Development of a three-dimensional finite element model for simulation of groundwater flow in the tropical river catchment of the Upper Ouémé (Benin / West Africa)

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Abstract The Republic of Benin is one of the poorest countries in West Africa. Especially in the dry season the water demand in the rural areas is more and more dependant on exploitable groundwater. A finite element model is to be established as a prediction tool to facilitate groundwater management for the model area in the future. The model area lies in the centre of Benin which is an important region with regard to its agricultural potential and to its attraction to new settlers. It covers the Upper Ouémé river catchment by approx. 14.500 km². The hydrogeology is to be taken into account by the separation of three layers of different hydraulic characteristics: soil zone, saprolitic aquifer and the fractured basement aquifer. However, local hydrogeologic data sources are scarce and necessary data has to be obtained in the field by an ongoing regional hydraulic, hydrochemical and environmental isotopes sampling campaign.

Key words groundwater flow model; finite elements; data acquisition; saprolite; fractured aquifer; Benin; Ouémé catchment

INTRODUCTION

The Republic of Bénin is one of the poorest countries in the world. It is situated at the northern coast of the Gulf of Guinea (Fig. 1). The country has common borders with Nigeria in the East, Niger in the Northeast, Burkina-Faso in the North and Togo in the West. Its major river, the Ouémé, has its source in the centre of the country and flows towards the Atlantic in the South. While the South of Benin shows 4 seasons, two rainy and two dry seasons, the central and the northern part only shows one rainy season from Mai to August.

Fig. 1 Benin and the location of the study area at the Upper Ouémé catchment.

Like in most developing countries the population is still fast growing with increasing concerns about the availability of potable water. The long drought period in the Sahel since the 1970s shows its impact mostly in the very North of the country and causes migration of people towards the still more humid south increasing the pressure on the available water resources. Especially in the dry season the water demand in the rural areas is more and more dependant on exploitable groundwater. The determination of the potential of groundwater resources for satisfying the increasing water demand in the Upper Ouémé river catchment is of decisive importance. In this context a numerical groundwater flow model is to be established as a prediction tool to facilitate groundwater management for the model area in the future. The software used for modelling is FEFLOW 5.1 (WASY, 2004).

The study presented in this paper is part of the framework of the IMPETUS West Africa project. IMPETUS is a multi-disciplinary research approach in order to describe the impact of climatic change on the water resources of Benin.

HYDROGEOLOGY / FIELD WORK

Most of the area of Benin is situated on the crystalline basement of the West African craton except three major sedimentary basins: the coastal basin (Meso-Cenozoic) in the south, the Kandi basin in the northeast (Palaeozoic) and the Precambrian voltaic basin in the north-west (Faure & Volkoff, 1996).

The conceptual hydrogeological model (Fig. 2) has been developed by Fass (2004) during the first IMPETUS campaign from 2000 – 2003. Hydrochemical sampling and stable isotope analysis proves the application of the model for the whole study area.

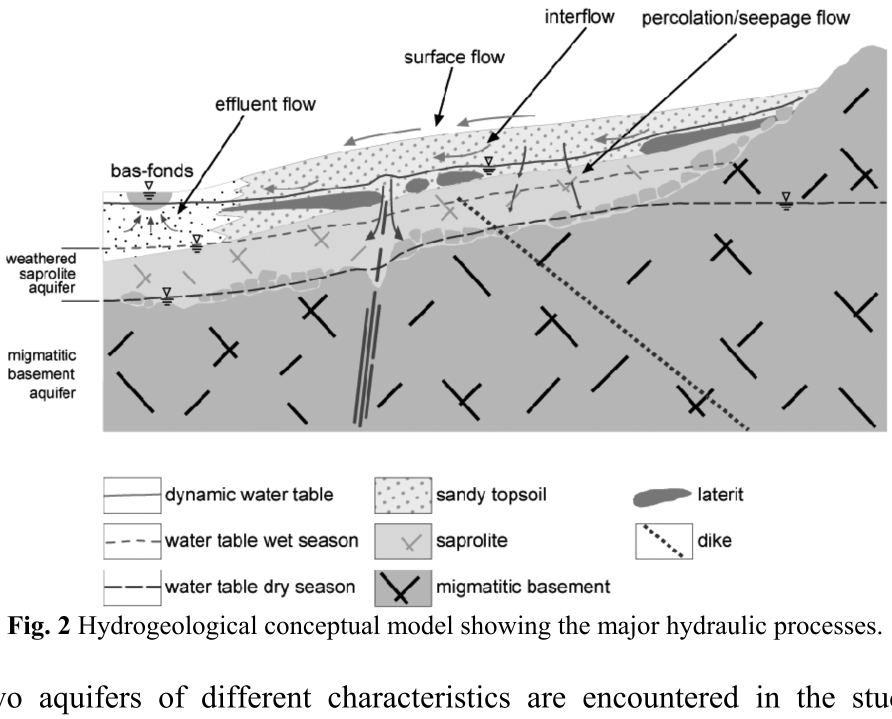

Fig. 2 Hydrogeological conceptual model showing the major hydraulic processes.

