



Evaluating Aquifer Response to Variable Groundwater Pumpage Scenarios in Indus Basin through Finite Element Modeling

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Abstract: A three-dimensional numerical groundwater flow model was developed using Feflow 5.1 software to investigate the aquifer behavior of Upper Jhelum Canal command under variable scenarios of groundwater pumpage. The results of the study show that the groundwater system is effected by variable conditions of the groundwater pumpage thus influencing the watertable status in the Indus irrigated plain. The groundwater levels indicated sensitivity to both increase in numbers of tubewells and pumpage rates. Although lowering of the watertable due to increase in groundwater pumpage may result in minimizing the negative effects of waterlogging and salinity in the area but other influential factors (physical and management) also need to be investigated in order to reduce future risks of these problems on sustainable basis. A detail investigation of the groundwater system is required in context of increasing number of private/public tubewells and rapidly changing environment in the Indus irrigated plain.

Keywords: Finite element modeling, groundwater system, Indus basin

1. INTRODUCTION

The agriculture production in Pakistan depends on canal irrigation of Indus basin. The canal supplies are not adequate particularly during winter season when rivers discharges are low due to less snowmelt and rainfall. The overall irrigation efficiency is only about 30% [1]. A significant percentage of irrigated area is totally dependent on groundwater alone and the larger part of it is used in conjunction with surface water supplies [2]. The induction of local diesel engines along with subsidized power supply resulted in rapid growth in numbers of private tubewells e.g. increase from 10,000 to about 0.8 million within 1960-2006 period. The total groundwater abstraction from these tubewells is estimated at $51 \times 10^9 \text{ m}^3$ against a recharge of $40 - 60 \times 10^9 \text{ m}^3$ [3]. Out of this, about $33 \times 10^9 \text{ m}^3$ is extracted through private tubewells whereas the rest $18 \times 10^9 \text{ m}^3$ comes from large

capacity public tubewells [4]. The total estimated recoverable groundwater potential is about 67.84 BCM (55 MAF). This leaves about 8.63 BCM (7 MAF), which remains to be exploited [5]. Although, exploitation of the useable groundwater has provided an opportunity for the farmers to supplement their irrigation requirements but the problem of overdraft of the aquifers has emerged in many areas of the Indus basin due to uncontrolled and unregulated use of groundwater [6]. In some of the central and southern parts of Chaj Doab in Indus basin, waterlogging and salinity have also created a problem mainly due to high seepage from canal system, ineffective water management practices and poor drainage system. The main cause behind some of these groundwater problems might be non-synchronization of the groundwater resource management and its development [7]. Tariq and Latif [8] studied the optimal management

of groundwater and suggested various strategies for management under high watertable areas and declining watertable areas. Alam and Chaudhry [9] studied the environmental issues relative to groundwater management and presented guidelines for its environmental sustainability. There is a need to study the groundwater behavior under different stress conditions of discharge for sustainable management and use of groundwater in the Indus basin area in future.

The technique of groundwater modeling is known as a powerful tool to evaluate groundwater systems quantitatively. The finite element method (FEM) has been adopted as an effective tool to solve groundwater problems in various fields like civil engineering [10] and groundwater hydrology [11]. In this method, the domain is discretized into regular elements where heads/concentrations are computed on each node of the flow domain. In this paper, response of the groundwater aquifer has been studied under different scenarios of groundwater withdrawals for effective water management and coping situation of groundwater depletion in the target Indus basin area.

1.1 Study Area

The study area of Upper Jhelum Canal command lies within longitudes 73° to $74^{\circ} 5'$ E and latitudes 32° to $32^{\circ} 45'$ N in the Indus plain of Punjab, Pakistan (Fig. 1). The area comprises of Mandi Bahauddin and part of Gujrat districts between Jhelum and Chenab Rivers. It is fairly level and slopes towards southwest direction. The elevation ranges within 200-238 meters above sea level (masl). Major landforms in the area include alluvial plain and bar uplands while piedmont plain and sub-mountainous ravines exist over minor area in the north. The area is mainly irrigated by canal system. Under irrigation by water wells, the main crops are wheat, sugarcane, tobacco and fodder [12]. The climate is generally sub-humid to semi-arid. Rainfall is erratic and the mean annual is about 778 mm. About two third of the rains are received during monsoon period i.e. between July and

mid September. In summer, the mean maximum temperature is about 39.5°C and mean minimum temperature is about 25.4°C while in winter, the mean maximum and minimum temperatures are about 21.5°C and 5.1°C [13].

