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Comparative analysis of different boundary conditions and their influence on numerical hydrogeological modeling of Palmital watershed, southeast Brazil

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ABSTRACT

Study region: The study is based on field data of a shallow phreatic aquifer occurring at a small watershed in Viçosa, Minas Gerais, Brazil.

Study focus: The present study aims to evaluate numerical hydrological models generated using different boundary conditions as field data did not allowed a proper definition of the most adequate boundary condition to simulate the field characteristics observed within the study area. Data field was used to build a conceptual model and to determine initial and some of the boundary conditions of model mesh. Three numerical hydrogeological models were generated on Visual Modflow®. Once created, the models were calibrated using the WinPEST®. GHB, River and Stream boundary conditions resulted on a calibrated standard Root Mean Square (RMS) varying from 7.3% to 13.02% and showed high correlation coefficients, varying from 94% to 97%. Using another set of hydraulic head field data, these models were later validated.

New hydrological insights for the region: Results show that, for all three boundary conditions, the normalized RMS obtained in calibration was similar to that obtained in validation, confirming its validity. The Rivers boundary condition have presented the most representative values for normalized RMS, absolute average error and correlation coefficient, and are the most indicated boundary conditions for areas with similar physical characteristics to the area under study.

Introduction

Brazil has more than 113,000 km^3 of groundwater in its territory and around one third of total Brazilian territory—approximately 3,000,000 km^2, is considered to be in recharge zones (CREA-MG, 2013). The use of groundwater is rapidly increasing in the country due to an increase in consumption and degradation of superficial water bodies (Cabral et al., 2006). There is an estimate that at least 416,000 wells are currently operating in the country, and every year 10,800 new wells are being installed (Hirata et al., 2010). Given the relevance of aquifers for the Brazilian economy, their use should follow a good management program including actions to promote sustainable use and prevent their contamination and allow maintenance of groundwater quality and quantity for its multiple uses.

Despite being low storage aquifers, superficial unconfined aquifers are an important source of water for rural populations because there is no water supply for these areas in Brazil. Even with their importance, there are not many studies regarding aquifers in Brazil.

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Only in recent year has attention been given to these issues, especially in developing countries, because these aquifers comprise an important source of water for the rural areas (Appiah-Adjei et al., 2013; El Samanoudy et al., 2013; Flores-Marquez et al., 2008).

In Brazil, there is also an urgent need for promoting studies involving distribution and forms of occurrence of groundwater on different geological environments. This includes the following: comprehension of superficial and groundwater relationship, its vulnerabilities and storage capacities, recharge areas, flow identification, groundwater quality, and water table monitoring (Krebs and Possa, 2008; Soares, 2010).

These studies should address environmental management perspectives and also allow the creation of hydrogeological models (Marthers et al., 2012). Once calibrated, these models could be used as a tool to predict changes in those aquifers and on water storage and supply as a response to the introduction of new pumping wells, or for analysis of underground contaminant movement. Aigler and Ge (2013) have modeled Fraser River watershed, in order to simulate groundwater flow and to examine the simulated localized depression resulting from a proposed increase in groundwater withdrawal, in an approach similar to the one used in this study.

Xi et al. (2010) studied a superficial aquifer at Ejina Basin, North China, simulating groundwater level variations, both spatial and temporal, using MODFLOW, and have reached good calibrated results that matched well with the observed data.

Carrol et. al (2009), studying the Death Valley Regional Flow System using MODFLOW, pointed out that its most significant limitation was that the model was built using the confined layer assumption to improve numeric stability, considering that the saturated thickness remains constant throughout the entire simulation. They considered that this approach allows unrealistic estimates of drawdown to occur in transient simulations.

In Brazil, Filho and Cota (2002) performed a sensitivity analysis for conductivity through a simulation of a hypothetical superficial, homogeneous and isotropic aquifer involving a GHB (General Head boundary) contour condition and aquifer drawdown by pumping. These authors also presented a comparative analysis of mathematical features of MODFLOW packages or modules, which are forms of implementation of boundary conditions (GHB, River, Drain and Evapotranspiration-EVT). The results contributed to a greater understanding of the operation of these mathematical routines, helping thus the hydrogeologists to develop models that best represent these characteristics.

Computer simulations of groundwater flow systems numerically evaluate the mathematical equation governing the flow of fluids through porous media. To determine a unique solution, it is necessary to specify boundary conditions around the flow domain for head or its derivatives in a so-called boundary-value problem (Collins, 1961). Not only the location of these boundaries is important but, their numerical representation is also critical. This is because many physical features (that are hydrologic boundaries) can be mathematically represented in more than one way, and determining the best mathematical representation usually depends upon the objectives of the study and can affect the ability of a model to make accurate forecasts (Reilly, 2001).

Determining of contour (boundary) conditions for hydrogeological mathematical simulations is an essential step of numerical modeling, but it is not trivial, as it depends on a detailed knowledge of the simulated system and on some mathematical specificities of the chosen model (Filho and Cota, 2002). As no sufficient knowledge was available for a proper selection of boundaries conditions that could represent the characteristics of the drainage system existing in the study area, the authors have developed a study focusing on an evaluation of the effects of the use of three different (GHB, River and Stream) contour conditions on numerical hydrogeological simulations of an unconfined (phreatic) aquifer occurring in a rural watershed of Southeast Brazil, and to and to define the most suitable boundary condition to the model. This study was part of a major study involving hydrogeological modeling of Palmital watershed, and the effect of increased groundwater withdrawal by new pumping wells in terms of both its quantity and its quality.

The study area is a small watershed (125.6 ha) located in the rural area of Viçosa, a small city in the Southeast state of Minas Gerais, Brazil (Fig. 1). It is located between UTM plane coordinates (23S Zone, SAD69 Datum): 723,100 m and 724,400 m East and 7,695,900 m and 7,697,400 m North. Palmital watershed belongs to the Rio Doce Federal Watershed and it is an important fountainhead for Viçosa (Fernandes, 1996). The Rio Doce watershed is of great interest for hydrological studies because it presents a wide range of economic activities that are influenced by water availability, such as agriculture, agro-industry, mining, steel, pulp and dairy products. It must be pointed out that besides the Palmital watershed being small, its characteristics (geology, pedology, vegetation, soil uses, topography, and climate) are representative of an extent region of Southeast Brazil region.

2. Methods

All field data was obtained from the work developed by Carvalho (2013) and Andrade (2010). The following sections detail some of the methods used. Additional information can be found in Carvalho (2013) and Carvalho et al. (2014).

2.1. Conceptual and numerical model construction

Data collected in the field by Carvalho (2013) and Andrade (2010) have allowed the definition of geology, pedology, land use, and topography, and were used to determine the hydrogeological conceptual model for the watershed under study.

All data was converted from the conceptual model to numerical model through Visual Mod Flow Pro 2009.1® software using finite differences method. In addition, data from the register of all springs found in the watershed, SPT and auger boreholes, five monitoring wells, and water level monitoring during one hydrological year on each of the five wells and slug tests have been used.

2.1.1. Model mesh definition

The watershed was divided into 25 m^2 cells and the area outside its limits was not modeled and was considered as inactive cells.