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Regional groundwater flow modelling of Upper Chaj Doab of Indus Basin, Pakistan using finite element model (Feflow) and geoinformatics

A. Ashraf[1] and Z. Ahmad[2]

[1]*Water Resources Research Institute, National Agricultural Research Center, Islamabad, Pakistan. E-mail: mashr22@yahoo.com*
[2]*Department of Earth Sciences, Quaid-i-Azam University, Islamabad, Pakistan*

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SUMMARY

A 3-D finite element model (Feflow) has been used for regional groundwater flow modelling of Upper Chaj Doab in Indus Basin, Pakistan. The thematic layers of soils, landuse, hydrology, infrastructure and climate were developed using Geographic Information System (GIS). The numerical groundwater flow model is developed to configure the groundwater equipotential surface, hydraulic head gradient and estimation of the groundwater budget of the aquifer. Integration of GIS with groundwater modelling and satellite remote sensing capabilities has provided an efficient way of analysing and monitoring groundwater status and its associated land conditions. The Arcview GIS software is used as additive tool to develop supportive data for numerical groundwater modelling, integration and presentation of image processing and modelling results.

The groundwater behaviour of the regional model shows a gradual decline in watertable from year 1999 onward. The persistent dry condition and high withdrawal rates play an influential role in lowering down the groundwater levels. Different scenarios were developed to study the impact of extreme climatic conditions (drought/flood) and variable groundwater abstraction on the regional groundwater system. The results of the study provide useful information regarding the behaviour of aquifer in order to organize management schemes on local and regional basis to monitor future groundwater development in the area.

Key words: Time series analysis; Image processing; Spatial analysis; Geomorphology; Hydrology; Permeability and porosity.

INTRODUCTION

Groundwater modelling is increasingly recognized as a powerful quantitative tool available to hydrogeologists and water resource managers for evaluating groundwater system. 3-D numerical groundwater flow modelling using Finite element flow model-Feflow ver. 5.1 (WASY 2004) coupled with decision support tools of geoinformatics was used for analysing the behaviour of regional groundwater flow of Upper Chaj Doab area in Indus basin. Geographical information system (GIS) is used for spatial database development, integration with a remote sensing (RS) and numerical groundwater flow modelling capabilities to simulate regional groundwater flow behaviour. GIS facilitates rapid transfer and assembly of various input data sets for groundwater modelling and is found extremely helpful during the process of model calibration and forecasting. The RS image capability was used to analysis surface hydrological conditions and landcover/landuse status in order to conceptualize the recharge/discharge sources of aquifer. It provides an economic and efficient tool for landcover mapping and has its advantages in planning and management of water resources for optimum use. The developed model provides effective tool for evaluating better management options for groundwater use for sustainable development of agriculture in the target area.

In Upper Chaj Doab area (‘Doab’ is a local word used for land between two rivers) of Pakistan, irrigation supplies are mainly fulfilled through conjunctive use of surface and groundwater resources. Groundwater is mainly utilized to supplement canal water supplies where these are not adequately met especially during summer season when river discharges are at their lowest. In the last drought of 1999–2002, the groundwater abstractions have been increased due to rapid increase in number of private tubewells for irrigation purpose. Excessive pumpage of groundwater from these wells is causing a gradual decline in watertable. Moreover, development of irrigation potential with canals also has a negative environmental impact. In low relief area of central Doab, seepage from the conveyance system and excessive irrigation in the fields often disturb the pre-existing natural ground water balance, especially at locations where natural drainage is inadequate due to topographic and soil reasons. Accumulation of water causes problem of waterlogging and salinity in the Indus basin which threatens the livelihood of farmers (Bhutta & Wolters 1996). In such circumstances, to study the impact of extreme conditions like prevailing drought/flood and over exploitation of groundwater on the subsurface aquifer system is vital for better management of groundwater resource for future development of agriculture in the area.

GIS is an application-oriented spatial information system with a variety of powerful functions for decision support to problems with a spatial dimension. Efficient management of groundwater resource relies on a comprehensive database that represents characteristics of natural groundwater system (Josef 2004). There is a need to utilize the techniques of GIS coupled with hydrological modelling to investigate environmental problems related to excessive groundwater use and irrigation water supplies in the Indus basin. The GIS technology provides suitable alternatives for efficient management of large and complex databases (Saraf & Choudhury 1997). Arora & Goyal (2003) highlighted the use of GIS in development of conceptual groundwater model. The effort to perform analysis of management scenarios will be substantially reduced by an easily accessible database, a convenient interface between database and groundwater models, visualization and utilities for model inputs and results (Pillmann & Jaeschke 1990). Integration of GIS with groundwater modelling and remote sensing capabilities has provided an efficient way of analysing and monitoring groundwater status and its associated environment. At the time, integration of GIS and hydrologic models follows one of the two approaches: (1) To develop hydrologic models that operate within a GIS framework and (2) to develop GIS techniques that partially define the parameters of existing hydrologic models (Jain *et al.* 1997). The latter approach has been followed in this study.

