Simulation of the complex karstic hydrogeological system of Zakros-Crete using the finite element code FEFLOW

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Data scarcity combined with spatial heterogeneity of hydraulic parameters are two of the most important issues that engineers face when applying distributed flow models to karstic systems. In the present study the possibility of applying such a model on a typical Mediterranean karstic aquifer is examined and the importance of input information is discussed.
The site of interest is located at the eastern part of Crete and extends to an area of 227 km^2 mainly of nude limestone. As a result of tectonic action, the karstic terrain has been divided into two aquifer subsystems, one at the north part and one at the south. The northern subsystem is an open to the sea aquifer while the southern one is bounded by impervious formations. The proposed modeling approach is a combination of Equivalent Porous Continuum and Discrete Element flow. The finite element code FEFLOW, which allows for the integration of fractures in determined spaces of the matrix, is used for the development of the model. The flow in the matrix is considered darcian, while the Manning-Strickler or the Hagen-Poiseuille laws are applied within the fractures. The model concept is based on a 3D reservoir approach and the input data include the geological heterogeneities and a zonal recharge map developed in a GIS environment.

I. INTRODUCTION

Over the past decades groundwater modeling has been a very useful tool for developing water management schemas and dealing with environmental issues [1][2]. However, the application of distributed models on karstic systems is a rather delicate task, mainly because of data scarcity and the spatial heterogeneity of hydraulic parameters that these systems often present. An additional issue in karstic system modeling is the integration of the epikarst and the representation of its influence in groundwater recharge [3][4].
The possibility of applying a distributed flow model on a typical Mediterranean karstic aquifer is examined in the present study.

II. APPLICATION SITE

The area under study is the karst system of Chochlakies which constitutes the northern subsystem of the Zakros karst. It receives about 800 mm of rain annually over an area of 72 km^2 and borders the sea to the east. The aquifer body consists of a series of limestones and dolomites that overlies the impermeable formation of phyllites. Many karst features such as cavities, gorges and the palaeokarstic spring of Flegas are present in the southern part of the aquifer. The spring of Flegas is a temporal spring of high potential located at the gorge of Flegas. It is the outlet of a perched palaiokarstic system which drainsa significant part of the upstream basin. The main outlet of the aquifer is a number of submarine springs at the Golf of Karoumes for which the discharge rate has not been estimated so far. Fifteen (15) wells have been recorded in the area; thirteen (13) of these pump water for irrigation purposes, one supplies water to the town of Palaikastro and one has no pumping infrastructure.

III. MODEL SETUP

The proposed modeling approach is a combination of Equivalent Porous Continuum and Discrete Element flow [3][5]. This approach expresses the duality of flow in karstic systems, by dividing the aquifer in matrix blocks and fractures. Flow within matrix blocks is assumed darcian, while within fractures channel or pipe flow is applied.

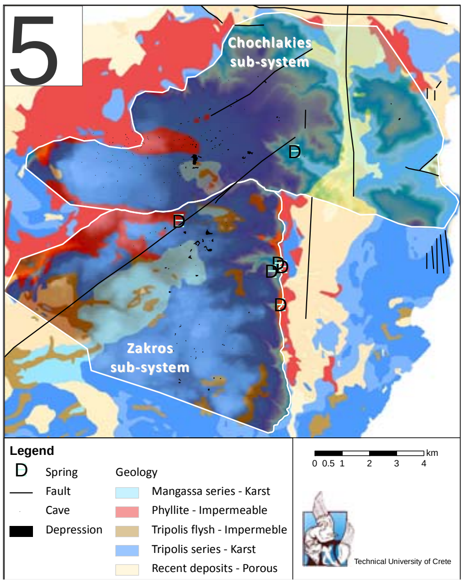


Figure 1 – Simplified hydrogeological map of the study area.

III.1. The FEFLOW code

FEFLOW (WASY) is a finite element code for groundwater modeling which allows fracture, channel and pipe flow in discrete features within the matrix [6]. Three different laws of fluid motion can be defined within the discrete features: Darcy's law, the Manning-Strickler law or the Hagen-Poiseuille law. The finite element mesh has also the advantage of incorporating the heterogeneities of the model domain. The aquifer domain of the study area was discretized using six (6) nodal triangular prism elements with 961080 mesh elements and 511980 mesh nodes. The vertical discretization includes 20 layers and 21 slices, in an effort to minimize numerical errors in the vertical direction. The top slice was defined as free and movable (water table), the elevation of the bottom slice was interpolated based on data from boreholes that reach the phyllitic basement, and for the rest of the slices, a decrement of 5 m was assigned.

