14-16 September 2012
Tulcea - Romania

Romanian Limnogeographical Association

Danube Delta Biosphere Reserve Authority

Danube Delta National Institute for Research and Development

Water resources and wetlands

CONFERENCE PROCEEDINGS
14-16 September 2012, Tulcea - Romania

Editors:
Petre Gâştescu
William Lewis, Jr.
Petre Breţcan

Editura Transversal

www.limnology.ro

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Water resources and wetlands, *Editors: Petre Gâştescu, William Lewis Jr., Petre Breţcan*
Conference Proceedings, 14-16 September 2012, Tulcea - Romania
ISBN: 978-606-605-038-8

PERMEABILITY IN A LARGE CRYSTALLINE WATERSHED

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Abstract

In crystalline rock, permeability is controlled by the geometric characteristics of the fracturing. The most common geometric characteristics used to study permeability focused on aperture or connectivity of fractures which are difficult to define at regional scale. In this paper, the possibility to estimate permeability from the number of fractures or fracture density was studied using an equivalent porous medium model (continuum model). The numerical model was calibrated by inverse modeling and the evaluation of the calibration results is presented. It was shown that, the permeability of the fractured aquifer can be efficiently estimated from the fracture density using a continuum model.

Keywords: permeability, crystalline rock, numerical model, inverse modeling

1 INTRODUCTION

Permeability, the ease of fluid flow through porous rocks and soils, is a fundamental to quantify the sustainability of water resources. Study of permeability has generally aimed to solve two groundwater problems: 1) locating and delineating the exploitable aquifer and 2) prediction of aquifer response due to human intervention or to climate change. But the direct quantitative estimation of the permeability is difficult at regional scale because it varies over more than 13 orders of magnitude and is heterogeneous and dependent on flow direction. One way of determining permeability is to calibrate a model flow with hydraulic, thermal or chemical data. Models flows are built by representing permeability and other attributes of an aquifer (shape, boundary conditions, etc.) which consist of the basis of a discretisation process of water flow equations. The goal of the present work is to evaluate the permeability of the regional aquifer of the N'zo watershed (Ivory Coast) using a model flow. The methodology used is based on continuum model, the quivalent permeability zones are defined from fractures density (Cokuner, 1998). The numerical model built was calibrated by inverse modeling, then evaluation of the calibration results are presented. The study area is an agricultural watersed (called basin versant du N'zô) located in Ivory Coast between longitudes 7°15' and 8°05' west and lalitudes 7°50' and 6°50' north, it covers an area of 4310 km^2. The northern of watershed is situated in mountains region (called les 18 montagnes), and the elevation varies from 200 m up to 1200 m above the sea level. The climate is warm and humid with annual recorded rainfalls of about 1600 to 2100 mm/yr.

2 METHODOLOGIE

2.1 Data and materials

The image processing software ENVI 4.5 has been used to produce a detailed map of the lineaments from Landsat and Radar images. This lineaments map has been validated by the geological map and on-field recorded data. ArcMap 9.3 has been used as well to create a potential recharge zones map by crossing the information of the pedological, topographical and land use maps. The creation and refinement of the model mesh has been achieved with the 2D mesh generator Triangle. The transfer of the information read on maps in the model has been realized with GridBuilder. The numerical code used to run the model flow is HydroGeoSphere (Therrien *et al.*, 2005), and the parameter estimation software PEST (Doherty, 2005) has been run to perform an automatic calibration of the model.

2.2 Conceptual model

2.2.1 Parameterisation

The numerical model for this study is based on an equivalent porous medium model (continuum model), and on the hypothetical concept of representative elementary volume (REV) (Bear, 1972). The permeability distribution in the aquifer has been realised from a detailed lineament density map of the study area.

Defining equivalent permeability zones need the lineaments to be classified in families. This classification in families of lineaments or fractures is usually depending on their geometric shape (aperture, length, direction, etc.); this method has been illustrated in a number of publications (Cacas *et al.*, 1990; Donado, 2005). The classification focused on fracture density is very little attention in the literature, because it is difficult to demonstrate experimentally the relation between permeability and fracture density. Nevertheless there are some references such as Cokuner (1998) where the relation between permeability and fractures density is showed. In the present study, we use lineament networks to define an equivalent permeability zones, the density fracturation map has been created at a 1 km^2 scale. In order to reduce the number of parameters, the various zones generated have been put together in 4 families (figure1). These families are of high, moderate, low and very low permeability potential (figure 2).