The hydrologic monitoring studies were started in the Upper Chaj Doab area in year 1968 in order to control problem of waterlogging and salinity. Under Salinity Control and Reclamation Project (SCARP), numerous drainage tubewells were installed by Water and Power Development Authority (WAPDA) to monitor the behaviour of groundwater levels on pre- and post-monsoon seasonal basis. Later on, Directorate of Land Reclamation was involved in regularly monitoring the water levels and water quality of number of piezometers and tubewells and maintaining its spatial databases in GIS (DLR 2002). The consultants of Punjab Private Sector Groundwater Development Project (PPSGDP) had carried out groundwater flow modelling using MODFLOW numerical model for analysis of groundwater flow in Chaj Doab for period 1987–1997 (PPSGDP 2000). The study was mainly focused on monitoring the behaviour of waterlogging and salinity in Chaj Doab area in order to reclaim the land for agricultural development. The present work considers the impact of extreme climate events like the recent drought that has occurred during 1999–2002, on the groundwater development of Upper Chaj Doab area.

A steady-state model was calibrated for 1985 hydrologic conditions when water levels in the aquifer were near equilibrium. Automatic parameter estimation method-PEST (Doherty 1995) was used for model calibration. The calibration results indicated an average residual of 0.06 m and variance of 1.46 m of the observed and calibrated heads. The model was rerun for transient-state calibration for 6-month period of wet season, that is, April–September 1985, using steady-state heads as initial condition. An average residual of −0.002 m and variance 1.84 m were achieved after the model calibration. Using the model, values of recharge, hydraulic conductivity and specific yield of the aquifer were calibrated. The sensitivity of the model results were evaluated to variations in hydrologic parameters and modelling assumptions. The calibrated model was used to simulate future changes in piezometric heads during predictive period 2006–2020. The groundwater development was studied under different scenarios of extreme climatic conditions (drought/flood) and variable groundwater abstraction.

STUDY AREA

Upper Chaj Doab area lies within a fertile agriculture belt of Punjab plains, between longitudes 73° to 74° 5′E and latitudes 32° to 32° 45′N in the northeastern territory of Pakistan (Fig. 1). The area is bounded by Jhelum and Chenab Rivers in the northwest and southeast, and Upper Jhelum canal (UJC) and Lower Jhelum canal (LJC) in the northeast and southwest. The canal system in the area is mainly fed by water supplies of the Jhelum River. The major portion of river flows is contributed by monsoon rainfalls and a minor by snow and glaciers melt water flowing down from high mountains of Himalaya in the north. Administratively, the area comprised of Mandi Bahauddin and part of Gujrat districts which are subdivided into tehsils. The elevation in the area ranges between 200 and 238 m above sea level (m a.s.l.) and the general slope is towards southwest direction. The main topographic features are submountainous ravines, piedmont plain in the northeast, and alluvial plain and bar-uplands in the rest of the area. The drainage pattern is mainly dendritic in nature.

The Chaj Doab forms a part of the vast geo-syncline that lies between the Himalayan Mountains and the central core of Indian subcontinent (Soil Survey Report 1967). Quaternary alluvium has been deposited on semi-consolidated Tertiary rocks. Test drilling has revealed that the uppermost 183 m of the alluvium consists predominantly of fine to medium sand and silt. Alluvium was encountered in test holes drilled to a maximum depth of about 457 m (1500 ft), hence no information is available concerning the total thickness of alluvium and the depth to basement complex in the Chaj Doab area (Kidwai 1962).

The main landuse is irrigated agriculture. Most of the natural vegetation has been cleared off from the plains for agriculture farming. There are many *Rakhs* and *Belas* on alluvial lands; *Rakhs* are the government wasteland that had originally been demarcated as government property considered to be in excess of the needs of the villages, *Belas* are alluvial lands on the banks of Chenab and Jhelum Rivers that were taken up by the government in the same way as the *Rakhs*. Both lands are greatly valued by the people as pastures. There is a large protected forest at Daffar in southwestern part of the area. The principal tree species found in the area are Shisham (*Dalbergia sissoo*), Kikar (*Acacia nilotica*), Beri (*Zizyphus jujuba*), Poplar, Simal, Willow, Eucalyptus, Tut (*Morus alba*), Bargad, Piple (*Ficus religiosa*) and Dharaik (*Melia azedarach*). Uncontrolled grazing and cutting of wood have much damaged the density of the vegetation.

The climate is mainly subhumid in the north to semi-arid in the south. Rainfalls are erratic and are received in two rainy seasons; about two-third of annual rains are received during monsoon season (July to mid-September) and remaining one third in winter season (January–March). The mean annual rainfall is 778 mm. The mean maximum and minimum temperatures during summer are about 39.5 and 25.4 °C. The temperature may rise up to 47 °C during the month of June in summer. The mean maximum and minimum temperatures in winter are about 21.5 and 5.1 °C (Qureshi *et al.* 2003).

