MODELING OF A KARST DRAINAGE RESPONSES WITH RESERVOIRS IN THE ITXINA KARSTIC AQUIFER (BASQUE COUNTRY, SPAIN)

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Abstract. The aim of this study is to apply a parsimonious hydrologic model to the Itxina karstic aquifer, capable of predicting changes in discharge resulting from variable inputs (recharge). The Itxina aquifer is divided in four cells corresponding to distinct recharge areas. Each cell was treated as a tank to characterize the conditions within cell. In the model when the reservoir boundaries coincide with the position of the siphons, the signal simulated is sensitive to input pulses of the recharge. The good agreement between predicted and measured discharges demonstrates the ability of the model to simulate the flow in the Itxina aquifer. These results demonstrated that the hydraulic conductivity increases downstream within the aquifer. The hydraulic conductivities obtained by numerical calibration varied between 4.2×10^{-3} m/s upstream of the Itxina aquifer, 6.0×10^{-2} m/s in the central region, and 9.5×10^{-1} m/s in the lower region of the aquifer. These values seem reasonable because the underground features in the principal caves show that the density of caves increases downstream in the Itxina aquifer.

Key words. Karst, Modeling, Reservoir, Spring, Itxina Aquifer, Basque Country.

INTRODUCTION

A growing concern with groundwater contamination by agricultural chemicals and potential spills of hazardous materials, calls for some method of prediction and possible tools for remediation. This is especially applicable in the case of a karstic aquifer, which is known to be highly vulnerable to contamination. However, the lack of spatial knowledge in the karst parameters, and the relative unpredictability and the extreme heterogeneity in aquifer properties, has often discouraged researchers from attempting to model such aquifers.

In most cases, hydrologic interpretations are based on the analysis of recession hydrographs by using the different hydrograph separation methods [1], statistical analysis of the whole spring hydrograph [2,3], or analysis of transfer functions between input (infiltration) and output (spring hydrograph) obtained by black-box models [4] used time moment analysis to relate a time series of inputs (recharge) to a series of outputs (spring flow). Simple regression models also have been used to predict water levels in karst aquifers [5]. The limitation of these global models is because they lack predictive power.

Direct verification of interpretations based on global methods is obviously very difficult because of the scarcity of empirical observations in real karstic aquifers. In the other hand, conventional groundwater models are overly difficult for this task given the uncertainties in parameterization and the difficulties associated with estimating changes in recharge characteristics. In addition, most of the studies are ideal simulations, which frequently do not represent the natural system accurately. Consequently, the main goal of this paper is to apply a parsimonious hydrologic model for the Itxina karstic aquifer, capable of predicting changes in discharge resulting from changes in the inputs (recharge). This modelling effort is to demonstrate the applicability and practical use of the modelling concepts for the simulation of groundwater flow, while retaining the simplicity resulting from using lumped regional scale parameters.

DESCRIPTION OF THE STUDIED AREA

The aquifer of Itxina, located in the Basque province of Vizcaya, is represented by a flat area of triangular geometry and rough relief, known as mountains of Itxina, whose highest points are the peaks of Aitzkorrigane (1090 *m.a.s.l.*), Lekanda (1308 *m.a.s.l.*) and Ipergorta (1225 *m.a.s.l.*). Sideways it shows a divergent hydrographical network, structured in two watersheds. That way, while to the north, the superficial flows are piped by the Nervion and Ibaizabal rivers, to the south the draining is done towards the Zadorra river, through the Bayas river. In the same way we could emphasise the existence of the depression known as Campas of Arraba, which is characterized for having an own internal draining net which comes to an end at the feet of the mountains of Itxina (Fig. 1).

The aquifer of Itxina is represented by a 6,15 km^2 outcrop of reef limestone which can go over 300 meters of width. It shows a free aquifer kind typology, with a pending structure, and gets characterized for showing high permeability levels for karstification and fracturation, what makes the infiltration to be fast. With a rain of about 1300 mm with an almost full infiltration of it, its underground resources can be estimated as about 7.7x10^6 m^3/year, which discharge is done in a minority way by the springs. In general, such sources show low volume and a great irregularity which workings would be associated to the draining of low structures and near depressions.