Two aquifers of different characteristics are encountered in the study area: a saprolite aquifer and a fractured basement aquifer. Saprolite is an in-situ weathering product of the bedrock. Its thickness depends on its morphological position, less at hill tops and valley bottoms and thicker at hill slopes. The average thickness ranges from 15 to 20 m. The saprolite shows a good porosity of around 2-5 % but its permeability of 1-9 x 10^{-7} m s^{-1} is only weak. The groundwater flow in the crystalline basement is exclusively connected to fractures and faults. Rock types are often strongly metamorphous migmatites, granites, gneisses and schists. Fracture openings vary from mm to dm scale as well as the length of fractures ranges from m to km scale. Geophysical prospecting of the study area describes fracturing with a maximum depth of 120 m. In general the depth of fractures is around 40 to 60 m. Porosity is low with 0.1 – 0.2 % while its transmissivity depends on the fracture aperture but its generally around 10^{-4} - 10^{-6} m^2 s^{-1} (Jacquin & Seygona, 2004). The fractures drain groundwater from the saprolite.

Besides the sampling campaign snap shot measurements of the groundwater table at the end of the dry season as well as at the end of the rainy seasons are done at more than 100 points each time. A continuous monitoring system with 12 automatic measuring water level devices had been installed in April in observation wells and boreholes of pumps all over the study area. Measurements are made in a 3 hour interval. Groundwater tables from the early morning hours are considered as static water level. The groundwater table rises during the rainy season in the saprolite to a height of 1-2 m below ground and may drop to 10 to 15 m below ground at the end of the dry season (Fig. 3).

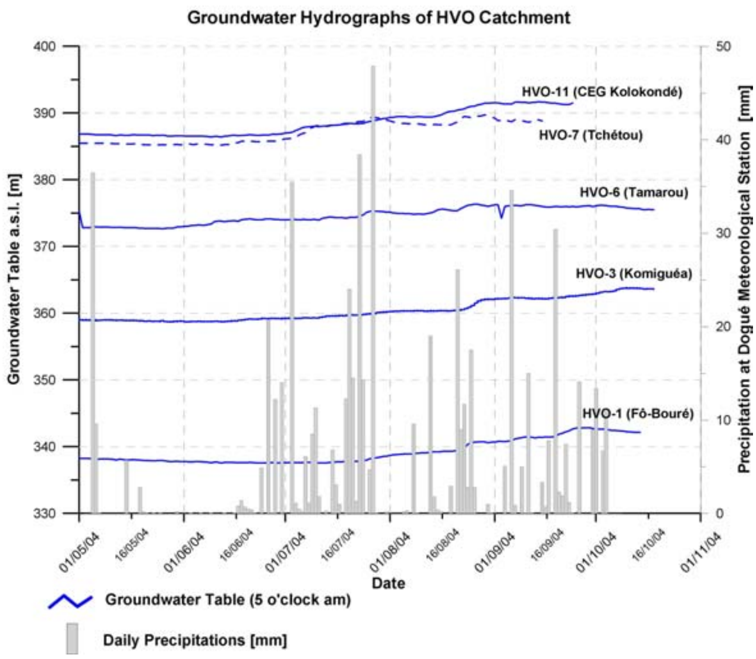

Fig. 3 Hydrographs of some data logger in the Upper Ouémé catchment and rainfall measurements at Dogué showing the rain dependant rise of the water table.

MODEL STRUCTURE

A regional groundwater flow model has been developed to determine flow characteristics and the availability of groundwater in the Upper Ouémé catchment (14.500 km²). Emphasis has been given to the possibility to refine the model step by step using the results of the ongoing data acquisition and field investigation. Therefore the finite element model FEFLOW 5.1 has been chosen as it shares the necessary abilities fur such procedures. As well FEFLOW 5.1 provides an interface manager which enables to couple the flow model eventually with other hydrologic and soil moisture models which are used by the IMPETUS modelling group.