DATA USED

The base map of study area was developed using topography map of scale 1:250 000 acquired from Survey of Pakistan. The remote

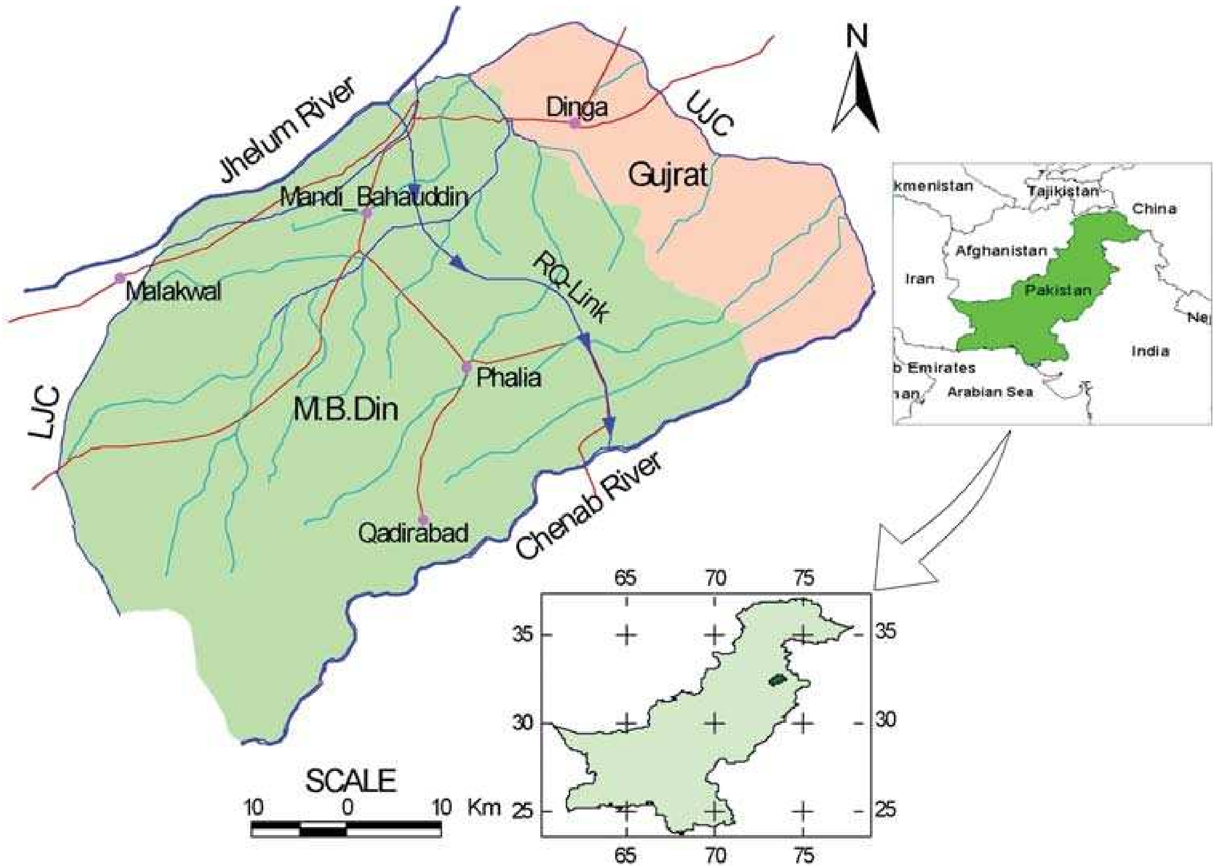

Figure 1. Location of the study area.

sensing data of Landsat TM and Enhanced Thematic Mapper plus (ETM) of periods 1990 and 2001 was used for landcover/landuse analysis. The spatial resolution of the image data is 30 m except addition of an extra panchromatic band of 15 mresolution in Landsat ETM data. The rainfall data of Jhelum and Sargodha stations of period 1970–2004 was acquired from Pakistan Meteorology department. Hydrological data comprised of river flows, irrigation discharge and tubewell pumpage of period 1985–2001 was acquired from Water and Power Development Authority (WAPDA), Pakistan. The thematic data of geomorphology, soils, drainage/canal network and previous landuse was collected from different sources like Soil survey of Pakistan and Punjab irrigation department. The observation wells data of 34 tubewells maintained by SCARP monitoring organization (SMO) of WAPDA was acquired for period 1985–2004. Among these wells, 28 wells which had almost complete and reliable historical record were selected for present groundwater modelling study.

GIS DATABASE DEVELOPMENT

The spatial data input in GIS was carried out through scanning, digitization and keyboard entry. A common coordinate system of Transverse Mercator was used for development of spatial data layers like geomorphology, soils, infrastructure, surface hydrology, cities/towns and administrative boundaries in Arcview 3.1 GIS software. Analytical functions of GIS were used to derive thematic map layers of elevation, slope and buffer zones. Theissen polygons and recharge zones were developed for model calibration while watertable depth and equipotential maps were generated during post-calibration phase of the groundwater flow modelling. Remote sensing analysis was carried out through visual and digital interpretation of the imageries to study landcover and surface hydrological conditions like waterlogging associated with canal network, swamps and surface moisture etc. Such natural indicators were found helpful in identifying potential recharge sources of groundwater besides shallow groundwater environment in the area. The image classification was carried out through supervised method following maximum likelihood rule in ERDAS imagine 8.5 software. Six landcover classes were demarcated through image classification (Fig. 2). Major landcovers consist of crop cover (70 per cent), soil (10.2 per cent), grassland (8.4 per cent) and forest (5.6 per cent) (Table 1). The wastelands which include swamps and waterlogged areas cover about 4 per cent of the area mainly in meander flood plain of Mandi Bahauddin district. The canal irrigated land which can be distinguished by homogenous crop cover in the northwestern part forms a potential zone of groundwater recharge as compared with rainfed agriculture land visible as heterogeneous crop cover in the northeastern part of the area. A low potential area of groundwater recharge also exists in the depressions in the central part of the area where drainage is poor and swamps were developed as permanent features.