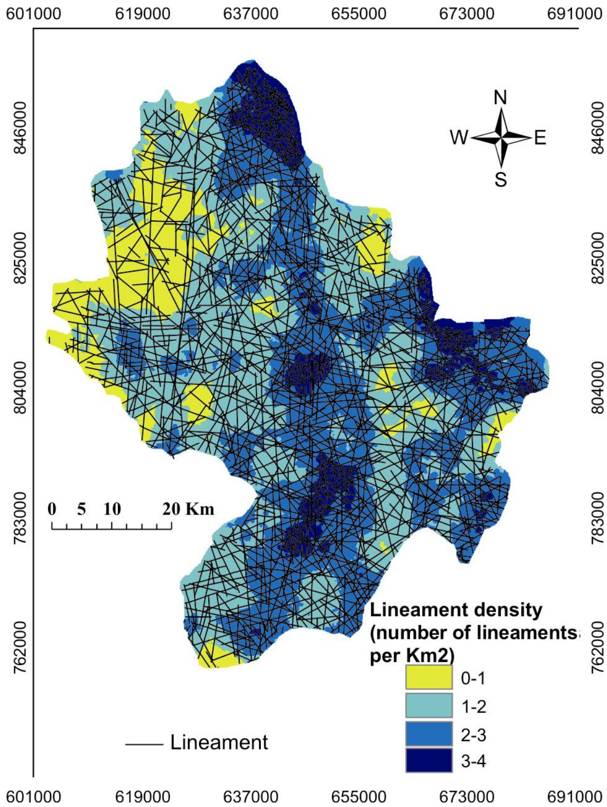


Figure 1. Fracturation density.

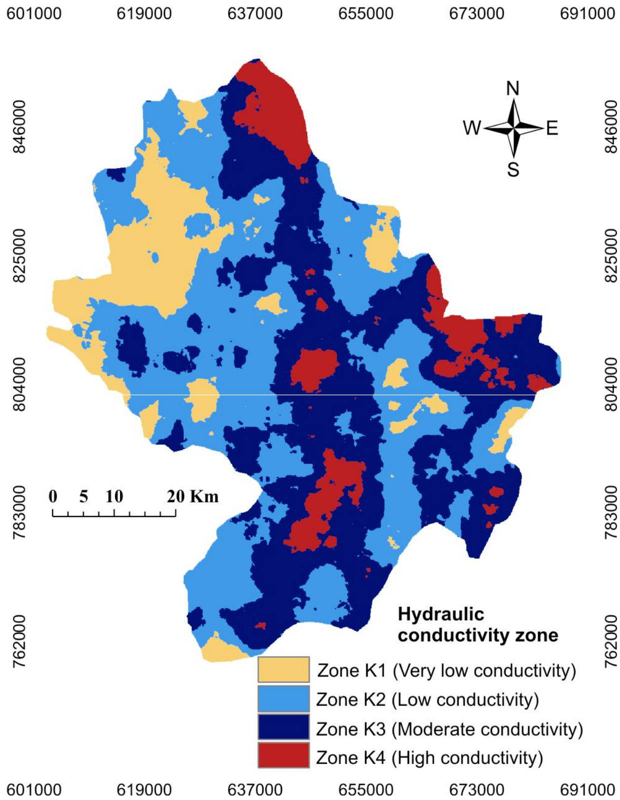


Figure 2. Hydraulic conductivity zones.

2.2.2 Model structure

We use Triangle software to generate the 2D mesh, the elements size varies from 100 m in the refined areas (along the lateral boundaries, rivers, etc.) to 500 m. The 3D mesh has been developed by creating 10 layers vertically from the surface to the bottom of the aquifer. As they are considered as part of an intense water flow zone, the 3 first layers under the ground surface have been refined; the upper limit is defined by the DEM. The vertical total thickness of these 10 layers has been fixed down to 100 m under the ground surface as it is known that under this limit the hydraulic conductivity become very low (Kouamé, 1999). The hydraulic conductivities are considered having constant values on the vertical axis but varies in the XY plane, as shown on figure 3. The 3D model is made of 431.341 nodes and 855.648 elements (figure 3).

