A three dimensional modeling approach to groundwater management in Paharpur Canal Command Area, Dera Ismail Khan, Pakistan

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Abstract: The main aim of this study was to analyze the groundwater flow system in Paharpur Canal Command Area, Dera Ismail Khan using MODFLOW 4.2. The model was run for both steady and non-steady state conditions. The area was modeled with a grid of 171 columns and 399 rows with three layers assigned on the basis of the varying hydraulic conductivity values. The upper 100 meter of the unconfined aquifer was modeled. The steady state model was simulated and then calibrated for the year 1980 using PEST. Non-steady state simulation was carried out from the year 1980 to 2010 to evaluate the effects of groundwater abstraction on the water table depths and flow direction. The groundwater model developed has resulted in better understanding of the groundwater flow of the study area. Water logged zones have also been identified with the aid of the model. Groundwater management of the area can be effectively carried out with the support of the model developed.

Key words: Groundwater, modeling, MODFLOW, calibration, water logging

1. INTRODUCTION

Fresh water is essential component of all forms of life and it is mainly obtained from two sources, i.e. surface water and groundwater (McMurry and Fay, 2004). Groundwater is an exceedingly important freshwater resource and its ever-increasing demand for agriculture, domestic and industrial use in Pakistan ranks it as of strategic importance (Amin, 2012). Agriculture is the largest sector of Pakistan’s economy. It accounts for about 70 percent of the export earnings (PWP, 2001). The uncontrolled and unregulated use of groundwater leading to the overdraft of aquifers and salt-water intrusion has emerged in many areas of the Indus Basin, Pakistan (Kijne, 1999). The secondary salinization associated with the use of poor quality groundwater for irrigation has further compounded the problem. The phenomenon of water logging and salinity is widespread in many agricultural areas all around the globe where it causes several socio-economic and environmental losses. In irrigation command areas, Groundwater models such as MODFLOW have been widely employed in general groundwater studies including water-logging problems (McDonald and Harbaugh, 1988).

Although research on climate change in Pakistan is still in its infancy, there is evidence that future changes in climate will have adverse effects on agricultural production (Hussain and Hanif, 2013). Hence, groundwater modeling is an important tool to provide guidance for management of groundwater particularly in the areas where the hydrological cycles are predicted to be accelerated due to climate change (Mall et al., 2006).

This paper is a part of the study aimed to analyze the groundwater flow system in Paharpur Canal Command Area. Numerical three dimensional finite difference steady and non-steady state flow models were prepared for the unconfined aquifers using MODFLOW version 4.2. The overall objective of the current work was to determine in detail the groundwater movement and access the interaction of the groundwater aquifers with the Paharpur Canal and Indus River. In non-steady state simulations, the effect of pumping wells on the groundwater flow and depth were determined.
2. STUDY AREA

The Paharpur Canal Command Area is located on the north eastern side of Dera Ismail Khan (Figure 1). Dera Ismail Khan is the southern most of the districts in the Khyber Pakhtunkhwa Province of Pakistan. Paharpur Canal Command Area falls within longitude 70° 55' to 71° 18' East and latitude 31° 45' to 32° 25' North (WAPDA, 1980). Chashma Barrage is on the northern side and to the south is the City of Dera Ismail Khan. The Paharpur Canal forms the western boundary. The Paharpur Canal emerges from the Chashma Barrage and ends near the south of Dera Ismail Khan City at Kotla Qaim Shah (Naqvi, 1977). The eastern boundary is formed by the Indus River. Agriculture is the principle source of income in Dera Ismail Khan District (Hussain and Hanif, 2013).

Physiographically the area consists of active flood-plains, meandering flood-plains and piedmont plains (WAPDA, 1980). Most part of the district is a dry alluvial plain (Qadir et al., 2014). The climate of Dera Ismail Khan is semi-arid (Naqvi, 1977). About 60% of the rainfall occurs in July and August in the monsoon season. Clay, silt and gravel of late Pleistocene to Holocene age constitutes the unconsolidated -sediments of the study area. At a greater depth the unconsolidated sediments in the area consists of clay. This clay section is overlain by deposits of Holocene age and consists of sand dune and alluvium which is more than 300 m thick (Hood et al., 1970). This alluvium constitutes the unconfined aquifers in the area. The alluvium mostly consists of sand with clay, silt and gravel in subordinate amount.

![Figure 1. Location of Paharpur Canal Command Area in Dera Ismail Khan, Pakistan.](image1)

3. METHODOLOGY

The methodology followed the standard procedures adopted from Anderson and Woesnner (1992), starting with the hydrogeologic model conceptualization. Then the modeling software is selected. The next step involves the numeric model development and its simulation. After that model calibration is executed. It consists of changing the values of input parameters in an attempt to match field conditions. Sensitivity analysis is carried out on the calibrated model to deduce how changes in each parameter affect the model results. Final step comprises the analysis of the model results.
4. MODEL DESIGN FOR THE PAHARPUR CANAL COMMAND AREA

