Envisaging the Sustainability of an Aquifer by Developing Groundwater Flow Model for a Part of Choutuppal Mandal, Nalgonda District, Telangana, India

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Abstract
Recurring droughts and increased exploitation of groundwater to meet the growing water needs have resulted in the decline of regional groundwater level and drying weathered zone in a part of the Choutuppal Mandal, Nalgonda district, Telangana, India. In this study, a preliminary steady state groundwater flow modelling has been carried out by using Visual MODFLOW Classic Interface (Build 4.6.0.168), well inventory data from the existing 20 observation wells and a base map for the subsurface structure in order to evolve the future pumping schemes. The area spreading about 0.43 km² is conceptualized as a two-layered model consisting of a weathered layer overlying a fractured aquifer. The model has been digitized into grids of 5m×5m in each layer. The integrated finite difference method has been utilized to discretize the groundwater flow equation and simulate groundwater flow with the help of calculated parameters along with the boundary conditions and acting stresses. Results show that the computed groundwater levels are in good agreement with the observed heads, and groundwater is flowing from the South to the North direction. The estimated velocities vary from 0.01 to 1.95 m/d. The optimum pumping schemes have also been simulated up to the year 2022. It has been observed that the maximum pumping rate should not go beyond 24 m³/day. Since the drinking water demand (10-15 m³/day) in the study site is below this limit, it can be inferred that the aquifer will sustain and provide enough drinking water.

Keywords
Groundwater, weathered and fractured aquifers, numerical simulation, MODFLOW, Choutuppal.

Introduction
Groundwater is indispensable for sustaining human life, economic growth, and a healthy ecosystem (Gleeson et al., 2012). Since groundwater is an essential source of water in semi-arid and drought-prone regions, it is imperative to understand groundwater quantity and quality along with flow conditioning these regions for sustainable aquifer management (Guihéneuf et al., 2014). Groundwater models can be used to develop such understandings and help in an informed decision-making process. These models represent the essential features of the actual groundwater systems employing a mathematical counterpart (Alley, 1999) and generate precise information for water resources management, groundwater protection, and remediation (Baalousha, 2008). The necessities of building the models comprehensively increase in the regions, which are complemented by undue exploitation of groundwater in order to fulfill the daily water demand. These models could be steady-state or transient, confined or unconfined or combined, one-dimensional, two-dimensional, quasi three-dimensional, or three-dimensional, which can be solved by using finite difference methods or finite element methods or combination of both (Todd & Mays, 2005).

Groundwater Modeling System (GMS), Finite Element Subsurface Flow System
FEFLOW), Modular Finite-difference Flow Model (MODFLOW), etc. are some of the advantageous software that has been developed to build groundwater models applicable for groundwater resource management. Such software can be applied to assess the waterlogged area (Singh 2013), simulate drawdown (Sklorz et al., 2017), and determine the interactions between the surface water and groundwater (Lasya & Inayathulla 2015).

MODFLOW, developed initially by McDonald & Harbaugh (1988), is now added with many capabilities to make it user friendly. Most of the hydraulically defined groundwater flows simulated by MODFLOW were independently verified as rationally isotope mixing model (Carrol et al., 2008). Visual MODFLOW, an integrated package combining MODFLOW, MODPATH, and Zone Budget, is the most complete and comprehensible modeling setting that can be applied conveniently in three-dimensional groundwater flow and contaminant transport simulations (Waterloo Hydrogeologic 2015). Fouépé Takounjou et al., (2009); Jovanovic (2009); Mondal and Singh (2009); Shi (2010); Mondal and Singh (2012); Sadrhavani et al., (2012); Steiakakis et al., (2016); Baharuddin et al., (2016); Kumar et al., (2017) and Sen et al., (2018) applied Visual MODFLOW for various research purposes. Based on the review study of research papers, Hariharan and Uma Shankar (2017) and Mondal (2019) found that Visual MODFLOW can be applied in a variety of groundwater flow simulation settings. Considering the full range of applicability and reliability of Visual MODFLOW, this study is aimed to develop a preliminary steady-state groundwater flow model for an experimental site using Visual MODFLOW Classic Interface (Build: 4.6.0.168). This model would be helpful to evolve the future pumping schemes in the study site located at Choutuppal Village, Nalgonda district, Telangana, India (Fig. 1).