2.2.2 Boundary conditions

The resolution of the water flow equations in the model needs the definition of boundary conditions. Different boundary conditions are define; a no-flux boundary condition has been define at the external lateral boundaries, and at the bottom of the model which is considered as impervious. The rivers are considered as head-dependant boundary. The recharge is considered as a fixed flux set at the ground surface. In order to take into account the recharge distribution variations, 4 recharge zones have been specified based on the potential recharge map: a uniform net flux has been set for each recharge zone. The values of these 4 recharge zones vary from 80 mm/yr to 360 mm/yr. The groundwater withdrawal in the study area is estimated to approximately 7,17 Mm^3/yr. This withdrawal rate is subtracted from the recharge rate

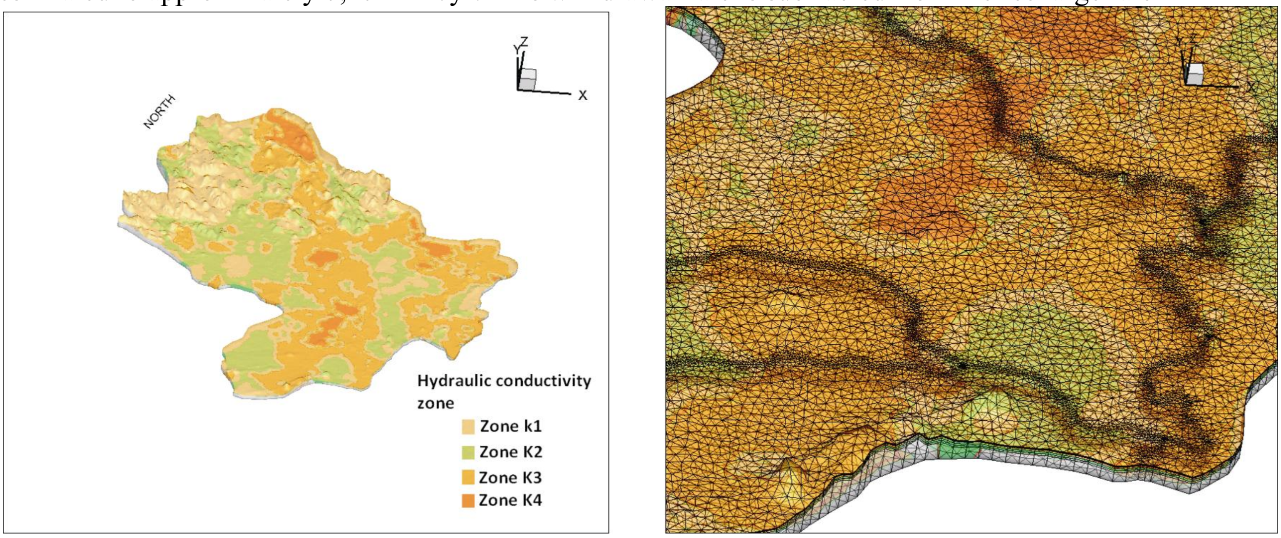


Figure 3. Geometrical structure and their hydraulic conductivity zones.

2.3 Calibration process

The numerical model was calibrated under a steady -state flow regime by inverse modelling. Calibration targets were initially 96 groundwater levels from borehole reports. Finally, 90 effective groundwater levels are used for the calibration process because 6 measurements were not relevant.

Before executing the calibration, an initial hydraulic conductivity value is assigned to each of the four zones defined previously. Then, the upper and lower calibration limit values are fixed. These values have to be as much representative as possible of the parameters zones defined. The values fixed here go from 10^{-4} m/s to 10^{-3} m/s for the upper limit and from 10^{-8} to 10^{-7} m/s for the lower limit. Afterwards, the calibration process starts and runs the water flow model HydroGeoSphere several times through the parameters estimator PEST which takes control of the model and changes its input parameters (hydraulic conductivity) until the minimum value of the objective function is reached. At this minimum value of the objective function, it is assumed that the optimum parameters values are set. However, the minimum value of the objective function is difficult to reach without an optimisation because of the local minimum phenomenon. Kavetski *et al.* (2006) give a comprehensive overview of this local minimum phenomenon. In the present work, the optimisation has been achieved manually for 200 simulations.