AQUIFER CHARACTERISTICS

Aquifer data of 10 pump-out tests performed by Water and Soil Investigation Division (WASID) of WAPDA, Pakistan is available (WASID 1964). The available data shows that horizontal hydraulic conductivity values in the area ranges between 39.6 to 118.6 m d^{-1}.

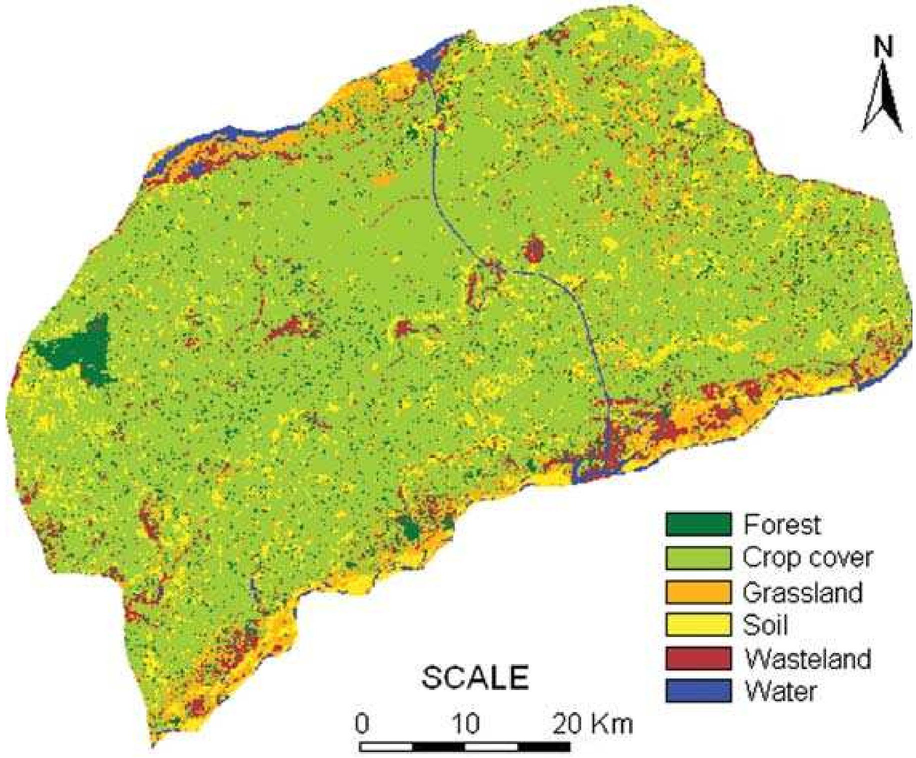

Figure 2. Landcover Map developed through image classification of RS data.

Table 1. Detail of landcover classes demarcated through image classification.

S. no.	Landcover	Area (km^2)	Percentage
1	Forest	190.3	5.6
2	Crop cover	2391.8	70.0
3	Grassland	286	8.4
4	Soil	348.4	10.2
5	Wasteland	145.9	4.3
6	Water	54.7	1.6
	Total	3417.2	

The transmissivity (T) values evaluated through pumping tests range between 1565.2 and 4045.6 m^2 d^{-1}. The aquifer is divided into three layers on the basis of subsurface lithology encountered in the borehole wells and pumpage depth of different tubewells. The first layer is unconfined with free and movable surface. Sediments occurring at shallow depths are composed of finer materials, that is, silt and fine sand, therefore, the first layer has been assumed to extend 8 m below the average watertable. The second layer is assumed to extend from 8 to 40 m depth (thickness 32 m) to represent groundwater withdrawals from comparatively shallow tubewells, that is, private tubewells. The third layer extends from 40 to 107 m depth (thickness 67 m) to count for abstractions from deep tubewells, that is, SCARP tubewells. The thickness of these layers is assumed constant during the process of groundwater flow modelling.

Aquifer recharge mainly occurs from canal seepage, rainfall, return flow of groundwater pumpage and percolation from drains and ponds. Discharge sources of the aquifer are; pumpage from deep and shallow tubewells, evapotranspiration (ET), outflows to the rivers and drains, and subsurface flows from one zone to another. The loss of water by ET has been adjusted in the groundwater flow model while estimating the net recharge of the groundwater. The water balance for estimating net recharge in the area is shown in Table 2. The available recharge data was used to define recharge of different stress periods in model calibration. The recharge of SCARP tubewells pumpage was estimated 25 per cent of the withdrawals by WAPDA (assuming equal to the percentage of canal water supplies available at watercourse heads). The pumpage of SCARP tubewells is gradually decreasing due to abandoning of these wells on account of their high operational cost. The groundwater discharge and utilization factor of private tubewells are less than that of SCARP tubewells so 20 per cent recharge has been estimated from pumpage of these wells. The rainfall recharge estimated 17.9 per cent of the annual rainfall is based on the area under rainfall percolation (total area minus built-in area), recharge assumed for similar type of soil and recharge factor by NESPAK (PPSGDP 2000). The recharge from large boundary link canals and inflows from adjacent areas are considered implicitly in the groundwater modelling by assuming constant head boundaries along these canals (Sarwar 1999).