Fig. 1. Showing the EHP site with the observation wells, Choutuppal Mandal, Nalgonda District, Telangana, India (Image Source: Google Earth, retrieved on 20 January 2019)

Study area
The Experimental Hydrogeological Park (EHP) (Latitudes: 17°17′23.5″-17°17′52.5″N;
Longitudes: 78°54′59.2″-78°55′27.6″E) is situated in the Nalgonda district close to Choutuppal village in Telangana state, 60 km south-east of Hyderabad city (Fig. 1). Constituted of weathered and fractured Archean granite, the EHP site covers an area of 0.43 km² with an altitude range of 363 to 375 m (Fig. 2). The EHP site has more than 28 boreholes (available 20 boreholes data were used for this study) that are being used for studying aquifer properties.

Geological structure

The typical geological profiles of two boreholes (shown in Fig. 3) are obtained at the EHP by drill cuttings analysis. The lithological description is given by Guiheneuf et al., (2014), which are from top to bottom up to the explored depth of around 80 m, below ground level (bgl). It has been observed that the top red sandy soil ranges from the first decimeters to the first meter. The sandy regolith is varied from about 1–3 m deep, and the saprolite (mainly laminate structure) is from about 3 to 13–24 m deep. It is derived from the in-situ weathering of granitic rocks. In the deeper part, poorly fractured crystalline rock overlies upon the fresh basement (Boisson et al., 2015; Guihéneuf et al., 2017). The upper part of the granite is highly weathered and fractured, but the fracture frequency decreases rapidly with the depth.

Climatic condition

Nalgonda district has a semi-arid climate with an average annual temperature of 28°C and a maximum of 45°C in the summer season. The mean annual rainfall is around 751 mm, which ranges from 2 mm in February to 171 mm in July. The dug well depth ranges from 30 to 300 m below the ground surface (m bgs) in the district (CGWB, 2013). Water levels at the district are highly variable depending on the monsoon and usually range between 2 and 26 m (m bgs). Water level measurement at the EHP site during the last four years has shown that only monsoon precipitation has recharged the aquifer.

Methods

The Visual MODFLOW Classic Interface was used, which can simulate the groundwater flow model under the steady and transient states either 1-D, 2-D, or 3-D for both anisotropic and heterogeneous systems by adopting the
finite-difference method. The governing 3-D groundwater flow equation used by MODFLOW (McDonald & Harbaugh 1988) is as below.

$$\frac{\partial (K_x \frac{\partial h}{\partial x})}{\partial x} + \frac{\partial (K_y \frac{\partial h}{\partial y})}{\partial y} + \frac{\partial (K_z \frac{\partial h}{\partial z})}{\partial z} + q_s = S_s \frac{\partial h}{\partial t}$$

Where, $K_x$, $K_y$, and $K_z$ are the values of hydraulic conductivity along the x, y, and z coordinate axes oriented parallel to the principal axes of hydraulic conductivity [L/T], $h$ is the hydraulic head [L], $q_s$ is the volumetric flux of groundwater sources and sinks per unit volume [1/T] with positive values indicating flow into the groundwater system, $S_s$ is specific storage [1/L], and $t$ [T] is time.

The modeling process involves necessary steps that include objective identification, data collection, and review, model conceptualization, model design, model run, model calibration along with improvements in the conceptual model, verification of the model, analysis of sensitivity and uncertainty, and finally reporting the outcome. The methodology generally adopted to set up a groundwater model is described in the flow chart mentioned in Fig.4. For this study, the same steps were followed to develop a steady-state groundwater flow model.

**Data collection**

Elevation data of the EHP site were collected from Google Earth Map using a TCX converter with an accuracy of ±5.0 m. To maintain the accuracy, 20 elevation data collected at the observation wells were compared with the field level Global Positioning System (GPS) data that showed on an average variation of +2.0 m. The altitude data deduced from the Google Earth Map have been corrected accordingly by reducing 2.0 m and used for this study.