III.2. Stress periods

The selected length of each stress period takes into consideration the response of the karstic system to precipitation events-infiltration and water table changes.

Thus, the hydrological year was divided into:

- A wet period with active infiltration (from October to April)
- A dry period with active infiltration (from May to June)
- A dry period where no infiltration occurs (from July to September).

The phase shift of two months after the wet period illustrates an enhanced retardation of the recharge due to water transport through the infiltration zone and the epikarst.

III.3. Recharge map

A recharge map is a graphical representation of the spatial distribution of effective infiltration. It differs from precipitation maps because precipitation is considered to be attributed homogeneously or within predefined topographic zones, while recharge also depends on the karstic geomorphology and the structure of the infiltration zone. Therefore, the construction of a recharge map could replace the modeling of the unsaturated zone.

In this application fractured zones, depressions and cavities are classified in fast infiltration areas and the rest in slow infiltration. Recharge rates are calculated separately for every zone and for each stress period.

By convention the recharge at the fast infiltration zones for the second stress period is zero. To the west border of the model domain a lateral influx was assigned following the same principle.

The particular case of the perched spring of Flegas was also integrated in the recharge map. At first the alimentation zone of the spring was estimated according to topography. Then, based on precipitation data and daily spring discharge records, the amount of water that reaches the subjacent aquifer was calculated. Borehole logs of the area around spring indicate the existence of a perched aquifer at the depth of 30 to 50 m. This perched aquifer regulates the recharge of the groundwater table. Therefore, the total volume of water that aliments the aquifer at this area was attributed homogeneously at all three stress periods.

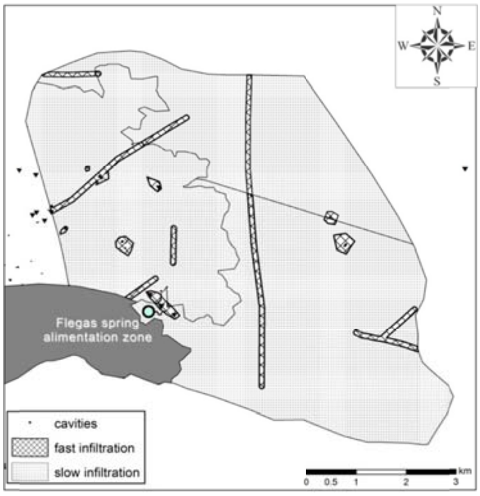


Figure 2 – Recharge map of the model domain

III.4. Boundary Conditions

A constant head Boundary Condition of 0 m was assigned along the sea border, while no flux Boundary Conditions were assigned at the north, north-east and south-west borders of the domain where the impermeable layer outcrops. To the west border of the model domain a lateral influx was assigned following the same principle that was used for the calculation of recharge.

III.5. Flow materials

Hydraulic conductivity range was estimated from pumping test curves and was attributed into zones presenting a difference of two orders of magnitude between highly fractured and moderately fractured zones. Storativity was also estimated from pumping test data and was attributed homogeneously.

III.6. Conduit flow

A straight discrete feature of 2 km of length and a cross section of 1 m^2 representing a karstic conduit was introduced at layer 20 connecting the gorge of Flegas to the sea. The law of Manning-Strickler was applied to describe the flow in the conduit [6].

IV. MODEL CALIBRATION

For the purposes of this study a detailed calibration of hydrologic parameters has not been attempted. The aim was to evaluate the influence of recharge distribution and reservoir geometry on model calibration. Measured, estimated and calibrated parameters that have been used for this application are presented in Table 1.