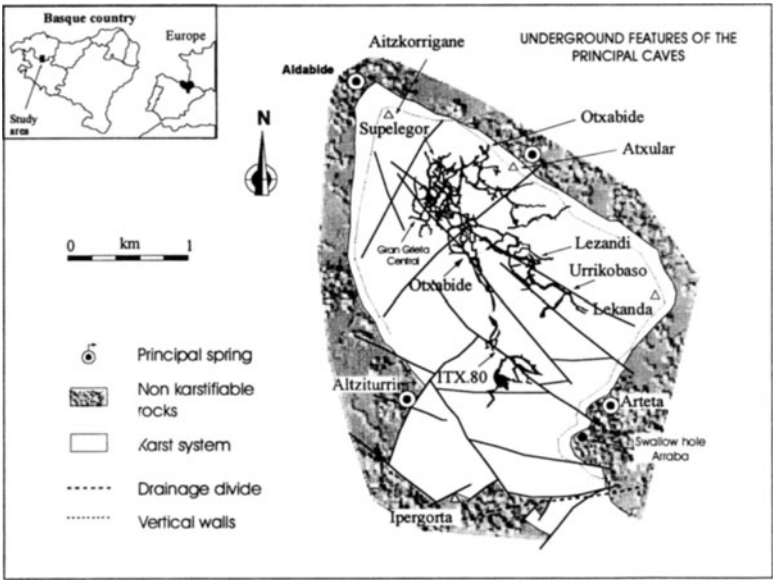

Fig. 1. Geological description of the study area and simplified plans of the morphology of the karst aquifer.

The most important spring of the aquifer is the source of Aldabide, located in the north end of the massive and in the lower height of it (725 *m.a.s.l.*). Through this point the main discharge of the massive of Itxina (85% of the resources) is done, with an average annual volume next to 250 *l/s*. It is a spring characterized by important volume oscillations, with response times of few hours, which show the low regulation capacity of the aquifer, shown in other studies [6, 7, 8]. In the same way, can be said that the water in the aquifer is taken through wide conduits according to a general circulation scheme, in north-north-west direction, from its south-eastern extremity, in the sinks existing in the Campas of Arraba, to the source of Aldabide, main collector of the aquifer.

Model formulation

In order to understand the movement of storm pulses in the basic model, the aquifer prototype is translated into four zones of different type and complexity. Upstream of the Itxina aquifer (Campas de Arraba), this watercourse drains entirely in the swallow hole (Arraba). Cave investigations and underground flow show that preferential flow directions between the Campas de Arraba and the Aldabide spring are related to the high permeability zones and the existence of rapid flow channels running in direction of the two siphons (Figure 2). The first siphon is located at ITX-80 (820 *m.a.s.l.*), and the second is located at Otxabide (797 *m.a.s.l.*). Therefore, the geometrical model of the structure of the karst can be used to show that the Aldabide spring is supplied by four reservoirs. The first in the shallow hole at Arraba, the second in the siphon ITX-80, the third in the siphon Otxabide, and the last in the Aldabide spring. The waters of these four reservoirs mingle downstream to form the waters at the Aldabide spring. These reservoirs are fairly evenly spaced which suggested the use of a four-cell model to predict the behavior of the aquifer.