NUMERICAL MODELLING OF GROUNDWATER FLOW

Numerical modelling employs approximate methods to solve the partial differential equation (PDE) which describes the flow in porous medium. The emphasis here is not on obtaining an exact solution but on obtaining reasonably approximate solution (Thangarajan 2004). Feflow is a fully integrated modelling environment with a full-featured graphical interface and powerful numeric engines that allow the user to perform any flow and contaminant transport modelling. The components ensure an efficient process for building the finite element model, running the simulation and visualizing the results.

A model grid consisting of superelement mesh of five elements was drawn over the model area using the base information of

Table 2. Net recharge (million m^3) estimated for period 1985–2001.

Period	Canal supply	Seepage 15 per cent of canal supply	Canal recharge 80 per cent of seepage	STWs[a] 25 per cent of withdrawals	PTWs[b] 20 per cent of withdrawals	W/C[c] + field 25 per cent of W/C head delivery	Rainfall 17.9 per cent	Total recharge recharge	Net pumpage pumpage	Net recharge recharge	Net recharge (m d^{-1})
1985–86	1924.3	288.6	230.9	294.5	165.0	408.9	318.5	1417.8	1543.3	−125.6	-1.01×10^{-4}
1987–88	1862.6	279.4	223.5	363.9	210.0	395.8	332.7	1525.9	1931.8	−405.9	-3.25×10^{-4}
1988–89	1270.5	190.6	152.5	247.0	229.2	270.0	493.8	1392.4	1657.7	−265.3	-2.13×10^{-4}
1989–90	1948.9	292.3	233.9	224.8	255.4	414.2	385.0	1513.2	1696.0	−182.8	-1.47×10^{-4}
1990–91	1936.6	290.5	232.4	218.0	284.2	411.5	577.8	1724.0	1791.0	−67.1	-5.38×10^{-5}
1991–92	1998.3	299.7	239.8	206.6	306.3	424.6	487.4	1664.6	1844.8	−180.2	-1.45×10^{-4}
1992–93	1961.3	294.2	235.4	167.8	334.8	416.8	610.6	1765.3	1842.3	−77.0	-6.18×10^{-5}
1993–94	2072.3	310.8	248.7	170.2	416.9	440.4	378.1	1654.3	2178.2	−523.9	-4.20×10^{-4}
1995–96	1800.9	270.1	216.1	128.3	534.2	382.7	547.7	1809.0	2521.5	−712.6	-5.71×10^{-4}
1996–97	1973.6	296.0	236.8	99.3	573.9	419.4	501.0	1830.4	2593.6	−763.2	-6.12×10^{-4}
2000–01	2146.3	321.9	257.6	61.7	613.7	456.1	336.4	1725.4	2639.7	−914.3	-7.33×10^{-4}

[a]STWs represent SCARP tubewells.
[b]PTWs: private tubewells.
[c]W/C: watercourse.

landuse, landforms and drainage/canal network of the area. The superelement mesh represents the basic structure of the study domain. The Finite element mesh was generated from the superelement mesh using triangulation option of 6-noded prism for 3-D model. The 3-D mesh consists total of 5343 elements and 3928 nodes. The model layers were developed from point data using Akima's bivariate interpolation method.

In order to estimate the recharge of the model domain, the model area was divided into five zones or subareas (Fig. 3). The recharge zones were based on the hydrological setup of the area, geomorphologic characteristics and land capability for agriculture use. The recharge of the five zones was characterized by variable infiltration rates of different soil types and varying groundwater pumpage in the study area.

MODEL CALIBRATION

In the first phase, steady-state calibration was performed which was fully implicit. The groundwater levels of June 1985 (pre-monsoon period) of 28 observation wells were used as initial condition for executing steady-state simulation. Automatic parameter estimation (PEST) method was applied for calibration of the steady-state model (Doherty 1995). The previous values of hydraulic conductivities were used to develop conductivity zones using Theissen polygons for model calibration. The hydraulic conductivity and the recharge values estimated previously were used as initial conditions in the steady-state calibration. The values were adjusted during the calibration runs until the calculated head values became close to the observed heads. Similarly, the specific yield zones were developed using its field data for use in transient state-calibration. The model was rerun for 6-month period, that is, April–September 1985, for transient-state calibration. The scattergram plots of the steady-state and transient-state calibration output are shown in Figs 4a and b. The mean residuals of observed and calculated heads in steady-state and transient-state calibrations are 0.06 and 0.002 m with variances of 1.46 and 1.86 m, respectively. The calibration results indicated a reasonable agreement between the calculated and observed heads.

