Calibration of a groundwater flow model in a karst aquifer using EPM approach: case of Elhajeb-Ifrane aquifer, Morocco

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Abstract. Numerical models constitute a powerful tool for groundwater resources management, as they can provide information about flow path, water balance, and effects of future actions. In karst aquifers, groundwater modelling may be challenging because of the heterogeneity of the system. Indeed, karst aquifers have concentrated recharge in sinkholes and preferential flow patterns through fractures and conduits. Modellers used several approaches to simulate karst aquifers. The equivalent porous media approach was used by many researchers and showed an acceptable performance of the application of MODFLOW in regional and sub-regional aquifers. The objective of this study is to simulate the sub-regional aquifer of Elhajeb-Ifrane. The groundwater flow model was constructed using a Python package and was calibrated using the parameter estimation code. The results show a good fit between simulated and observed heads. The model reduced RMSE values to 0.49, 0.56, and 0.58 for piezometers 1098/22, 1448/22, and 1830/22, respectively. The annual water balance results show that the aquifer meanly discharges to the springs with 71.8% and 80.8% in 2016 and 2017, respectively, followed by streams with 5.9% AND 5% in 2016 and 2017, respectively, then discharges to Sais aquifers with 2.6% and 3.8% in 2016 and 2017, respectively.

Keywords : Numerical modeling, Parameter estimation, Water balance, Elhajeb-Ifrane aquifer.

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1 Introduction

Karst aquifers serve drinking water for an estimated population between 9 and 20% of the total world population [1], hence they are very important in water supplies. Of the top 10 GW abstraction countries, seven countries are using karst water in considerable amounts (China, USA, Iran, Mexico, Saudi Arabia, Indonesia and turkey). In Morocco, karst aquifers have significant extension, especially in the Atlasic and Rifain mountains. In most of these aquifers, agricultural activities are increasing in feeding areas of springs. Consequently, groundwater became more vulnerable to contaminants coming from fertilizers and pesticides [2]. In this context, the assessment of karst dynamics is more important and necessary. Numerical models may be used for understanding in detail the hydrogeological behaviour of the aquifer (estimating hydraulic parameters), and for forecasting the impact of different scenarios on the groundwater flow system and water balance [3]. However, assessing the impact of the heterogeneity of karst aquifers on water dynamics is challenging. There is no data about how permeability changes with depth and how fractures are interconnected under the ground. Also, because of the fact that the saturated zone is deep, there are a few boreholes for hydraulic head measurements and for carrying out pumping tests. Furthermore, the non-laminar flows through the conduits and direct infiltration in shallow sinkholes have their influence on the heterogeneity and complexity of the system. In this context, different types of distributed models can be applied to simulate karst aquifers, depending on the characteristics of the studied system and the purposes of the modelling: Equivalent porous medium (EPM), Discrete fracture network (DFN), discrete conduit network (DCN) and hybrid models [4].

EPM is the first approach used for simulating groundwater flow within a karst aquifer. The EPM approach assumes that the aquifer is a continuum media and a representative elementary volume of aquifer properties can be defined, this can be an adequate method when fractures are uniformly distributed and well connected. The flow is assumed to be laminar and governed by Darcy's law on the full study domain. This approach can simulate transient spring flow for annual and monthly averages, but may not reproduce flows for a storm event because of the predominant non-laminar flow during storms. It was successfully applied in [5], [6] [7] [8]. The discrete fractures (DFN) or conduits (DCN) network approaches are used when the permeability of the rock is negligible. The flow is simulated only within a network of fractures or conduits. The discrete fractures or conduits network approach is proposed to problems where transient solute transport responses are required for aquifers dominated by conduits. Fractures geometry is required for application of this approach. Generally, these approaches are rarely used. A hybrid model is a coupling of a EPM model with a one-dimensional conduit or pipe network model. The hybrid model allows the integration of detailed information about the geometry of the major conduits when available. The hybrid model links an EPM model with a conduits network model that can have laminar or turbulent flow. The main advantage of this approach is that it can simulate high transport velocities under laminar or non-laminar conditions and account for the presence of lower hydraulic conductivity rock matrix [9].

In annual, monthly and seasonal average hydrologic conditions, all methods met calibration criteria. Thus, the efforts and time of using hybrid models are not needed for long period's simulations. But, simulation of a large storm event with daily stress periods indicates the importance of turbulence for matching daily spring flow hydrographs. Therefore, the mapping of conduits network and non-laminar simulations are required [10]. The main challenges in applying hybrid models are related to the difficulty of simulating the conduits network and having a rich data set to calibrate these models. In our study, we used the EPM approach for some considerations, namely the extent of the aquifer and the Availability of calibration data.