1.2 Hydrogeology

The Chaj Doab belongs to Indus plain that form part of Indo-Gangetic Syncline [14] where Quaternary alluvium is deposited over semi-consolidated Tertiary rocks [12]. The area's groundwater reservoir is contained almost exclusively in the alluvial deposits. The general flow of the groundwater is from NE to SW direction. Hydraulic gradient ranges between 0.4-1.35 m/km [15]. There is a vast unconfined aquifer underlying around 6 million ha. The watertable exhibits an annual cycle of rise and fall. It is lowest in the period prior to the monsoon (April-June) and as a result of the Kharif canal supplies and the effect of the rains, it rises and comes closest to the land surface in October before declining again. The watertable of April-June is used as index of waterlogging because it persists throughout the year. There lie three schemes of SCARP-II project of WAPDA namely Sohawa, Phalia and Busal (Fig. 1) where SCARP tubewells were operating to reduce waterlogging in the area. The aquifer data of 10 test holes of WAPDA [16] was used to estimate base conditions for model simulation in this study. According this data, the horizontal hydraulic conductivity ranges from 39.6 m/day to 118.6 m/day while transmissivity (T) values range within 1565.2-4045.6 m^2/day in the study region.

The main recharge sources include seepage from the canal system, precipitation, return flow and seepage from watercourses and fields. Aquifer discharge sources are groundwater pumpage, evapotranspiration, outflows to drains and the rivers, and subsurface flows from the model domain. The groundwater is mainly obtained through hand pumps i.e. from depth of 2.5-8 m and through shallow tubewells i.e. from depth of 32-40 m for domestic and irrigation purpose [13].

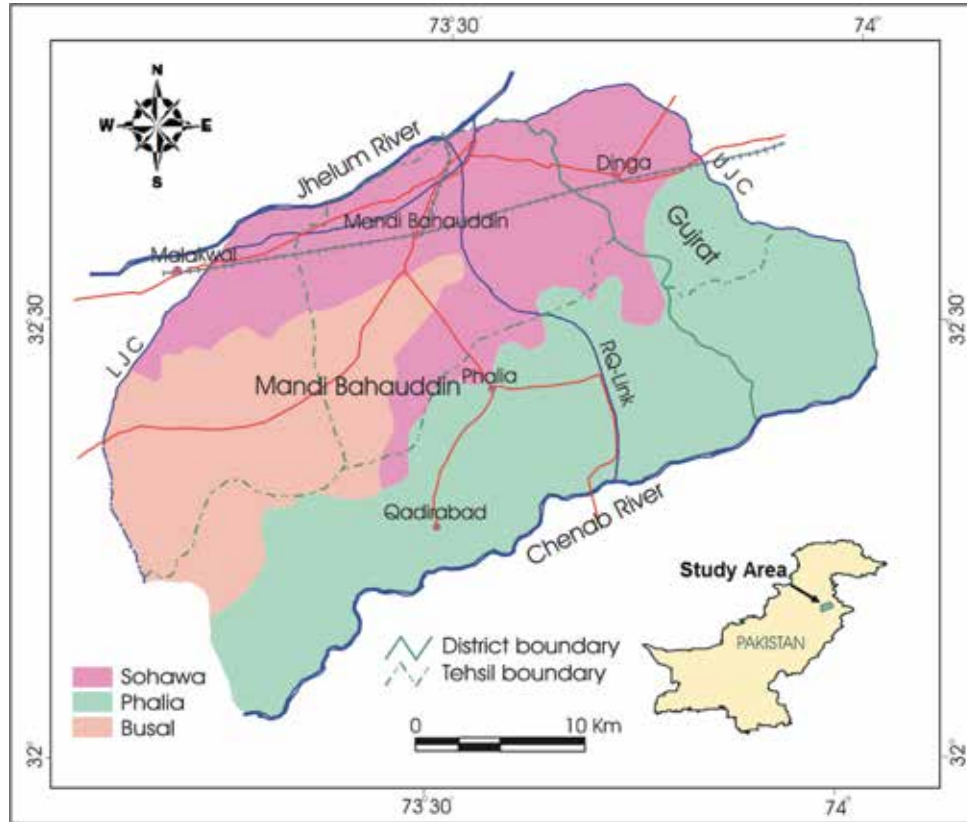


Fig. 1. Location map of the study area.

A large number of electric and diesel tube wells are functioning besides numerous hand pumps in the area. The data of public tubewells is fairly accurate but the pumpage from private tubewells is based on sporadic surveys carried out by various organizations at one time or the other.