3 RESULTS

The automatic estimation of the parameters may induce some difficulties highlighted in numerous publications. A good description of these difficulties has been pointed out by Kavestki *et al.* (2006). The evaluation of the efficiency of calibration in this study include two steps (Hill, 1998): 1) fitting evaluation, and 2) uncertainties analysis or non-uniqueness of the estimated parameters

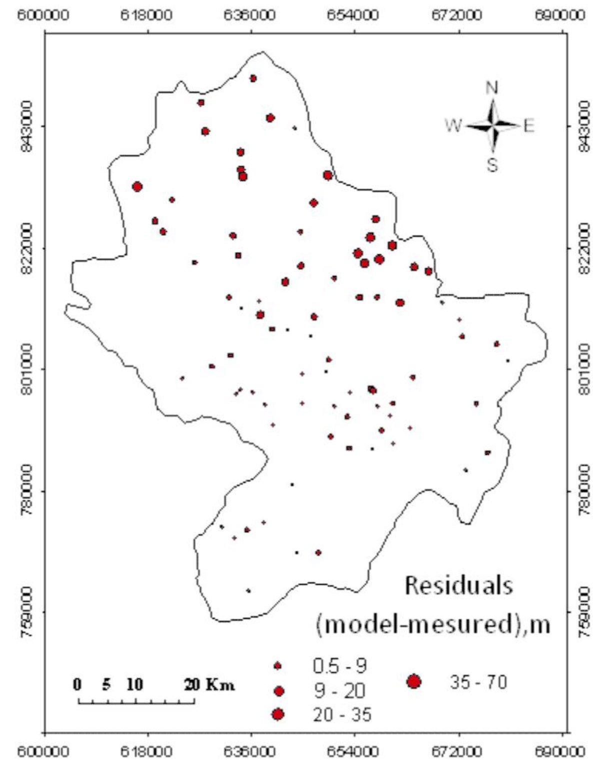
3.1 Evaluation of the model fitting
3.1.1 Analysis of residuals and correlation coefficient R

The residuals values represent the differences recorded between the groundwater level (observed head) and the simulated groundwater level (simulated head). They have to be non-correlated and distributed randomly in the model following the linear regression hypothesis (Hill, 1998). This may be verified graphically: the residuals values have to be uniformly distributed around the zero axis. Figure 5 shows the graph of the standardised residuals values vs. observaed head values of the calibration process. We can notice that this graph shows a few irregularities. Indeed the variance is higher for the head situated in the high topographical parts of the model (mountains), whereas the variance is lower in the relatively flat parts of the model (plain). The influence of the topographical gradient on head variance has been pointed out in numerous publications (e.g. Garabédian, 1986; Zyvoloskia, 2002). This issue is usually encountered in high topographical gradient regions where the topography varies over several hundreds of meters while the groundwater table varies over a few tens of meters. In the study area, the residuals values fluctuate from 0 m to 70 m and the topographical gradient shows variations from 200 m to 1100 m. Figure 4 shows the spatial distribution of the residuals; we can notice that the sizes of the residuals are the biggest in the northern part of the model (mountainous part).

The correlation between the simulated head values and the observed head is calculated through the R coefficient defined by Cooley and Naff (1990). In our case, the value of the R parameter calculated is 0,96 and it is illustrated at figure 6. The R value has to be higher than 0,9 for the correlation between simulated and observed head values to be accepted as relevant (Hill, 1998).

3.2 Uncertainties evaluation
3.2.1 Confidence interval

The 95% linear confidence interval may be defined as a value range that has a high probability to contain the real value of calculated parameters owing to their non-uniqueness. In fact, the smaller the range the closer to the real value the calculated parameters are. However, in some cases where the parameters are highly correlated, the confidence interval cannot be calculated by a non-linear regression because of a high uncertainty level of the parameters (Doherty, 2005). Figure 7 illustrates the confidence intervals of the 4 parameters zones of the aquifer calculated by a non-linear regression (K1, K2, K3, K4).