2 Study area

Elhajeb-Ifrane aquifer is located in northern of Morocco (Fig. 1), and considered a part of the Tabular Middle Atlas Mountains, covering an area of 682.64 Km^2. The topography of this aquifer is characterized by high altitudes ranging from 2095m upstream to 700m downstream. The aquifer is mainly formed by carbonate units of the Liassic age overlying clays of Trias forming the bedrock of the aquifer. Hydrogeological units and their thickness were set up based on geological logs in [11]. The lower Lias is formed by massive dolomites, sandy dolomites and bedded dolomites with a total thickness of 120 to 150 m. The middle Lias is made up of dolomitic limestones 10 to 15 meters thick, followed by upper limestones 60 to 70 meters thick. Finally, quaternary basalts cover the previous rocks with a thickness ranging between 8 and 17 m. The degree of karstification is low, as sinkholes and fractures appear in the surface, but no large conduits are discovered. The mean annual precipitations are comprised between 587.33 mm/year in the north and 979.76 mm/year in the south. While the mean annual temperatures range from 3.95 °C in the south and 15.2 °C in the north. Annual evapotranspiration calculated by Thorenthwaite method is about 418.25 and 437.19mm/year from the south to the north, respectively. Hydrographic network is weakly developed and is represented meanly by Tizeguit stream crossing the middle area from the south to the north.

3 Methodology

The MODFLOW code is a flexible framework that allows for addressing complex groundwater flow problems, as it provides various packages which simulate different hydrogeological features [12]. This code can simulate steady and time-variant flow through different hydrogeological formations in three dimensions using the differential equation (1):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-Q=S_S\frac{\partial h}{\partial t} \quad (1)$$

Where x, y, z are Cartesian coordinates aligned along the major axis of Kxx, Kyy and Kzz, h is the groundwater head [h], Q represents sources and sinks of water in a volumetric flux per unit time [L3.t-1], SS is the specific storage [L-1] and t is time [t].

We used in our study the last version of MODFLOW [13], implemented in the open-source Flopy package of python [14]. The Flopy package allows for automating the construction, loading, execution and output analysis of MODFLOW models.

The model grid comprises six layers, 130 rows, 105 columns, and 7250 active cells, each with a uniform grid size of 360m by 360m. boundary conditions were defined based on hydrogeological settings [15]. The eastern, western, and southern boundaries were set as no-flow boundaries, while the northern boundary was simulated as a general head boundary (GHB) to simulate outflows to Sais aquifers. The springs were simulated by the drain (DRN) package. Groundwater abstraction was modeled using the Well package. The simulation timing was discretized into 24 monthly stress periods from January 2016 to December 2017. Time discretization was chosen based on available monthly measurements from piezometers and springs.

Model calibration was undertaken using the PEST code [16]. The parameters selected for estimation consisted of hydraulic conductivity; specific storage, GHB conductance, stream bed conductance and recharge. The available observations for piezometric measurements and springs flows were used for calibration. During the calibration process, the outputs of the model were assessed using performance criteria such as Root Mean Square Error (RMSE) and the Nash-Sutcliffe Efficiency (NSE) coefficient [17].