2. MATERIALS AND METHODS

2.1 Conceptual Model of Groundwater Flow

A conceptual model represents different aspects of the physical hydrogeological system along with its hydrological behavior in a simplified and an adequate manner [17]. However in developing an adequate conceptual model, sufficient degrees of freedom need to be incorporated in a model to allow simulation of a broad range of responses. Based on the characteristics of subsurface lithology and groundwater pumpage from various tubewells, three layers were defined in the aquifer: 1) The first layer which contains mainly fine material (silt and fine sand) is assumed to have 8 m depth

below the average watertable, 2) The second layer extends from 8 m to 40 m depth representing zone of groundwater pumpage from relatively shallow tubewells and, 3) The groundwater zone within 40-107 m depth from where the pumpage from deep tubewells is made.

The first layer was simulated as an unconfined unit, the second layer as convertible from a confined to an unconfined unit depending upon the position of the watertable, while the third layer is treated as a confined unit of the aquifer. Canal seepage has been observed as a major source of recharge in the study area. Groundwater in the irrigated areas is derived mostly from seepage from the conveyance system and fields and as such its renewability is dependent on the availability and use of surface supplies.

2.2 Galerkin's Method

In finite element model (FEM), the major goal is not just to approximate the governing equation but rather is to approximate the solutions [18]. Galerkin

method of weighted residuals is the main function operating behind the FEM that attains the best approximate solution for the finite element mesh by reducing the weighted sum of the residuals for each of the finite elements. Galerkin's method and the finite element technique are combined so frequently in computer solutions of groundwater problems that the two have become practically synonymous. The method is based on a particular weighted residual principle which turns out to be equivalent to a variational principle, if one exists for the problem under consideration [19]. The nodal heads are obtained as the solution of a system of algebraic equations if a particular weighted average of the residual is forced to vanish. The first step is to define an approximate or trial solution, $\hat{h}(x, y)$ expressed as a series summation; each term is a product of a nodal head h_L and an associated nodal basis function $N_L(x, y)$ (Equation a)

$$\hat{h}(x, y) = \sum_{L=1}^{NNODE} h_L N_L(x, y) \quad (a)$$

The subscript L indicates nodal number and $NNODE$ is the total number of nodes in the problem domain.

The next step is to require a total of $NNODE$ conditions to determine the $NNODE$ values of h_L . In the Galerkin's method, the $NNODE$ conditions are that the residuals of the governing equation weighted by each of the $NNODE$ basis functions be zero when integrated over the entire domain of the problem (Equation b).

$$\iint_D \left(\frac{\partial^2 \hat{h}}{\partial x^2} + \frac{\partial^2 \hat{h}}{\partial y^2} \right) N_L(x, y) dx dy = 0 \quad (b)$$

Where $L = 1, 2, \dots, NNODE$, and D signifies that the integration is done over the entire problem domain. The quantity in parentheses is the residual. If the trial solutions $\hat{h}(x, y)$ were exact, Laplace's equation would be satisfied throughout the problem domain and the residual would be zero everywhere. In Galerkin's method, the requirement imposed is that $NNODE$ weighted average of the residual

vanish; the basis function $N_L(x, y)$ are the weighting functions.

2.3 Development of Groundwater Flow Model

A three-layered 3-D numerical groundwater flow model was developed using Feflow 5.1 software [20]. The active area of the model is about 3,417.2 km². The finite element model comprised of 5,343 elements and 3,928 nodes was generated from mesh of 5 super elements drawn over the model area. The super elements mesh represents the basic structure of the study domain. The model area with locations of 34 observation wells is shown in Fig. 2. The rivers and main canals are treated as constant head boundaries in the numerical groundwater flow model. In vertical discretization of the grid, topographic surface defines the upper boundary and the alluvium cover up to 107m depth the lower boundary of the aquifer. Ten hydraulic conductivity zones were developed using Thiessen polygon method from the point data of hydraulic conductivity values obtained from pumping tests analysis. Based on the hydrological setup, geomorphology and land capability of the area, 5 recharge zones were developed to estimate the recharge in the model domain (Fig. 2).