The boundaries of the model were determined by using a base map created in Global Mapper. MODFLOW imported the base map from Global Mapper in .dxf format. MODFLOW developed by the USGS, is a computer program using the finite-difference method to describe the movement principle of groundwater flow. The modeled region has a total area of about 2,727 km$^2$. The block centered grid consists of square cells of 171 × 399 grid cells, 0.04 km$^2$ each. The thickness of alluvium in this area is approximately 300 meters (Hood et al., 1970). Top 100 meters of this alluvium was modeled. This portion has been divided into three layers on the basis of varying permeability. The horizontal and vertical hydraulic conductivities were assigned to the three layers. Initial hydraulic head distributions for the model were obtained from the test holes and test wells drilled and installed by Water and Power Development Authority (WAPDA). The latitude and longitude of the wells together with their groundwater table elevation values were imported in the model. The Paharpur Canal consists of five distributaries. These include the Takarwah, Kot Hafiz, Rakh, Girsar and Rakh Mangan distributaries (WAPDA, 1980). Stream boundary conditions have been applied to the Paharpur and its five distributaries. Indus River was assigned the constant head boundary. The discharge rates along the Indus River were gathered from Indus River System Authority (IRSA). The annual average rainfall for the year 1980 is 239.3 mm per year, obtained from the Mianwalli Observatory. According to the report by Amin, 7% of the precipitation in the area contributes to the recharge. Therefore, recharge value of 16.75 mm per year was assigned to the first layer of the model. An evapotranspiration value of 1,350 mm per year as calculated from the Thornthwaite equation was assigned to the model. The elevation values of the modeled region were obtained from the elevation contour map of the area cartographed by WAPDA and then the depth to the static water level values is subtracted from the elevation values obtained. The resultant calculations are used as initial prescribed hydraulic heads for the initial specification of the head values.

5. MODEL CALIBRATION AND SENSITIVITY ANALYSIS

After the model has been designed and the initial parameters and boundary conditions have been assigned, the model is run and executed. The study area model had been executed using Slice Successive Over Relaxation method (SSOR).

The purpose of the calibration of a groundwater flow model is to demonstrate that the model can response field measured heads and flows (Anderson and Woessner, 1992). The calibration of the model had been carried out using PEST (acronym for parameter estimation). The hydraulic heads generated by the steady state simulation were used to calibrate the model with the measured hydraulic heads in the field. The hydraulic heads (measured in the year 1980) from twenty four wells were used to calibrate the model. Recharge and hydraulic conductivity values of the three layers were chosen for the calibration purpose. The scatter diagram after calibration is shown in the Figure 2.

During calibration, PEST calculates the composite sensitivities for all the estimated parameters (Doherty, 2005). In the study model, the hydraulic conductivities of the first layer (kx-1, ky-1 and kz-1) have higher sensitivity than the sensitivities of the hydraulic conductivities of the second (kx-2, ky-2 and kz-2) and third (kx-3, ky-3and kz-3) layer. The model is highly sensitive to ky-1. These sensitivities are calculated only for the estimated parameters.


6.1 Steady state model

Equipotential head map of the first layer of the steady state model for the year 1980 is shown in
the Figure 3A. The general movement of the groundwater as indicated by the equipotential contours is from north east towards the south. In the upper and lower parts of the modeled area, the water is dominantly moving from the Indus River towards the Paharpur Canal as indicated by the direction of the velocity vectors. However, in the central part of the model area there is some localized movement of the groundwater towards the Indus River.

Figure 2. The steady state calibration results of the groundwater flow model.

Figure 3. The equipotential map of the years 1980, 1990, 2000 and 2010, (A–D) for layer 1. Equipotential contours of 1m interval.

The water table depth map for the steady state simulation is shown in Figure 4A. In the upper and central parts of the area the water table ranges between 0 to 4 meters therefore in these areas
water logging problems are being encountered. Water logging can lead to salinization in the area. In the southern part the water table ranges from 5 to 7 meters below the surface.

Figure 4. The water table depth maps of the years 1980, 1990, 2000 and 2010, (A–D), showing the changes in the water table depth.

6.2 Non-steady state model

The transient model is built from the year 1980 to 2010 to see the influence of pumping on the groundwater flow and its level. Each year here represents a stress period. Each stress period comprises of two time steps, one time step represents six months. Cumulative discharge has been assigned to the pumping wells in the modeled area.

The dominant groundwater flow direction during the non-steady simulation is the same as in the steady state simulation, i.e. from north to south (Figure 3). However, there have been localized changes in the groundwater flow directions as a result of pumping wells. By analyzing the equipotential contour maps we see that the drawdowns are becoming more pronounced with time.

By analyzing the successive water table graphs it is inferred that the depth of the groundwater is increasing across the modeled region as a result of pumping (Figure 4). There has been a significant change in the water depth in the water logged regions in the upper and central parts of the study area. The areas formerly shown with the dark blue color have been replaced by relatively light blue color as the non-steady simulation proceeds.

In the southern parts of the modeled area the water depth has also increased as indicated by increase in the red zone and reduction in the yellow zone. Hence there is an overall decline in the water depth as a result of pumping.

7. GROUNDWATER BUDGET

Mass balance computation involves the identification and quantification of all flows in and out
of the aquifer. The calculated mass balance components include pumping from wells, recharge, evapotranspiration, river losing and gaining, changes in storage, stream leakage and constant head boundary. On the basis of groundwater budget analysis of the system, it is inferred that the aquifer recharge is lesser than the discharge (Figure 5). Thus we can deduce that the depth to the groundwater is increasing with time.

8. CONCLUSIONS

From the groundwater model developed we deduce that on long term basis the heavy pumping of groundwater will result in the decline of water table in the study area. However it would be useful for the areas facing the water logging problem.

The results of the study will be useful to predict the sustainability of the groundwater resources of the study area in the coming era of climatic changes and to evaluate possible management actions. Water logging and salinity can be improved by various water management practices. Hence future subsurface water conditions in the area can be forecasted and appropriate measures can be foreseen with the aid of this model.

REFERENCES

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