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A step-wise semi-distributed simulation approach to characterize a karst aquifer and to support dam construction in a data-scarce environment

R. Adinehvand [a], E. Raeisi [a], A. Hartmann [b,c,*]

[a] *Department of Earth Sciences, Shiraz University, Iran*
[b] *Institute of Earth and Environmental Sciences, University of Freiburg, Germany*
[c] *Department of Civil Engineering, University of Bristol, UK*

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ABSTRACT

Karst systems provide significant volumes of drinking water for large parts of the world population. Due to chemical weathering, karst systems are characterized by strong heterogeneity resulting in a complex flow and storage behaviour. Presently available karst modelling strategies account for the karstic heterogeneity but often a lack of data limits their applicability in data-scarce regions. In this study, a step-wise simulation approach with a semi-distributed karst model is proposed to characterize a karst aquifer at a data-scarce region in Southwest Iran and to evaluate the leakage potential related to a future dam construction project at a river that cuts through the aquifer. Observed groundwater level time series were applied to calibrate and validate the model. In order to avoid over-parameterization, the karst aquifer was split into three sections down the hydraulic gradient. At each section, groundwater level observations were used to iteratively calibrate the model from the first to the last section. A spatial split-sample test and sensitivity analysis served to evaluate the prediction performance and the identifiability of the model parameters. Finally, simple scenarios of the river infiltration into the aquifer were applied to evaluate the leakage potential of the aquifer for future dam constructions. The spatial split-sample test showed that the semi-distributed model provided reliable predictions but prediction performance and parameter identifiability decreased from the first towards the last aquifer section, most probably due to increased aquifer complexity and propagation of uncertainty from the up-gradient model section. Using sensitivity analysis, we also show that parameter sensitivities increase significantly if parameter estimation was applied simultaneously to all three aquifer subsections. Using the model to assess the leakage potential indicated that, without further technical measures, the all river flow would be able infiltrate into the aquifer and the dam would never be filled up completely.

1. Introduction

About 7–12% of the earth's continental surface is covered with carbonate rocks and a quarter of the world population is partially or completely supplied by water from karst aquifers (Ford and Williams, 2007). Karst is the result of a dissolution process which acts on soluble rocks, for instance carbonate rock (Milanovic, 1981). Karst aquifers are characterized by a great heterogeneity in structure and hydrological behaviour (Bakalowicz, 2005; Goldscheider and Drew, 2007; Hartmann et al., 2014a,b; Kiraly, 2003; Kovács et al., 2005). Heterogeneity can be found on the surface (karren fields, dolines, sinkholes etc.) and in the subsurface (caves, shafts, conduits, large springs etc.). In terms of hydrology, karstic heterogeneity expresses itself by highly variable hydraulic properties that result in a duality of flow and storage processes, for instance a duality of flow regimes, recharge, and discharge (see e.g. Bonacci, 1987; Dreybrodt, 1990; Ford and Williams, 2007; Goldscheider and Drew, 2007; Klimchouk et al., 2000; Romanov et al., 2007; White, 1988).

Due to the favourable water yields of karst aquifers, many dams have been built in karst regions to store and provide additional drinking water. However, due to unknown karstic heterogeneity, many operating dams have leakage problems, e.g. the Hales Bar dam, USA (Frink, 1946; Lienhart, 2013), the Anchor dam, USA (Jarvis, 2003), the Kalecik dam, Turkey (Turkmen, 2003; Turkmen et al., 2002), the Mosul dam, Iraq (Al-Saigh et al., 1994), or the Tangab (Karimi et al., 2005; Mohammadi and Raeisi, 2007) and Khersan 3 (Karimi et al., 2007; Mohammadi et al., 2007; Raeisi et al.,

* Corresponding author at: Institute of Earth and Environmental Sciences, Hydrology, University of Freiburg, Friedrichstrasse 39, 79098 Freiburg, Germany.
E-mail address: andreas.hartmann@hydrology.uni-freiburg.de (A. Hartmann).

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2005) dams in Iran. To overcome leakage problems, elaborate hydrogeological and geotechnical methods such as grouting and other works related to limestone solution features (Bedmar and Araguas, 2002; Milanovic, 2004), geophysical (Al-Fares, 2011; Al-Saigh et al., 1994; Chalikakis et al., 2011) and modelling (Romanov et al., 2007, 2003; Uromeihy and Barzegari, 2007) methods have to be applied.

Modelling approaches for exploring and understanding karst systems are divided into two main groups of distributed and lumped approaches (Hartmann et al., 2014a; Ladouche et al., 2014; Rimmer and Salingar, 2006; Teutsch and Sauter, 1991). Selecting the best approach depends on the complexity of the system, available data, the dominant flow regime (matrix, conduit flow), and the modelling objective. Distributed models are based on discretization of the karst system into grid cells and applying flow and transport equations in each cell (Birk et al., 2006; Doummar et al., 2012; Oehlmann et al., 2013). Their parameterization requires distributed information on hydraulic and geometric properties of the aquifer. In contrast, lumped models consider physical processes by a set of simplified equations that transfer input to output of the whole system (Charlier et al., 2012; Hartmann et al., 2012a; Long and Mahler, 2013; Schmidt et al., 2014; Tritz et al., 2011). In data-scarce regions where distributed models are not capable of capturing spatial distribution data and tend to have high error propagation, lumped models are applied more commonly (Jukić and Denić-Jukić, 2009), as their model structures are more flexible to adapt to the limited available data while still considering the most dominant karst hydrological processes (Hartmann et al., 2014a,b). Since conduit and fracture system geometry can rarely be measured directly, permeability structure still remains a major challenge to distributed modelling of karst systems. When detailed spatial data are missing, lumped models can simulate the hydraulic behaviour of karst aquifers without specifying conduit properties or the permeability field. In complex karst regions where hydrological data are costly or impossible to obtain and only measurements of flow, temperature, and geochemistry are available, lumped models with flexible structure to involve each hydrological process are more user-friendly and require low data having a great advantage over distributed modelling techniques (Le Moine et al., 2007). In some cases, a segmentation of the karst system into small sub-systems by semi-distributed karst models was found to be more practical than lumped and distributed models (Hartmann et al., 2014b; Ladouche et al., 2014; Rimmer and Salingar, 2006).