The steady-state simulation of groundwater flow was performed, which is fully implicit. The steady-state modeling refers to the arrival of a condition in the groundwater regime when hydraulic heads are no longer changing and the magnitude and direction of the flow velocity becomes constant with time [21]. The model was calibrated for steady-state simulation using initial conditions through Parameter estimation 'PEST' module [22] in Feflow model. Later, the model was rerun for transient-state calibration for a six-month period. The sensitivity analysis was carried out to evaluate performance of various parameters and model assumptions. The flow chart of methodology followed for groundwater modeling modified after [23] is shown in Fig. 3. The steady-state calibrated model was rerun for pre-stress period of variable time steps until 2005. The average watertable values (the spatial average over the whole region) was used

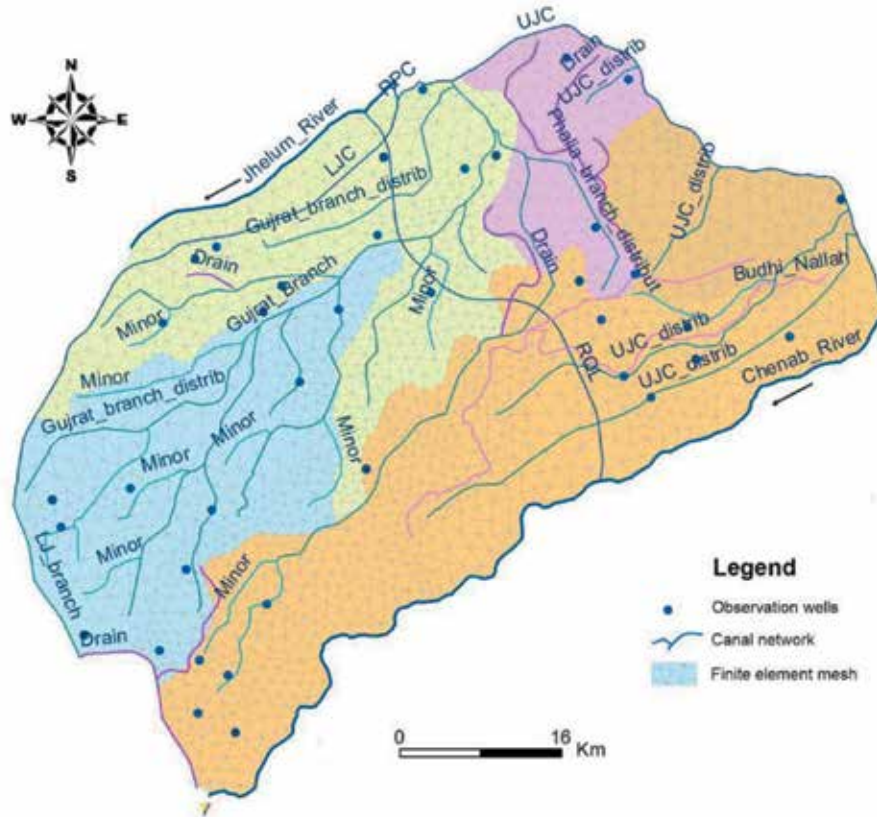


Fig. 2. Location of the observation wells and canal network in various recharge zones of the model domain.

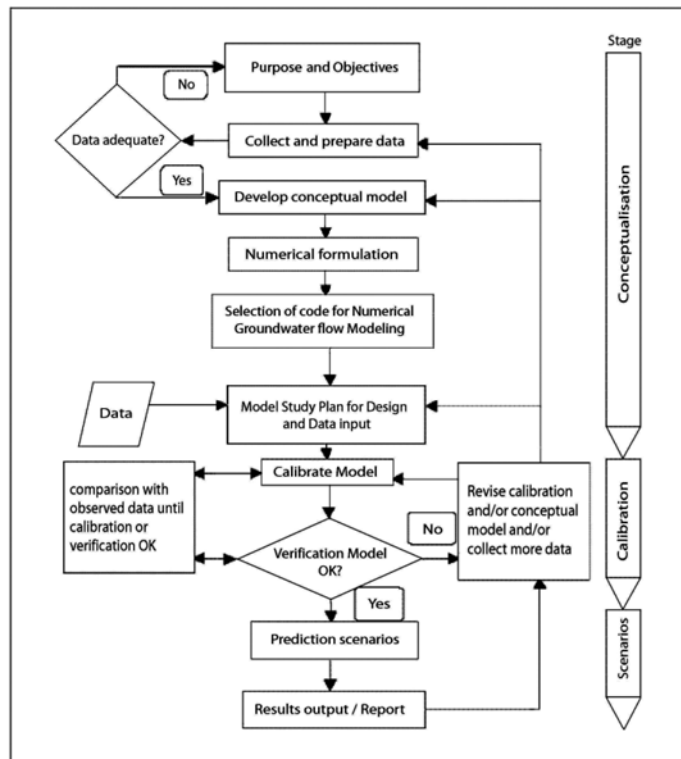


Fig. 3. Flow chart of numerical modeling steps followed in the present study. Modified after [23].

to foresee the overall effect of the watertable in the model domain. Different scenarios of groundwater pumpage were developed to analyze its effect on the groundwater levels of base year 2005.