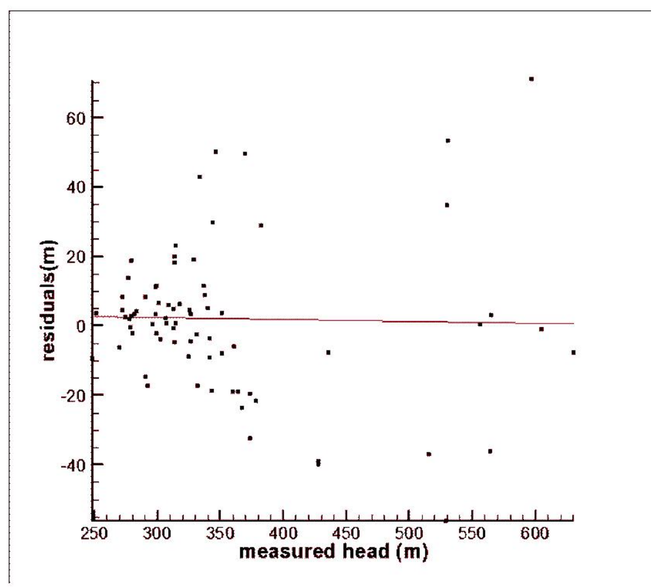
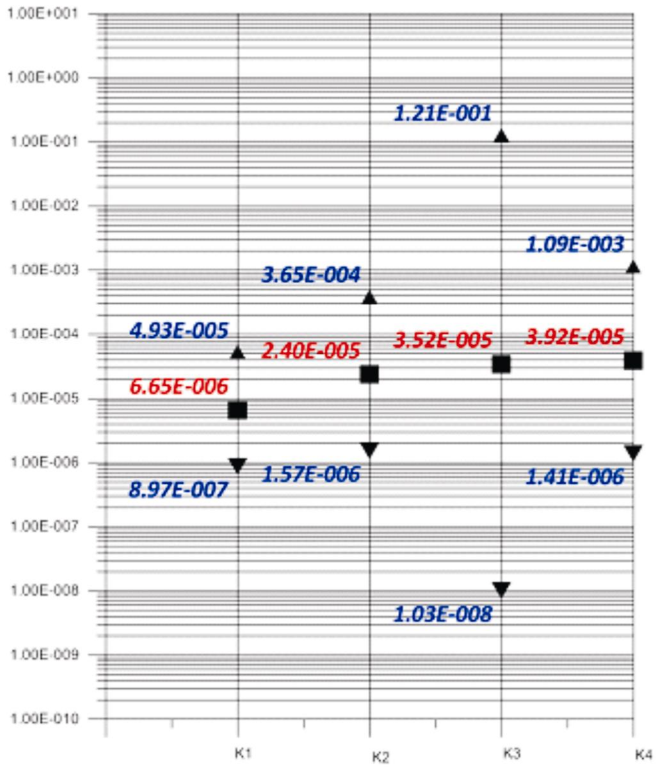


Figure 4. Residue values spatial distribution **Figure 5. Residue values vs. groundwater head values**

4 DISCUSSION ET CONCLUSION

From the calibration of the water flow model built up on the available data, we have calculated the hydraulic conductivity of the different zones of the N'zo watershed regional aquifer. The number of hydraulic conductivity zones defined in the aquifer is 4. The minimum value of the hydraulic conductivity calculated is 6.65 x 10^{-6} m/s and its maximum value is 3.92 x 10^{-5} m/s (figure 7). These values match quite well the permeability range values defined in the study area by Kouamé (1999) and in the eastern part of the study area by Biémi (1992). The calculated value given by Kouamé is 1,3 x 10^{-6} m/s and the one given by Biémi is 3,5 x 10^{-5} m/s. In addition, this study shows that the permeability of fractured aquifers may be efficiently calculated from calibrating a groundwater flow model. The parametrisation (definition of parameters zones) of the model in this work has been achieved based on the fractures areal density and is based on the REV concept. This model might be improved in the future studies by inserting, as part of the definition of the hydraulic conductivity zone, geometrical characteristics of the fractures such as their aperture, direction, length, etc. As regards to the calibration process, it might be improved by taking into account geochemical data such as chemical tracers.



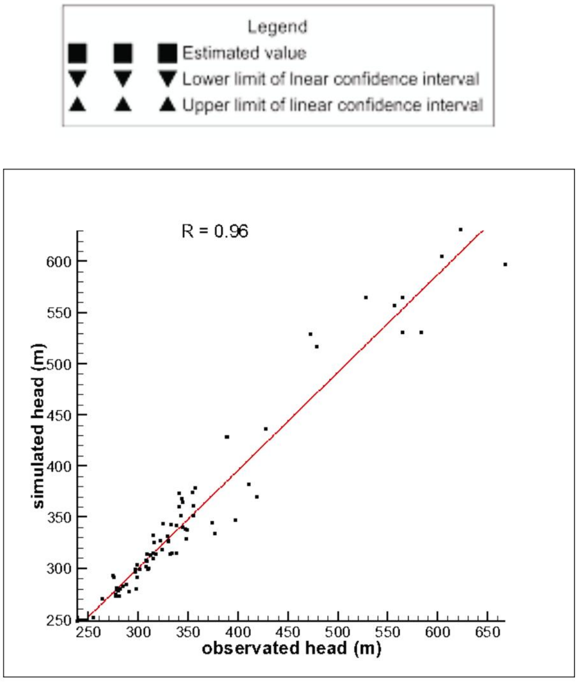


Figure 7. 95% linear confidence interval

Figure 6. Simulated head vs Observed head.

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