Discretisation is made by triangular finite elements. Information is given to the nodes connecting the elements. Therefore a number of nodes had already been placed during the mesh generating process on the coordinates of points with already available information. Such locations are the villages contained in the census 2002, the diver positions and the boreholes with sufficient information about exploitation and geology. Actually the model consists of 26.268 elements and a number of 18.204 nodes in 3 layers. Refinement is already performed on the rivers in order to allow the implication of streaming routes into the model.

The model surface is given by the interpolation of the digital elevation model derived from SRTM satellite images with a resolution of 90 x 90 m (Fig. 4). Thicknesses of the soil zone were taken from the soil map of the area and regionalised. The thickness of the saprolite aquifer has been interpolated either from the well logs available for the study area or from own field measurements. The determination of the depth and the distribution of the fractures are difficult as sufficient data does not exist. Thus pumping test data for the different geologic formations were generalised for each rock type corresponding to geological maps. The same procedure has been done to determine the average depth of fracturing for each rock type.

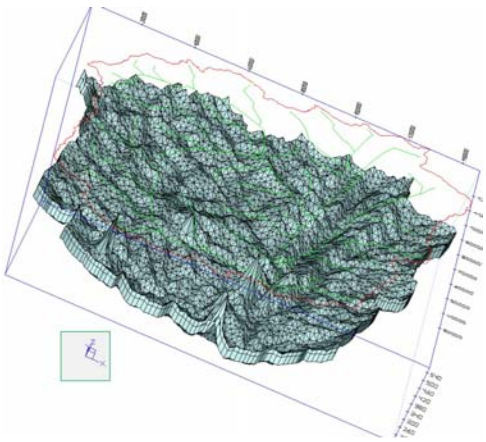

Fig. 4 View on the 3D model by FEFLOW 5.1.

A first stationary model was calibrated to represent the groundwater conditions at the end of the dry season. A second model was calibrated for the phase at the end of the rainy season. For each model boundary conditions are determined by groundwater contour lines along the water sheds (Fig. 5). Based on daily measurements from the divers validation will be done to connect both stationary models via a transient model.

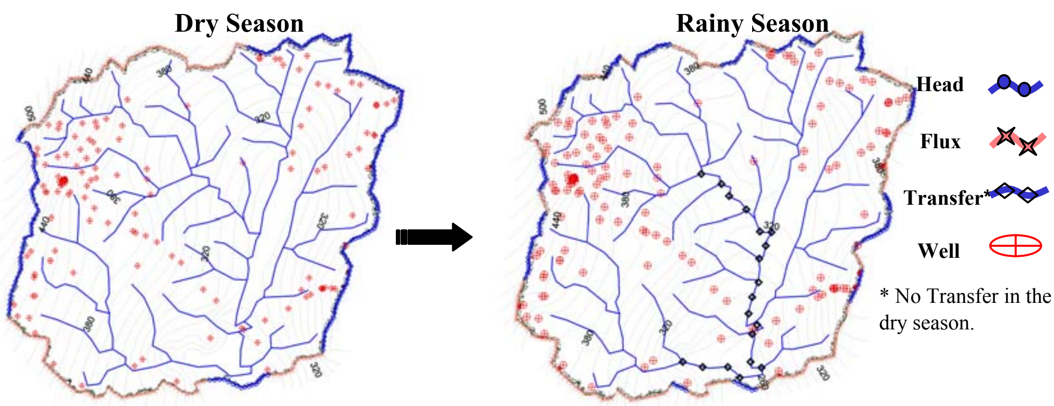

Fig. 5 Evaluation of the boundary conditions based on groundwater contour maps

Boundary conditions for the connecting time steps between dry and rainy season are interpolated using linear algorithms for the nodal points. So far the integration of the intermittent flow of the rivers (only rainy season) is not satisfactory solved.
The 4th kind well conditions show for the present state just small effects on the behaviour of the water table and is outweighed by the impact of climatic conditions. Demographic data from the census and observations concerning the public water use are applied to calculate the total consumption of groundwater for each census settlement. Ongoing implementation of new field data will constantly refine the model output. Sensitive validation practice gives way to use modelled input data from different IMPETUS subprojects for the future development of water and land use in Benin.

OUTLOOK

Benin started its national groundwater observation program only recently. This means the regular registration of water table depths at the 12 observation wells distributed all over the country and the integration of well data in one data base. As well a first water directive is on the way to be signed by the government in 2005. The successful use of groundwater flow models, especially in developing countries, is strongly limited by the availability of data and knowledge about the hydrogeology of the model area. Thus the presented model in its actual state can only be an approach to show the general behaviour of groundwater flow in the study area and its reaction towards changes in climate and exploitation schemes. New data is obtained by ongoing field work and allows the increasing refinement of the model.

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