Published literature was reviewed to collect hydro-geological and lithological information of the EHP site (Boisson et al., 2015; Guihéneuf et al., 2015).
Conceptualization and grid design

The conceptualization of the flow regime was conducted based on hydro-geological information collected from the literature review and existing physical conditions of the site. The model was divided into grids of 5m × 5m (Fig. 5) in each layer represented with 17,200 active cells. The area spreading about 0.43 km² was conceptualized as a two-layered model consisting of a weathered layer overlying a fractured aquifer, as mentioned in Fig. 6.

The top layer was considered as an unconfined aquifer, whereas the bottom layer was assumed to be confined aquifer. The top layer, weathered zone, lies in between 2 - 24 m, b.g.s underlying by 15 - 80 m fractured/semi-weathered layer. The top of the first layer (namely shallow aquifer) varied from 333 to 362 m (amsl), while the bottom of the second aquifer ranged from 261.0 to 285.7 m (amsl). These two layers have different hydraulic characteristics, and especially the fractured zone/semi-weathered layer has a lower storage coefficient comparatively the weathered zone. This weathered aquifer was considered as equivalent to a porous one. For the saturated zone connectivity in fractured media/semi-weathered layer, although a general decrease of the hydraulic conductivity with depth is known, only minimal information is available on the vertical connectivity of the dominant horizontal fracture network. This connectivity has been investigated through packer tests at a localized scale (Boisson et al., 2015) and indicated the semi-weathered layer with a large fracture density having low storativity. Thus the semi-weathered/fractured layer was also assumed to be a porous layer for the groundwater flow modelling.

Assignment of boundary conditions

The study site slightly slopes towards the North. Streams or rivers are absent. So, the constant head boundary was taken for the steady-state simulation towards the North direction of the...
micro-watershed. A constant head of 335 m (amsl) was taken in the model simulation. The no-flow boundaries were assigned in the other three sites of the watershed, where the water divides were observed and the watershed has only one outlet in the northern part.

**Assignment of aquifer properties**

Hydraulic conductivity and recharge values, along with the porosity, specific yield, specific retention, and specific storage, were assigned to each layer. The hydraulic conductivity of the first layer varies between 0.0864 and 8.64 m/d (Guihéneuf *et al.*, 2014). For this study, layer one was divided into three zones based on the variations of geological conditions, and hydraulic conductivity values were assigned as 5, 4, and 3 m/d, respectively, for Zones 1, 2, and 3 (Fig. 7). The hydraulic conductivity value of the second layer was calculated by interpolating the observed conductivity values at the observation wells using the Krigging method in the MODFLOW environment. The interpolated conductivity value for layer 2 ranges from 0.04 to 0.864 m/d. A maximum conductivity value of 0.864 m/d lies in the North-Eastern part, and the minimum value of 0.04 lies in the Southern part.

The mean annual rainfall in the study area in the year 2013 was about 1101 mm. Recharge is assumed to be 2-15% (Lerner *et al.*, 1990) of the annual rainfall in the semi-arid area, which was utilized for the natural groundwater reserve in the model. Therefore, the recharge values varied from 22.02 to 165.15 mm/yr. The recharge values assigned were 70, 80, and 90 mm/yr, respectively, for Zones 1, 2, and 3 (Fig. 8). Irrigation recharge was not considered due to the unavailability of data, which was not practiced in the modeled area. The assigned values of the other layer properties
Fig. 6. Cross-section view of the two-layered conceptual model of the EHP site at the Row: 91

Fig. 7. Showing the K- distribution in the first layer
were as given in Table 1.

Table 1. Other aquifer properties assigned to layers 1 and 2

| Properties          | Layer-1 | Layer-2 |
|---------------------|---------|---------|
| Porosity (%)        | 25      | 5       |
| Specific Yield (%)  | 12.5    | 2       |
| Specific Storage (1/m) | $1.032 \times 10^{-4}$ | $9.91 \times 10^{-5}$ |

**Steady-state model**

The purpose of the steady-state groundwater model is to demonstrate that the model can reproduce field measured heads and flows. The flow model was calibrated by adjusting numerous parameters such as recharge, conductivity, and porosity, etc. within an acceptable limit until the best fit was obtained between the observed and calibrated heads. The accuracy of the computed heads was judged by the root mean square error among the computed and observed head plots on the graph.