3. RESULTS AND DISCUSSION

During the calibration phase, the mean residual of 0.06 m and variance of 1.46 m was achieved for observed and calculated heads of the steady-state model. Similarly, the mean residual and variance obtained during transient-state calibration were 0.002 m and 1.86 m respectively. The equipotential surface map of steady-state condition indicated an overall groundwater flow from northeast towards southwest direction following the trend of topographic relief (Fig. 4). The hydraulic conductivity values estimated through calibration of steady-state simulation varied from 2 to 158 m/day for layer 1; 2 to 153 m/day for layer 2; and 0.7 to 168 m/day for layer 3 with mean values of 69.3, 72.2, and 74 m/day, respectively. In layer 1,

high velocity of groundwater (>0.12 m/day) was observed near Rasul Barrage. The velocity in the center and southern parts varied between 0.04 m/day and 0.08 m/day. The patches of low velocity zone (<0.02 m/day) were found in northern, northeastern and western parts which extend downward in other layers also. In layer 2, velocity zone 0.02-0.04 m/day dominates in most of the central part while the zone 0.04-0.08 m/day has reduced into a narrow belt in the centre and appears in the southern part of the area. In layer 3, velocity less than 0.02 m/day dominates in most of the northeastern part, 0.02-0.04 m/day in the center and 0.04-0.08 m/day in the southern part of the model area. The variations in the velocity of groundwater flow in each layer of the model domain are shown in Fig. 5. The regional groundwater flow component in the southern part is indicating existence of a potential aquifer zone in this area. The low velocity zone (<0.02 m/day) in the northeastern and western parts exists more or less in all the three layers thus indicating low potential of aquifer here.

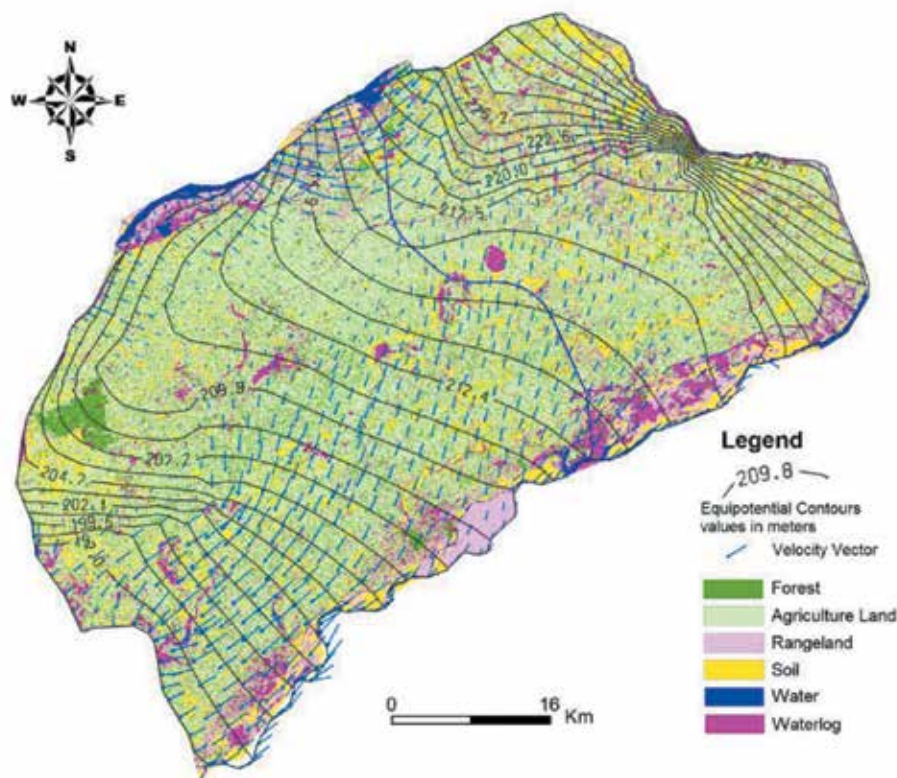


Fig. 4. Velocity vectors and equipotential contours indicating groundwater flow pattern (2005).