The sensitivity of the model results had been evaluated to variations in hydrologic parameters and modelling assumptions. The sensitivity of the model was tested by uniformly multiplying recharge and hydraulic conductivity values by factors of 0.2, 0.4, 0.8, 1.2, 1.5, 2.0, 2.5 and 3.0 throughout the model's interior nodes and the model was rerun. For each simulation, one parameter was changed keeping the others unchanged. Sensitivity curves were developed for both steady-state and transient-state models. The sensitivity analysis of steady-state model indicated sensitivity of the model to any change in hydraulic conductivity. High imbalance in water budget was observed against lower and higher conductivity values. Similarly the model was found sensitive to recharge also. The sensitivity analysis of transient-state model indicated model sensitivity to both higher and lower values of the specific yield.

GROUNDWATER BEHAVIOUR 1985–2020

Strategy of management for pre-stress period and post stress period was developed on the basis of availability of observed data until 2005 and projected hypothetical data for period 2006–2020. Time series records of previously observed data of precipitation, annual recharge and withdrawals from tubewells were examined which formed the basis to generate projected data for simulation of future groundwater behaviour. The predictive period of 15 yr, that is, 2006–2020,

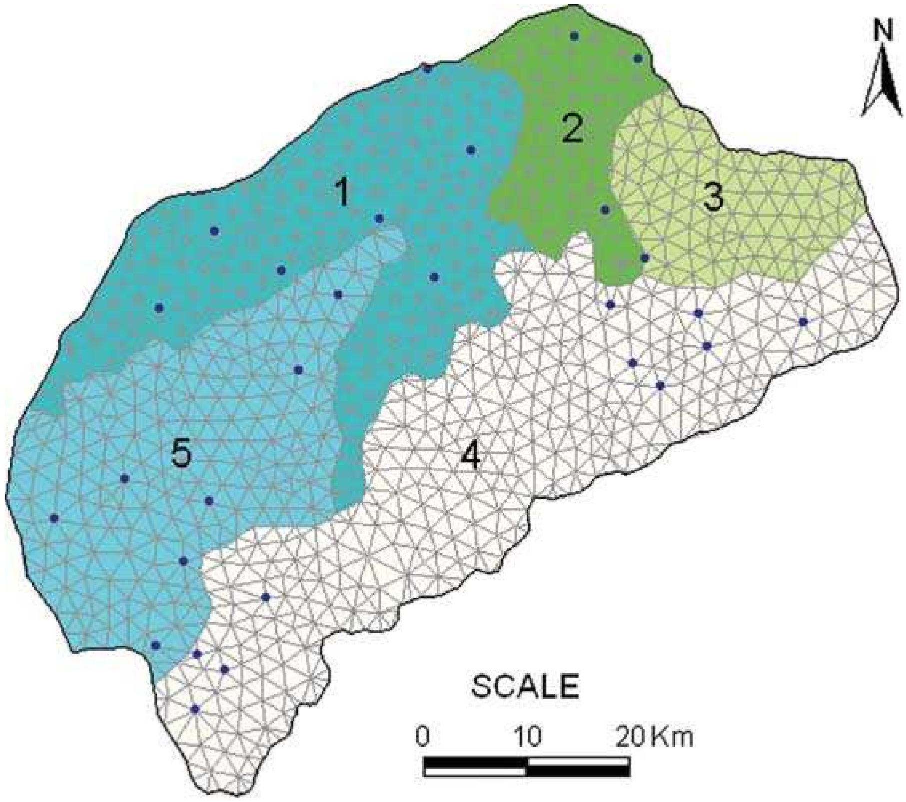

Figure 3. Recharge zones along with locations of observation wells in the study area.

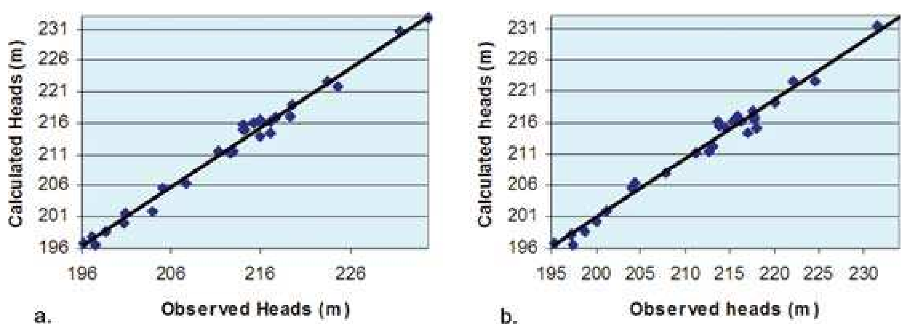

Figure 4. (a) Steady-state calibration. (b) Transient-state calibration.

was chosen to perceive the long-term impact of droughts/floods on the regional groundwater system. Based on the annual incremental increase/decrease in recharge and/or groundwater pumpage, the recharges for various stress periods were adjusted for calibration of the groundwater flow model. The recharge rate varies in each stress period in accordance with supplied delivery of water to canals, annual rate of precipitation, groundwater withdrawals, and stages of the rivers.