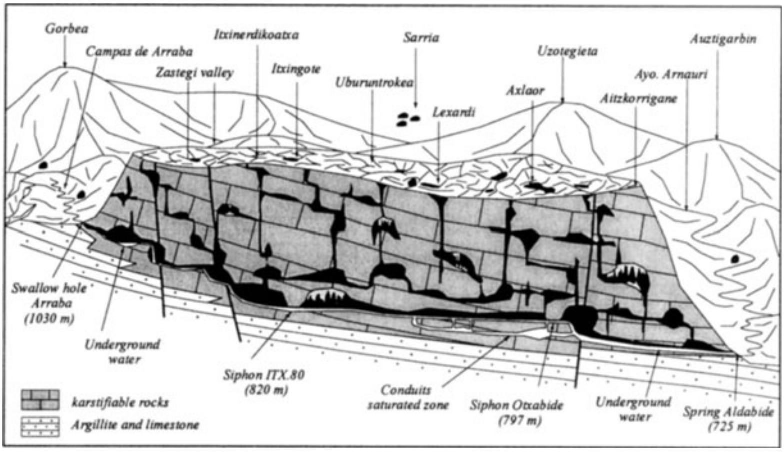

Fig. 2. Conceptual model of the karstic network of the Itxina aquifer.

Each cell is treated as a tank, which is, assigned an effective area (equivalent to the product of specific yield and surface area). At the present time, piezometric data and hydraulic conductivity measurements are not available owing to the topographical difficulties and the cost of drilling wells in mountainous areas with difficult access. The only hydrological information available for a long enough period of time is the daily spring discharges. Data for the period that ranges between January 1982 and June 1984, as well as the daily rainfall data from the precipitation station at Gorbea (Zastegui Valley) for the same period, have been used. A schematic diagram of the model is shown in Figure 3.

The model describes flow between the cells using Darcy's Law. The hydraulic conductivity was assigned to the boundaries between cells which was the method employed by [9], and the saturated thickness of the upstream cell was used to calculate the transmissivity. All external model boundaries were treated as no-flow boundaries, so there are only three boundaries where flow occurs. Flow rate across each internal boundary was calculated as:

$$Q_G = Kwb\left(\frac{\Delta h}{l}\right), \tag{1}$$

where Q_G is the groundwater flow rate across the boundary, w is the width of the boundary, Δh is the head difference across the boundary, b is the saturated thickness of the upstream cell, and l is the distance between the key wells in each cell.

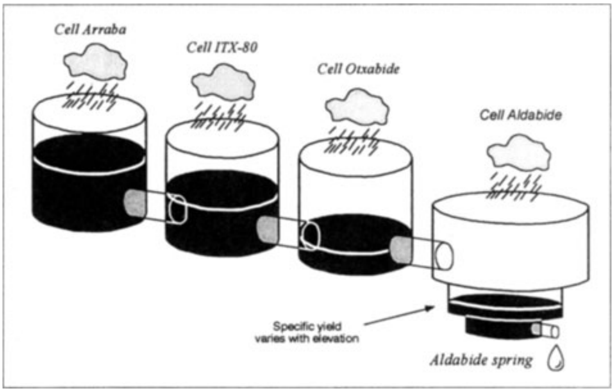

Figure 3. Schematic diagram of the aquifer model.

MODEL CALIBRATION AND RESULTS

To determinate aquifer properties during the study period, data from five events were used for model calibration. These events occurred between January 1982 to June 1984. Rainfall data, which was also available at this time, was also collected. The average discharge for the five events was 0.336 $m^3\ s^{-1}$, with a maximum recorded discharge of 4.7 $m^3\ s^{-1}$ and a minimum of 0.009 $m^3\ s^{-1}$.

For most groundwater modeling efforts, a model with a fixed structure is selected and parameters are chosen through the calibration process to achieve the best fit with measured field data. In this case, a number of different model structures were evaluated and within each case, parameters were selected to achieve optimum calibration. In this case, analyses were carried out for three situations to determine which model more accurately fitted the data. For this purpose, different simulations were made using three options that can modify a storm pulse moving through the model. The first situation (run 1) is a model with two reservoirs representing flow moving from a karst system. The second (run 2) is a system with four reservoirs that allow for overflow in the system. Finally, the third (run 3) is a system in which four reservoirs plus the vertical variation in aquifer properties in the last reservoir. These simulations were used to understand the variations due to input, and variations in the number of reservoirs.