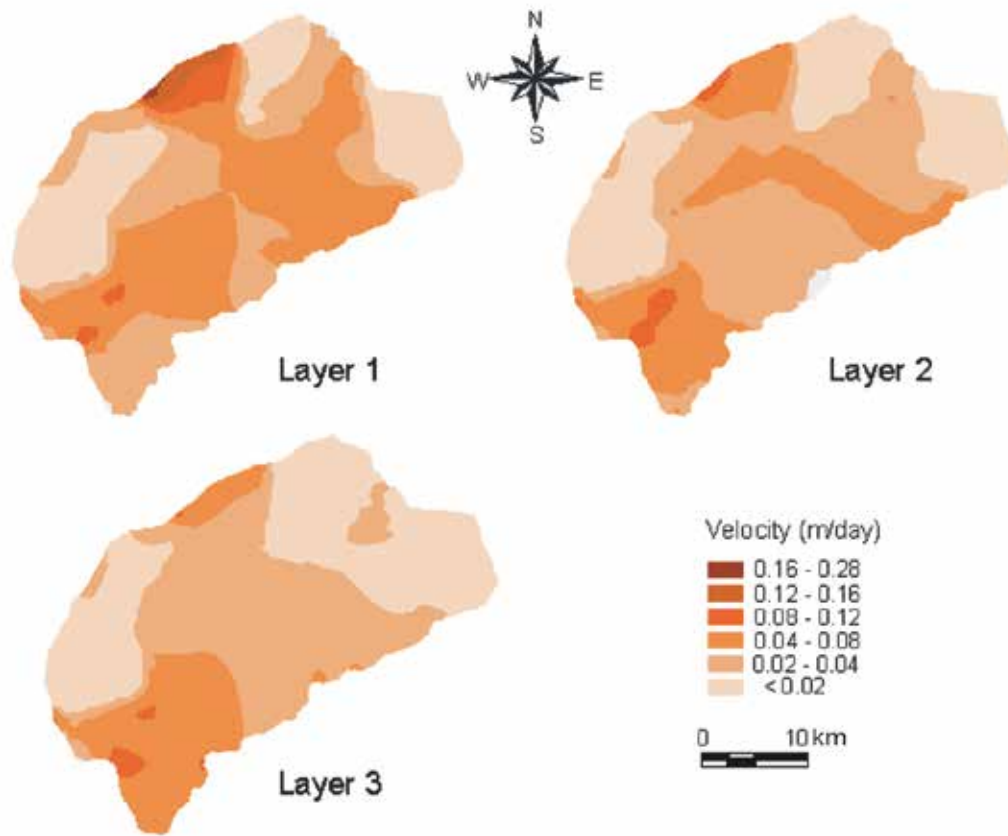


Fig. 5. Groundwater flow velocity during the steady-state condition.

In layer 1, the specific yield values vary between 0.06 - 0.15, in layer 2 between 0.04 - 0.22, and in layer 3 between 0.06 - 0.27. Mean of specific yield values for layer 1 and layer 2 appear to be 0.1 and for layer 3 is 0.15. The lower values in zones 3 and 4 can be attributed to the presence of piedmont deposits containing intercalation of clay and fine silt and sand. Likewise, the higher values of specific yield in zone 6 may represent thick alluvium deposits of medium to coarse sand, and gravels.

3.1 Scenarios of Groundwater Pumpage

The calibrated model of 1985-2005 period were used to predict future changes in average groundwater levels of the target area. The following scenarios were developed to analyze the groundwater behavior under varying tubewell pumpage conditions. The watertable depth of year 2005 was used as base for

the analysis.