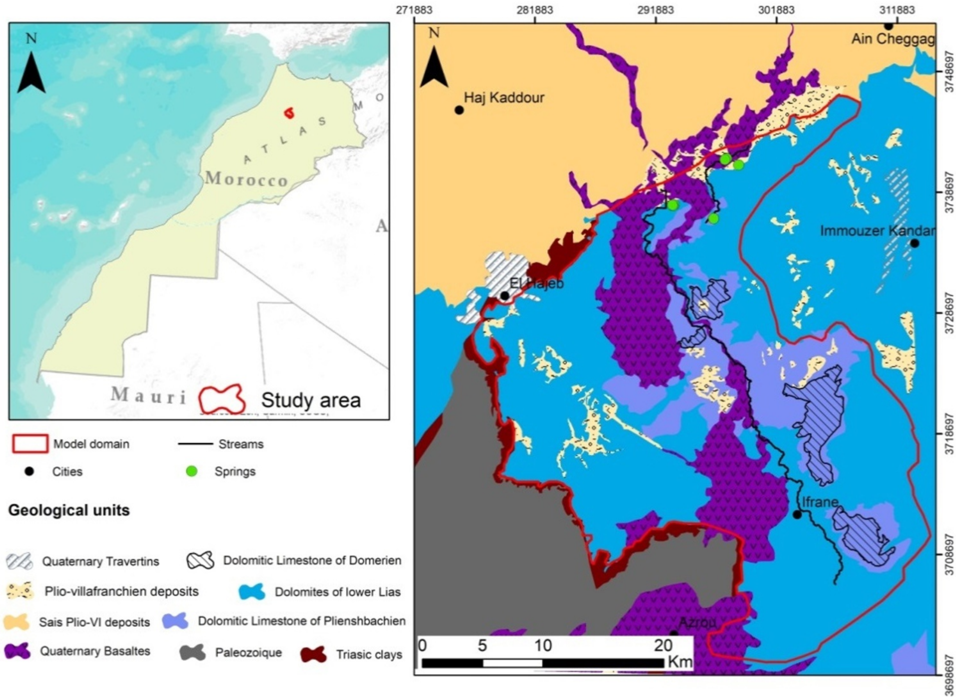

Fig. 1. Study area and geological settings.

4 Results

Modelling of groundwater dynamics in Elhajeb-Ifrane aquifer was carried out using the EPM approach and the model was successfully calibrated at a monthly temporal scale (Figure. 2). The results of performance criteria show that the model reproduces the groundwater dynamics for the available piezometers. These statistics indicate how much the model can reproduce the behaviour of the system. Values of RMSE were reduced to 0.49, 0.56, and 0.58 for piezometers 1098/22, 1448/22, and 1830/22, respectively. These values are considered good if compared with other studies, such as [7], who reported RMSE values between 0.28 and 0.66 meters in the Triffilia karst aquifer, Greece, and [18], who achieved an RMSE of 0.37 meters in the Manati-vega Baja karst aquifer, Puerto Rico.

The results of the annual volumetric water balance for 2016 and 2017 is plotted in Figure 3. Inputs to the system are only represented by natural recharge contributing a total of 102.5 Mm^3 in 2016 and 73.5 Mm^3 in 2017. A significant output of the system is the discharge to springs, which amounts to 73.5 Mm^3 in 2016 and 59.4 Mm^3 in 2017 representing a percentage of 71.8% and 80.8% in 2016 and 2017, respectively. The discharge to the streams 6.08 Mm^3 and 3.72 Mm^3 representing 5.9% AND 5% in 2016 and 2017, respectively. Discharge to the aquifers of the Sais basin constitutes a minor component of the water balance, with flows of 2.66 Mm³ in 2016 and 2.78 Mm³ in 2017 representing 2.6% and 3.8% from total recharge in 2016 and 2017, respectively. Additionally, Groundwater withdrawals from all surveyed wells result in an annual extraction volume of 4.65 Mm³, representing a relatively small portion of the total outputs.