Figure 4 shows three runs of the calibration process for October 1 to November 20, 1982. The first simulation involves two reservoirs, the second simulation four, and the last simulation uses four reservoirs plus the vertical variation of the aquifer properties of the last reservoir. For the first simulation, the response is erratic and overestimates the peak for the final pulse in the series. In addition, it was found that a lag period exists between the peak observed time and the peak simulated time. This is likely due to the lack of regulation with two reservoirs. For the second simulation, the regulation and the lag are improved. However, the sensitivity of the model with variations of input intensity was found to be not considerable. It is interesting to note the difference between run one and the run three, where the last fit introduce the vertical variation of the aquifer properties. The ability of the last scheme to perform is strongly supported by the hypothesis that the siphons were the controlling mechanism in the system during storm events. These results are the similar to findings by [10], who used a system theorize of three reservoirs to obtain the same suggestions. In [10] case, the series system acts as a feedback mechanism in the conduit system. In his configuration, the smallest section controls the response with a single configuration of four reservoirs with aquifer characteristics changing in the last reservoir. The signal simulated is also sensitive to input pulses of the rainfall.

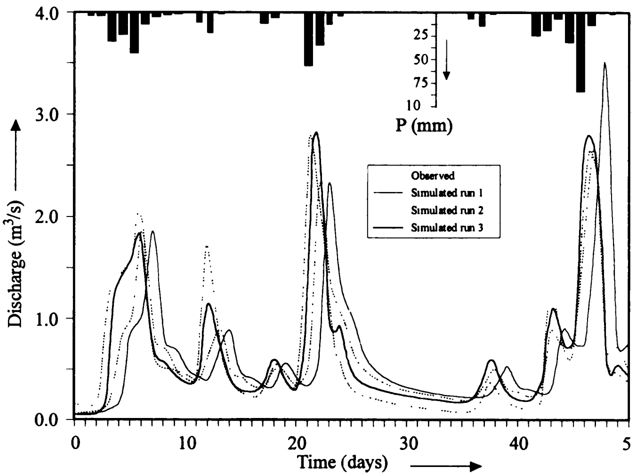

Fig. 4. Observed and model-simulated daily discharge at Aldabide spring between October 1 and November 20, 1982.

The hydraulic conductivities varied between 4.2x 10^{-3} *m/s* upstream of the Itxina aquifer, 6.0 x 10^{-2} *m/s* in the central region, and 9.5 x 10^{-1} *m/s* in the lower region of the aquifer. These findings have been used as representative values of the hydraulic conductivity, which demonstrates its usefulness in problems concerning groundwater resource evaluation. The hydraulic conductivities obtained are a result of the varying contributions of fractures (conduits) and regional matrix (fissure) in the system.

CONCLUSIONS

The presented results demonstrate that even a karst aquifer can be successfully modelled with a parsimonious model, which has the ability to accurately predict water movement in this complex karst aquifer. The study developed a lumped parameter model for the Itxina aquifer. When faced with the task of modeling extremely complex flow system, the natural tendency is to develop a more complex model. However, this research shows that a very simple model can provide useful information about the behavior of such a system. The results provide a quantitative tool to assess spring hydrograph, and illustrate mechanisms that can generate observed responses, which have previously been qualitatively interpreted.

The aquifer was divided into four cells, each of which is treated as a tank. This model differs from previous models in that it allows properties within the cell to vary with water elevation. A comparison of model predictions with historical data for five events for the period January 1982 to June 1984 demonstrate its accuracy. The results obtained by calibration of the model indicate that hydraulic conductivity increases downstream within the aquifer. This seems reasonable because the density of caves at the Itxina aquifer increases downstream of the cave system. This simple representation of the hydrologic system produced accurate results with fewer data requirements and calibration parameters than traditional groundwater models. Because of the horizontal stratification of the formation, vertical changes in aquifer properties have a greater influence on aquifer behavior than does horizontal variation. As water levels rise, caves, conduits, and other stratigraphic features, which submerged strongly, affect flow and storage in the aquifer. In fact, when the reservoir boundary coincide with the position of the siphons, the signal simulated is sensitive to input pulses of the rainfall.

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