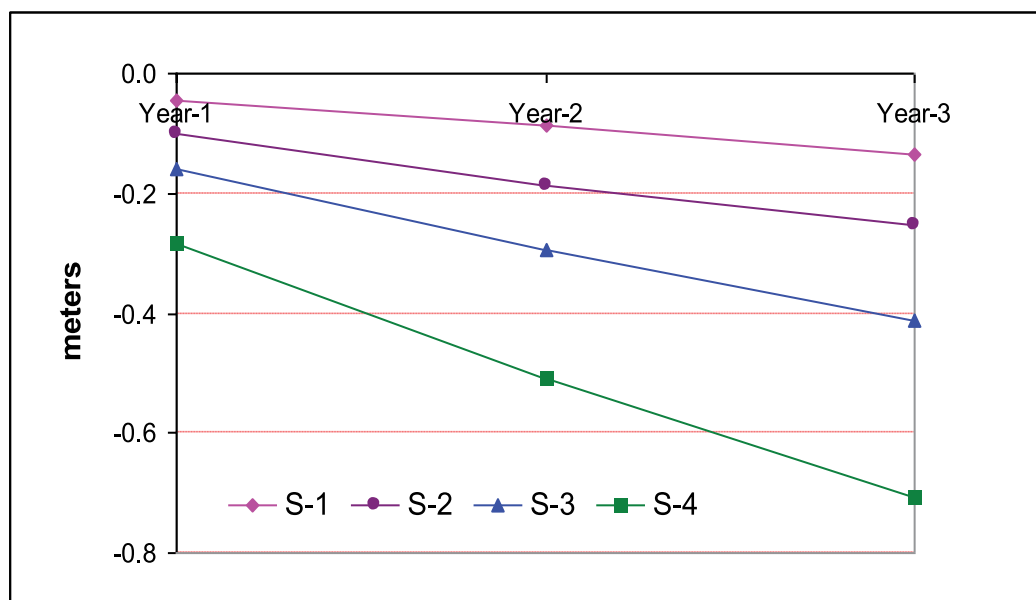
Scenario 1: In this scenario the pumpage from 33 deep tubewells continued at a constant rate of 5,000 m^3/d from 1 to 3 years period and its impact on the groundwater levels of base year was studied. The groundwater levels indicated an average decline from 0.04m in the 1st year to 0.135m in the 3rd year (Table 1, Fig. 6).

Scenario 2: The pumpage is increased upto 60 percent (at constant rate of 8,000 m^3/d) and continued from 1 to 3 years period. The increase in pumpage rate accelerated the watertable decline process. The average decline in groundwater levels was about 132%, 116% and 87% from that of 1st, 2nd and 3rd year decline values of the scenario-1.

Scenario 3: In this scenario, numbers of tubewells was increased two folds i.e. 66 and pumpage continued at a constant rate of 5,000 m^3/d from 1

Table 1. Summary of different scenarios of watertable variations (Base watertable depth: 2.95 m).

Scenario	Particulars	Year	Change in Watertable depth (m)
1	Groundwater pumpage from 33 TWs	1	-0.044
		2	-0.086
		3	-0.135
2	60% increase in pumpage from 33 TWs	1	-0.102
		2	-0.186
		3	-0.252
3	Groundwater pumpage from 66 TWs	1	-0.158
		2	-0.293
		3	-0.413
4	60% increase in pumpage from 66 TWs	1	-0.285
		2	-0.509
		3	-0.706

**Fig. 6.** Watertable response under different scenarios of groundwater pumpage during 3-year period.

to 3 years period. The decline of watertable ranges from 0.158 to 0.413m during 1-3year period from that of base year. This was about 259%, 241% and 206% from that of 1st, 2nd and 3rd year decline values of the first scenario. The situation shows a rapid effect of increase in tubewells use on the groundwater levels in the target area.

Scenario 4: The pumpage increased to 60 percent and continues from 1 to 3 years period. The decline of watertable was observed which ranged from

0.285 to 0.706 m during 1-3 year period from that of base year. The average decline in groundwater levels was about 548%, 492% and 423% from that of 1st, 2nd and 3rd year decline values of the scenario-1.

4. CONCLUSIONS

A 3-dimensional numerical groundwater flow model calibrated for Upper Chaj Doab in Indus basin indicated mean residuals of 0.06 m and

0.002 m between the observed and calculated heads during steady-state and transient-state modeling respectively. The results of the study show that groundwater system is affected by variable conditions of groundwater pumpage thus influencing the groundwater levels in the Indus irrigated area. During the process of groundwater flow modeling, the groundwater levels indicated sensitivity to both increase in numbers of tubewells and pumpage rates. In areas of gradual decline in groundwater due to over exploitation, introduction of water efficient crops and shifting in the cropping pattern can be a few options to increase the water productivity in future. Although lowering of the watertable due to increase in the groundwater pumpage may result in minimizing the high risk of waterlogging and salinity in the area but other influential factors (physical and management) also need to be investigated in order to cope with these problems efficiently in future. A detail investigation of the groundwater system is required to study the impact of growing number of private/public tubewells in the Indus irrigated area. The study findings would help in formulating effective groundwater monitoring and management strategies to ensure sustainable development in the Indus basin in future.