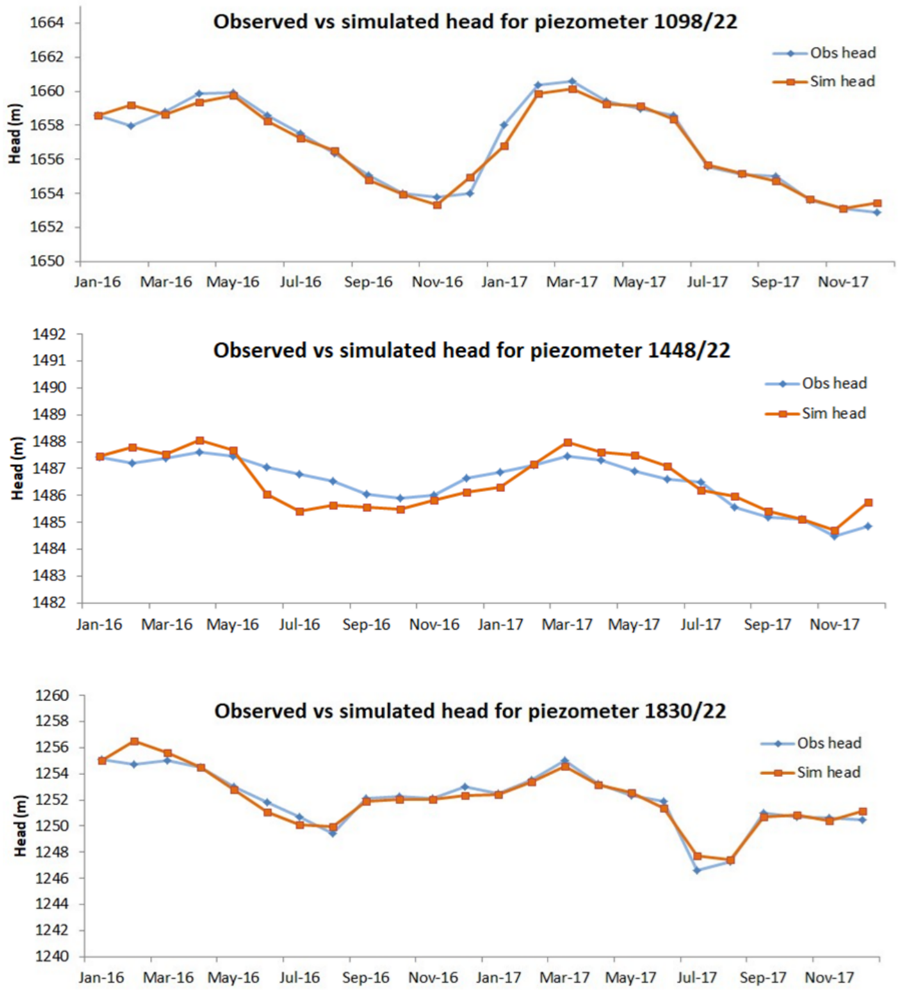

Fig. 2. Simulated and observed heads at the three piezometers.

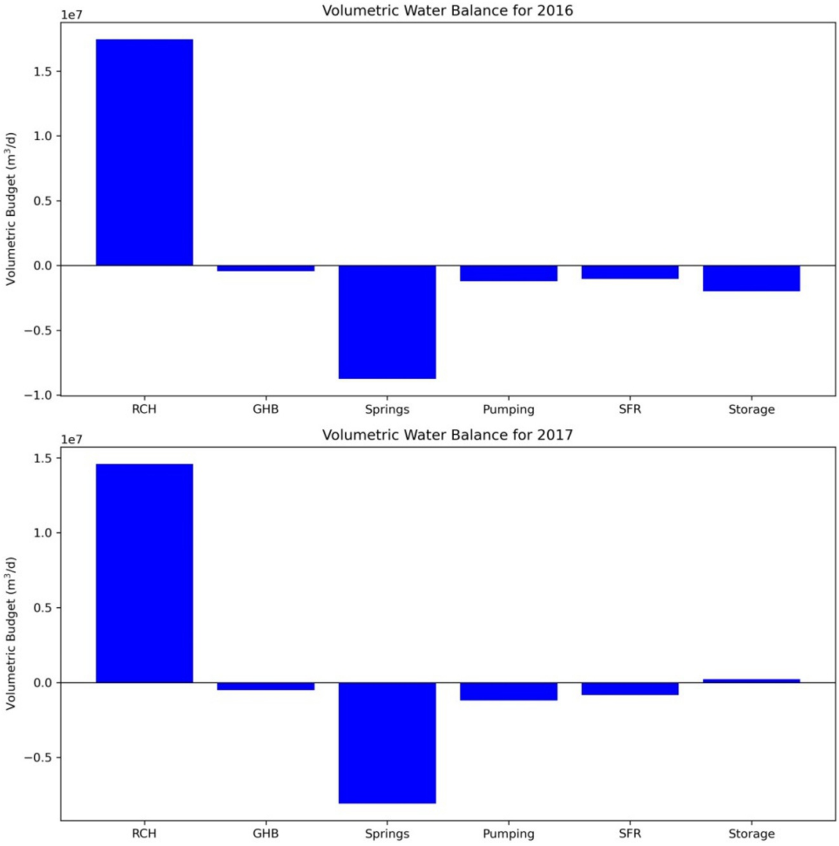

Fig. 3. Annual water balance of the aquifer in 2016 and 2017.

5 Conclusion

This study provides an implementation of the EPM approach for modeling groundwater flow in Elhajeb-Ifrane aquifer, demonstrating the effectiveness of this approach in assessment of the hydrodynamics of the aquifer. The Flopy package of python is a powerful for automating construction, processing and post-processing of MODFLOW models. The calibration process was undertaken using the PEST code, which demonstrates high performance in estimating hydraulic parameters. Performance of the model was tested by computing criteria (RMSE and NSE) yielding a good fit between simulated and observed heads. The results of the water balance can be used to evaluate the impact of increasing extractions by implementing new pumping wells or the decline of recharge in future periods on the groundwater resource. If high-resolution data are available, future study should focus on testing other approaches for simulating preferential flows in local scales.

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Author contribution
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Ethics approval and consent to participate

Not applicable.

Consent for publication

All the authors have agreed to publish this article.

Competing interests

The authors declare that they have no competing interests.

Data availability statement

Not applicable.

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