The groundwater steady-state flow model was developed for 365 days using available 20 observation wells data. The model was calibrated against the constant head boundary, recharge, and hydraulic conductivity through a sequence of sensitivity analysis runs. The values were adjusted during trial and error runs aiming at the smallest root mean square errors at the targets. Groundwater levels measured were used as initial water level conditions.

**Sensitivity Analysis**

Sensitivity analysis was performed in order to notice the effect of uncertainties on the calibrated model. It involved a series of simulations on the outcome model by changing the values of assigned aquifer parameters and boundary conditions. During the analysis, one parameter was changed with in a conceivable range by increasing and decreasing the value of the parameter multipliers.
Mass Balance

The results from steady-state or transient MODFLOW simulations can also be used to calculate sub-regional water budgets. The U.S. Geological Survey has developed a zone budget tool to calculate water budgets for user-defined zones in the model. This study applied the zone Budget tool to quantify the water balance and contributions of assigned parameters to the aquifer system.

Results and Discussion

The calibrated groundwater heads were in good agreement with the observed heads. The observed heads ranged from 348.42 to 356.18 m, amsl, and the calibrated heads ranged from 348.47 m to 356.83 m. The groundwater velocity vectors indicated the predominant flow towards the North with a velocity of 0.02 m/d in layer 2. In Fig. 9, the observed and calculated head values of well CH11 are closely simulated with an overestimation of +0.05 m, and the maximum over estimation of 0.77 m is at the well CH06 of the model. MODFLOW application may produce several reasonable as well as some unsatisfying simulations because of the complex hydrogeologic systems (Khadri & Pande 2016). One of the common ways to determine the accuracy of the results of calibration is calculating the root mean square error (RMS) value. The calibration result of the study has a low RMS value of 0.22 m (Fig. 9), demonstrating its satisfying responses to field measured heads. The results of the sensitivity analysis showed that the models are sensitive or reacting much to the parameters like hydraulic conductivity and recharge from rainfall in the different hydrogeological zones (Fig. 10). The micro-model is sensitive to the recharge in zone 3, resulting in a high RMS value than the other zones. The model is also comparatively more sensitive to hydraulic conductivity in Zone 1. The maximum RMS value obtained was 2.038 during the sensitivity analysis.

An outflow of 106.38 m$^3$/day was taken up by the Constant Head Boundary (CHB), and 1.81 m$^3$/day of groundwater was being used up by evapotranspiration. The inflow of the system was about 92.72 m$^3$/day. There was an overdraft taken only by the CHB because of there was no predominant abstraction well for the pumping.

The optimum pumping schemes simulated till the year 2022, assuming the population of 1200 based on the current growth rate of 1.36% at nearby villages, showed that the maximum pumping rate should not go beyond 24 m$^3$/day within this micro-watershed taken one representative bore well (at the CH 4, Fig.11). Since the drinking water demand (10-15 m$^3$/day) nearby the study site

![Calculated vs. Observed Heads: Steady State](image.png)

**Fig.9.** Calculated vs. observed heads in the steady-state calibration
is below this limit, it can be considered that the aquifer will sustain and provide enough drinking water to nearby the villages.

**Conclusion**

A groundwater model has been conceptualized and developed using the lithology information and aquifer parameters for the Experimental Hydrogeological Park (EHP) at Choutuppal Mandal, Nalgonda district, Telangana, India. The computed groundwater heads have shown to replicate the trend of observed groundwater heads. Groundwater is flowing from the South to the North direction, with the velocity ranges of 0.01 to 1.95 m/d. The output from the calibrated model can be used to develop the transient state,
particle tracking, and mass transportation models that will help in understanding the groundwater regime in the EHP. Further, the updated data can be used to refine the model and compare the findings with the model developed in this study to observe the accuracy of the assigned parameters. The current study has found that the maximum pumping rate should not go beyond 24 m$^3$/day for the drinking water supply to neighboring villages. The updated model may be applied to project the future scenarios of the aquifer system and estimate the sustainable pumping scheme at the EHP.

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