Parameter	Characteristics	
Kx, Ky, Kz	Elements - zonal	Estimated from pumping test data
Sc	Elements - globally	Estimated from pumping test data

Initial heads	Elements - globally	Known / Interpolated
BC 1st type	Nodes - border with the sea	Known
BC 2nd type	Nodes as lateral influx/outflux Zones as recharge	Estimated from geomorphology / Calibrated
Wells	Nodes	Known
Conduit	Discrete feature	Calibrated
Reservoir geometry	Layers elevation	Known/ Interpolated

Table 1 – Parameters of the model

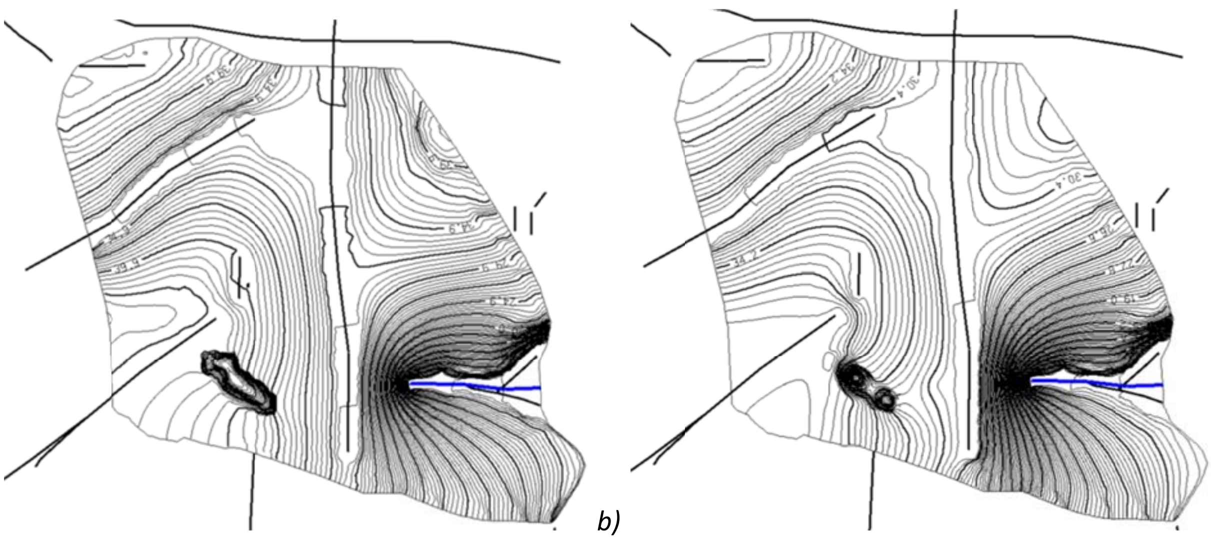
V. SIMULATION RESULTS - DISCUSSION

The present application is an effort to simulate the flow in a karstic aquifer at regional scale. It has been observed from the very beginning of the calibration effort that the global trend of the aquifer was easily achieved.

The influence of recharge is more evident at the zone near the perched spring, as this area received the same recharge at all stress periods.

However, the present model is not capable of simulating the aquifer at a local scale, as very local heterogeneities of the distribution of initial heads were quickly normalized during the simulation.

Simulation results for the end of the first stress period are shown in Figure 3a and for the end of the third stress period in Figure 3b.



a) b)

Figure 3 - Simulation results for a) the end of the first stress period and b) the end of the third stress period

References

[1] Bakalowicz, M. 2005 - Karst groundwater: a challenge for new resources. *Hydrogeology Journal, 13, 148–60*

[2] Papadopoulou M.P., E.A. Varouchakis and G.P. Karatzas. 2009 - Simulation of Complex Aquifer Behavior using Numerical and Geostatistical Methodologies", *Desalination, doi:10.1016/j.desal.2007.12.021, Vol. 237, pg. 42-53*

[3] Kiraly L. 1998 - Modeling karst aquifers by the combined discrete channel and continuum approach. *Bulletin du Centre d'Hydrogeologie, Neuchatel 16:77–98*

[4] Perrin J, Jeannin PY, Zwahlen F. 2003 - Epikarst storage in a karst aquifer: a conceptual model based on isotopic data, Milandre test site, Switzerland. *J Hydrol 279:106–124*

[5] Kiraly L. 2003 - Karstification and Groundwater Flow. *Speleogenesis and Evolution of Karst Aquifers 1 (3), www.speleogenesis.info, 26 pages*

[6] Diersch, H. J. 2002 - FEFLOW Reference Manual. www.wasy.de