conceptual or machine learning approaches. Both our test models have shown their effectiveness (Fleury et al., 2007, 2009; Jukić and Denić-Jukić, 2009; Kurtulus and Razack, 2007; Kong-A-Siou et al., 2011a,b), but with comparisons and analyses rarely presented in the same study by specialists of each method. The present study will therefore target that specific goal. Two models (a reservoir model and a neural network model) that utilize time series in their design will be presented in the following section and subsequently applied in Section 4 in order to model a karst aquifer associated with a critical water supply resource: the *Lez* aquifer.

2.1. The reservoir model: VENSIM

VENSIM is a conceptual model designed to simulate spring discharge as well as water level variations in the saturated zone, i.e. within the karst conduit, thus making it possible to estimate the quantity of reserves stored in the saturated zone. This conceptual model was implemented by considering that the karst system could be represented by several reservoirs, each with different characteristics and behavior: two reservoirs were used to represent fast and slow infiltration respectively, with connections to a third reservoir, introduced to represent the saturated zone of the karst. This model had previously been calibrated for the *Lez* Spring simulation (Fleury et al., 2009). The objective of the current study is to develop a new minimalist model with as few parameters as possible in order to enhance model robustness.

2.1.1. The one-reservoir VENSIM model: concepts and hypotheses

To provide a new, more parsimonious model, thus less sensitive to over-parameterization, only one reservoir was used instead of the three presented in the previous study (Fleury et al., 2009). In the previous work the model was intended to implement a physical assumption in modeling the saturated and unsaturated discharge. Both flows had been correctly simulated using Maillet's Law, which describes reservoir outflow through a porous outlet (Maillet, 1905). During high water level conditions, the model had thus evaluated volume in both the saturated and unsaturated part of the aquifer. In the present work the parsimony choice (only one reservoir), implied that only discharge and volume in the saturated zone were calculated. The aim of the present study was thus not to represent different parts of the aquifer as performed by a physical model but to simulate discharge and volume in a systemic way. To this end, both infiltration reservoirs were replaced by introducing the effective rainfall directly into the lone reservoir, which thus represents both the saturated and the unsaturated zone. The discharge from this type of reservoir is assumed to be proportional to water height in the reservoir. It is also assumed that the reservoir outlet discharge obeys Maillet's Law. This hypothesis is somewhat unrealistic in karst aquifer modeling,

[1] VENSIM Software. Ventana Systems, Inc. http://www.vensim.com.