The steady-state calibrated model was run for pre-stress period of variable time steps until 2005. The average watertable values (the spatial average over the whole region) was used to foresee the overall effect of the watertable in the model domain. During the calibrated period of 1985–2005, the watertable had shown an average decline of 0.96 m at the rate of 0.05 m yr^{-1}. The watertable indicated a rising trend from 1988 to 1999 followed by a gradual decline onward. The initial rise may be attributed to record rainfalls that had occurred in Muzaffarabad and Jhelum during period 1997–1998 (Siddiqi 1999). Those rainfalls exaggerated the problem of waterlogging especially in the Phalia tehsil of Mandi Bahauddin district. A major breakthrough of groundwater depletion was observed in the year 1999 when last drought prevailed for over 3–4 yr in Upper Chaj Doab area. The declining trend of groundwater levels continued in the remaining calibration period. During the drought period, there became shortages in canal water supplies that resulted in low recharge from canals seepage and over exploitation of the groundwater. The situation had affected the extent of waterlogging which was reduced significantly in some parts of the area. Quantitative analysis of the groundwater aquifer was performed using geo-processing tools of Arcview 3.1. Results had shown maximum head drop of about 21 m in Phalia tehsil, while minimum of 14 m in Gujrat tehsil during 2005. Maximum velocity range of 0.006–0.09 m d^{-1} was observed in Mandi Bahauddin while minimum range of 0.003–0.035 m d^{-1} in Kharian tehsil. Overall, minor variations in groundwater levels were observed in Gujrat as compared with Mandi Bahauddin district.

The calibrated model was rerun to predict the future changes in piezometric heads for period 2006–2020. The predictive model

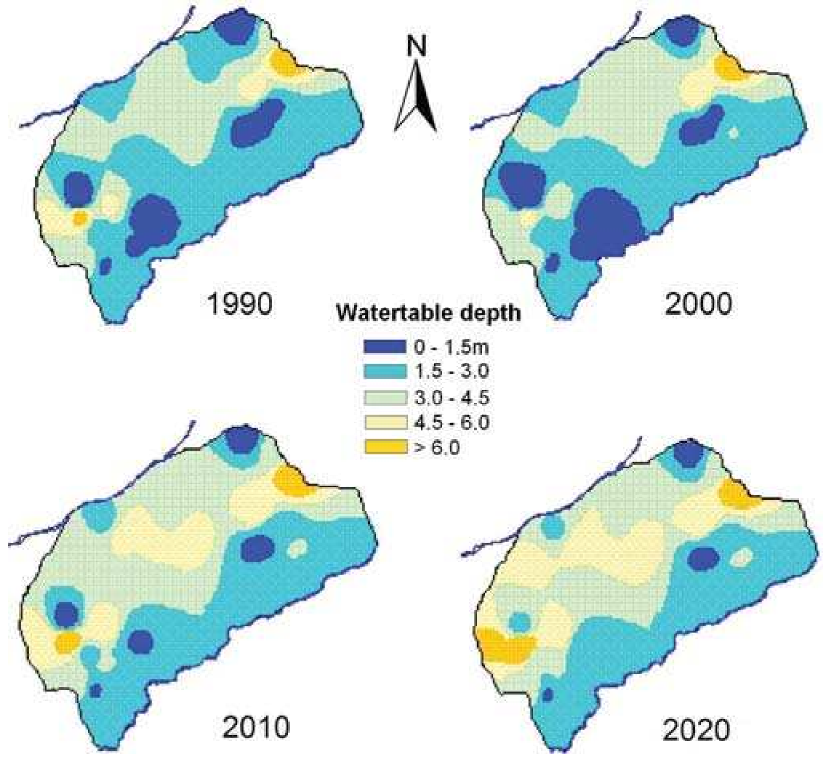

Figure 5. Variations in watertable depth (1990–2020).

showed an average decline of 0.81 m in watertable. The coverage of watertable depth range less than 1.5 m indicated a notable reduction from 226.9 km^2 in 2005 to 73.8 km^2 in year 2020. Similarly, the coverage of depth range 1.5–3.0 m indicated a decrease from 1299.4 km^2 in 2005 to 1104.8 km^2 in year 2020. The variations in watertable depth were mapped on decadal basis to observe trend of watertable during pre stress and post stress periods (Fig. 5). The watertable depth of ranges less than 1.5 and 1.5–3.0 m showed an initial increase in coverages during 1990–2000. The changes were significant in Malakwal and Phalia tehsils. The watertable depth less than 3.0 m indicates a declining trend in coverage during period 2000–2020 which may help reducing the extent of waterlogging in Chaj Doab area. On the other hand, watertable depth greater than 4.5 m is indicating a gradual increase in coverage during the same period.

Development of future scenarios

The calibrated model was used to predict future scenarios based on the variability of influential factors and parameters related to groundwater development in the model area. The impact of climatic variability generated persistent drought/flood conditions during pre-stress period was used to develop hypothesis for post-stress period. The basic idea is to consider rainfall extremes of the drought/flood events occurred in the area for the development of future climate scenarios. In the first scenario, severe drought condition was assumed to prevail over 4-yr period, that is, 2006–2010. The rainfall data of severe drought occurred during 1999–2002 was used as reference in developing the scenario. The hypothetical simulation indicated a mean decline of 0.7 m in watertable depth from that of base year 2005 (Table 3). In the second scenario, extreme wet condition was assumed to prevail over period of 4 yr, that is, from 2011 to 2015. The scenario was based on the reference rainfall data of wet period 1997–1998, when intense rainfalls occurred in the Jhelum area. It indicated a mean decline of 0.42 m in watertable from that of year 2005. In order to examine the effect of groundwater withdrawals on the aquifer, scenarios of varying pumpage rates were developed. In the third scenario, the pumpage from 33 deep tubewells was assumed to continue at a constant rate of 5000 m^3 d^{-1} for consecutive 3-yr period, that is, 2005–2008. The scenario had shown a mean decline of 1.63 m in watertable at the end of the discharge period. In the fourth scenario, an increase of 60 per cent in discharge (8000 m^3 d^{-1}) of the tubewells was assumed to continue for consecutive 3-yr period (2005–2008). It indicated a mean decline of 2.23 m in watertable at the end of discharge period. The high pumpage of the groundwater can be utilized to minimize waterlogging problem in the area.