The parameters of lumped models are usually assessed by inverse modelling procedures using automatic calibration to obtain a reasonable fit between simulated and observed discharges (Charlier et al., 2012; Hartmann et al., 2014b; Rimmer and Salingar, 2006). However, when only groundwater level observations are available, distributed groundwater models are the common choice as they are able to simulate groundwater hydraulic heads. Only few attempts have been made to include groundwater levels in lumped hydrological models (Kuczera and Mroczkowski, 1998; Mackay et al., 2014; Seibert and McDonnell, 2002), and even fewer attempts to include them into lumped karst models (Charlier et al., 2012; Long and Derickson, 1999; Fleury et al., 2007; Ladouche et al., 2014; Long and Mahler, 2013; Rimmer and Salingar, 2006).

In this study, we present an iterative approach to set up a semi-distributed karst model to simulate groundwater levels at different locations across a karst aquifer with limited data availability. We use prior information about the groundwater flow field and split the system into three separate sections. For each of the sections and their combination, we perform an individual calibration and sensitivity analysis. We evaluate the models of the individual aquifer sections with a spatial split-sample test. We exemplify our approach at a karst system and dam construction site in the southwest of Iran. The model is finally applied to assess the leakage potential of the dam using simple infiltration scenarios.

2. Study site, hydrogeological setup and data availability

2.1. Study site description and hydrogeological overview

The study area is located in the Zagros zone (Alavi, 2004; Berberian, 1995; Berberian and King, 1981; Falcon, 1974; James and Wynd, 1965; McQuarrie, 2004; Stocklin, 1968; Talebian and Jackson, 2004) and more precisely in the Izeh region (Sepehr and Cosgrove, 2004; Sherkati et al., 2005; Sherkati and Letouzey, 2004), southwest of Iran (Fig. 1). It has a semiarid climate with an long term annual precipitation (1976–2015) ranging from 379 to 907 mm, with an average of 622 mm. long term annual evaporation (1976–2015) ranges from 825 to 1843 mm, with an average of 1457 mm (Mahab Ghodss Consulting, Engineers, 2004). Long term daily temperature (1976–2015) ranges from −1 to 41 °C with an average of 21 °C. All precipitation typically occurs during November to May, mostly in the form of rain and some snowfall that occurs during the winter at high elevations. Runoff is dominated by rainfall between November and February, then, snow melt from higher elevations becomes dominating (Zarei et al., 2014). The Abolabbas river cuts through the Asmari limestone of the southern flank of the Malagha anticline creating a narrow gorge namely the Malagha gorge. The Abolabbas dam is planned to have a reservoir capacity of 113.4 MCM and a height of 138 m (Majd, 2011). It will be constructed to stow the Abolabbas river passing the Malagha gorge at the southern flank of the Malagha anticline.

The massive and thick-bedded Asmari limestone of the southern overturned flank of the Malagha anticline which is sandwiched between two impermeable formations of the Pabdeh-Gurpi marls below and the Gachsaran marl and gypsums above, has formed the karstic Malagha aquifer (Fig. 1). The Malagha aquifer is characterized by autogenic recharge which is spread out through joints and fractures over the whole limestone outcrop of the southern Malagha anticline flank (Fig. 1). The karst phenomenon seems to be limited to some solution features such as rillenkarren, rain pits and small shelter caves. In total, 23 of the boreholes in the aquifer have been equipped as piezometers for monitoring groundwater level (Mahab Ghodss Consulting, Engineers, 2012). There is no spring to drain the Malagha aquifer and according to stable isotope measurements and groundwater gradient, Qale-Tol plain is the only discharge point of the aquifer (Fig. 1). Measurement of water table elevations in piezometers on both sides of the Abolabbas dam site, borehole logs, hydrogeochemical and stable isotope data suggest an unconfined aquifer system (Adinehvand, 2016; see also supplemental material). The only water sources of the Malagha aquifer are recharge from precipitation and Abolabbas river seepage through the limestone at the Malagha gorge with which the bottom and sides of the river are in direct contact (Fig. 1).

2.2. Available data, prior understanding and preliminary conceptual model

In order to explore the aquifer system and its development and leakage potential, hydrogeological characterization, environmental and artificial tracers were applied at various locations in the study area (Adinehvand, 2016). Precipitation, evaporation and temperature at the Malagha station (at the Abolabbas dam site) and adjacent climate stations are available in daily to monthly time steps. The aquifer boundaries were determined using geological and stable isotope (^{18}O) analyses. Measurements of the water table elevation show that the general flow direction is towards the Qale-Tol