5. ACKNOWLEDGMENTS

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6. REFERENCES

- Bhutta, M.N. & L.K. Smedema. One hundred years of waterlogging and salinity control in the Indus valley, Pakistan: a historic review. *Irrigation and Drainage* 56: 581-590 (2007).
- Qureshi, A.S., H.M. Rust & I. Masih. An analytical approach to estimate groundwater pumpage. In: *Proceedings of 2nd South Asian Water Forum*, Islamabad, Dec. 2002. pp. 1-11 (2002).
- World Bank. *Punjab Groundwater Policy- Mission Report*. WB_SA_PK_Punjab GW Mission report, www.worldbank.org/gwmate (2007).
- Qureshi, A.S., M.A. Gill & A. Sarwar. Challenges and opportunities for sustainable groundwater management in Pakistan. In: *Proceedings of 1st Int. Conf. on Sustainable Water Management in Developing Countries: Challenges and Opportunities*, MUET, Jamshoro, 15-17 Sep. (2010).
- Lashari, B. & M.N. Mangrio. Sustainability of shallow groundwater tubewells: A case study of Dhoro Naro Minor Command Area of Sindh, Pakistan. In: *Proceedings of 2nd South Asian Water Forum*, Islamabad, Dec. 2002, p. 84 (2002).
- Kijne, J. W. *Improving the Productivity of Pakistan's Irrigation: The Importance of Management Choices*. International Water Management Institute, Colombo, Sri Lanka (1999).
- Qureshi, A.S., T. Shah & M. Akhtar. *The groundwater Economy of Pakistan*. Working Paper 64. Lahore, Pakistan: International Water Management Institute (2003).
- Tariq, A.R. & M. Latif. *Strategies and Optimal Management of Groundwater and Regulation of Groundwater in the Punjab*, Dec 6-7, 1999. Punjab Groundwater Consultant, Lahore, p. 33-50 (1999).
- Alam, M.M. & M.R. Chaudhry. *Groundwater Management: Environmental Issues*. Proceedings of Workshop, the Management and Regulation of Groundwater in the Punjab. Dec. 6-7, 1999, Punjab Groundwater Consultant, Lahore, pp. 14-32 (1999).
- Zeinkiewicz, O.C. *The Finite Element Method in Engineering Science*. McGraw-Hill, London (1971).
- Segerlin, L.J. *Applied Finite Element Analysis*. J. Wiley & Sons, New York (1976).
- Soil Survey of Pakistan. *Reconnaissance soil survey of Gujrat district*. Directorate of Soil Survey of Pakistan, Lahore (1967).
- Qureshi, M.K.A. et. al. *Geology and Environmental concerns of the Rasul-Mandi Bahaudin Quadrangle, Punjab, Pakistan*. Ministry of Petroleum and Natural Resources, Geological Survey of Pakistan, Quetta, Pakistan (2003).
- Wadia, D.N. *Geology of India*. The English Language Book Society and Macmillan & Co., London (1966).
- PPSGDP Report. *Groundwater Flow and Solute Transport Numerical Models for SCARP II and Shahpur Area of Chaj Doab*. Tech. Rep. No. 39, Punjab Private Sector Groundwater Development Project Consultants, Project Management Unit, Irrigation and Power Department, Govt. of Punjab, Lahore (2000).
- WASID. *Analysis of Aquifer tests in the Punjab Region of West Pakistan*. Water and Soils Investigation Division, Water and Power

- Development Authority, Lahore (1964).
17. Middlemis. *Groundwater Flow Modeling Guidelines, Murray-Darling Basin Commission*. Aquaterra Consulting Pvt, Ltd, S. Perth, Western Australia (2000).
 18. Thangarajan, M. *Regional Groundwater Modeling*. Capital Publishing Company, New Delhi, India (2004).
 19. Wang, H.F. & M.P. Anderson. *Introduction to Groundwater modeling- Finite Difference and Finite Element Methods*. W.H. Freeman and Company, New York (1982).
 20. WASY. *Feflow 5.1 Finite Element Subsurface Flow & Transport Simulation System User's Manual*. WASY Institute for Water Resources Planning and Systems Research Ltd., Berlin, Germany (2004).
 21. Freeze R.A. & J.A. Cherry. *Groundwater*. Prentice Hall, (Englewood Cliffs, NJ, USA1979).
 22. Doherty, J. *PEST ver. 2.04*. Water mark Computing, Corinda, Australia (1995).
 23. Anderson M.P. & W.W. Woessner. *Applied Groundwater Modeling, Simulation of Flow and Advective Transport*. Academic Press, San Diego, California (1992).