Table 3. Watertable behaviour in different scenarios (WT depth in 2005 = 2.95 m).

Scenario	Description	Mean watertable depth (m)
1	At the end of consecutive 4 yr of drought condition (period 2006–2010)	3.65
2	At the end of consecutive 4 yr of wet condition (period 2011–2015)	3.37
3	After 3 yr of pumpage from deep tubewells (period 2005–2008)	4.58
4	60 per cent increase in pumpage from deep tubewells (period 2005–2008)	5.18

CONCLUSION

The numerical groundwater flow modelling coupled with decision support tools of geoinformatics provides efficient way of analysing and monitoring the behaviour of regional groundwater system. GIS facilitates rapid transfer and assembly of various input data sets for groundwater modelling and is found extremely helpful during the process of model calibration and forecasting. The capability of remote sensing technology can be utilized to identify natural indicators, both direct and indirect, that can be interpreted in relation to potential sources of groundwater recharge. The results of the composite study show that factors including climatic conditions and over-exploitation of groundwater have long-term impact on the regional groundwater system. The high pumpage of groundwater on long-term basis may result in unsafe decline of watertable though it would be useful for areas facing the problem of waterlogging. The developed model provides effective tool for evaluating better management options for sustainable use of groundwater. The results can provide baseline information to the water resource managers, researchers and planners to organize management schemes on local and regional basis to monitor groundwater development for economic uplift of the area.

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REFERENCES

Arora, A.N. & Goyal, R., 2003. Conceptual Groundwater Modeling using GIS. GIS India 2003, *National Conference on GIS/GPS/RS/Digital Photogrammetry and CAD,* Jaipur.

Bhutta, M.N. & Wolters, W. 1996. Issue paper: drainage and the environment in Pakistan, in *Proceedings of the National Conference on Managing Irrigation for Environmentally Sustainable Agriculture in Pakistan,* Nov. 5–7,Vol. 1, IIMI, Lahore.

DLR, 2002. *Groundwater Monitoring: Prospects, Strategy and Data (Critical Areas: SCARP-II, III, IV & V),* DLR-GWM Report, Directorate of Land Reclamation Punjab Irrigation and Power Development, Canal Bank Moghalpura, Lahore.

Doherty, J., 1995. *PEST ver. 2.04,* Watermark Computing, Corinda, Australia.

Jain, S.K., Hemant, C., Sobhagya, M. & Rajesh, K.N.S., 1997. *Flood estimation using a GIUH based on a conceptual rain-runoff model and GIS,* ITC Journ. International Institute for Aerospace Survey and Earth Sciences (ITC), Enschede, The Netherlands.

Josef, F., 2004. *Integration of GIS and Groundwater Modelling,* http://www.technion.org/Media/TcsSample.doc

Kidwai, Z. Din., 1962. *The Geology of Rachna and Chaj Doabs,* Water and Power Development Authority, Water and Soils Investigation Division, Bulletin no. 5.

Pillmann, W. & Jaeschke, A. (eds.) 1990. *Proceedings of the 5th Symposium on Informatics for Environmental Protection,* Vienna 1990, Informatikfachberichte 256, Springer-Verlag, Wien.

PPSGDP Report, 2000. *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.

Qureshi, M.K.A., *et al.*, 2003. *Geology and Environmental concerns of the Rasul-Mandi Bahaudin Quadrangle, Punjab, Pakistan,* GOP, Ministry of Petroleum and Natural Resources, Geological Survey of Pakistan, Quetta, Pakistan.

Saraf, A.K. & Choudhury, P.R., 1997. Integrated Application of Remote Sensing and GIS Groundwater exploration in hard rock terrain, in *Proceedings of the International Symposium on Emerging trends in Hydrology,* Department of Hydrology, Roorkee, India.

Sarwar, A., 1999. *Development of a conjunctive use model, an integrated approach of surface and Groundwater modeling using a Geographic Information System (GIS),* Bonn 135 S., Landw. F., Diss.v.08.11.1999

Siddiqi, 1999. *Effect of El-Nino on Agriculture of Pakistan,* PARC, Islamabad.

Soil Survey Report, 1967. *Reconnaissance soil survey of Gujrat district,* Directorate of Soil Survey of Pakistan, Lahore.

Thangarajan, M. 2004. *Regional Groundwater Modeling,* Capital Publishing Company, New Delhi, India.

WASID, 1964. *Analysis of Aquifer tests in the Punjab Region of West Pakistan,* Water and & Soils Investigation Division, Water and Power Development Authority, Lahore.

WASY, 2004. *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.