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Simulation of Future Groundwater Behaviour in Sirhind Canal Tract of Punjab Using MODFLOW

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Abstract

Groundwater sustainability is one of most serious issue that is poignant to the State of Punjab. The rampant tubewell intensification is resulting in utilization of groundwater at a rate greater than annual recharge rate. In this study, a numerical groundwater flow model (MODFLOW) was employed to simulate flow and groundwater levels in the Sirhind Canal Tract (SCT) of Punjab. The aquifer of this region was discretized into 482 cells comprising of 21 rows and 23 columns, each cell representing 100 km^2 area. In general, the aquifers are unconfined and maximum depth up to 300 m was considered. The spatial heterogeneity of the aquifers was captured from lithologs available from 500 observation points spread across the region. The annual groundwater recharge and groundwater abstraction rates were estimated using the norms specified by CGWB. The model was calibrated for aquifer parameters viz. hydraulic conductivity and specific yield, boundary conditions using observed groundwater data for 15 years (1998- 2012) and validated for 5 years (2013-2017). Results showed that groundwater modelling fairly matched the historical groundwater pattern. The groundwater model was applied to predict groundwater level up to year 2030 under four different pumping scenarios: Scenario-I (Maintaining the current pumping and recharge rate for the study period); Scenario-II (Increase in pumping rate according to the historical trend); Scenario- III (Increasing canal water supplies and maintaining current groundwater abstractions) and Scenario-IV (Increasing canal water supplies and altering accordingly altering groundwater abstractions). The study identifies a useful strategy for sustainable groundwater development in the region.

Keywords: Groundwater Modelling; Groundwater Level; Groundwater Management; Management Scenarios

1. Introduction

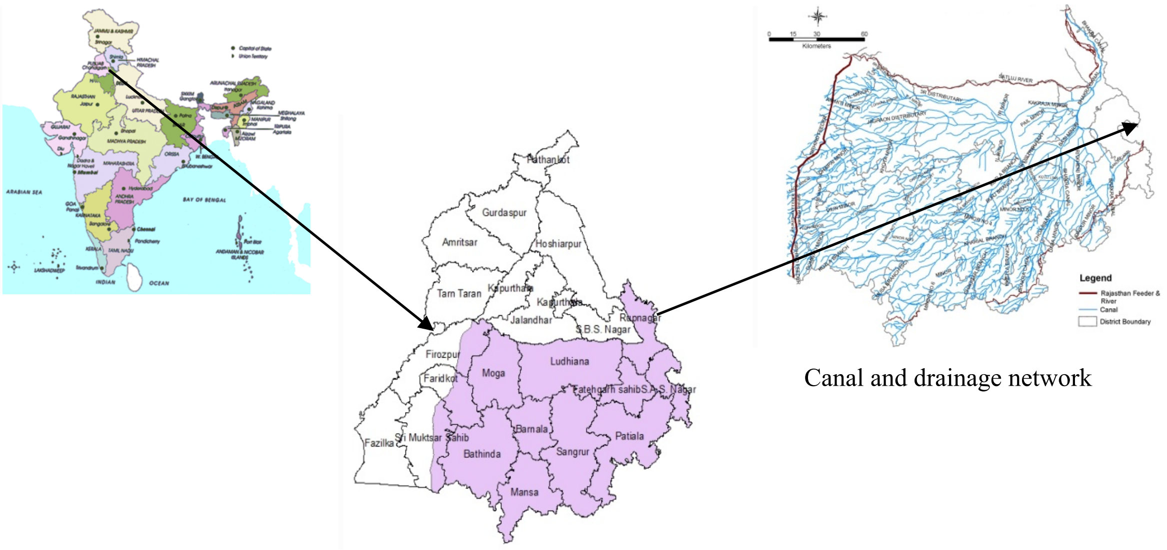
Groundwater makes up only 0.60 % of the Earth's total water yet accounts for approximately 20 % of the Earth's overall freshwater supply. Globally, around 1.50 billion people depend upon fresh water for their drinking water requirement. Groundwater is also the primary source of water for agriculture in arid and semi-arid regions of the world (Scott and Shah, 2004) as 38 % of cultivated lands are dependent on this for irrigation. In South Asia, over 50–60 % of the nation population had to depend directly or indirectly on groundwater irrigation. The use of groundwater in North China had risen from almost zero in the 1950s to 74 billion cubic meters in the 1980s and is more than 100 billion cubic meters after 2000 (Ministry of Land Resources, 2005). In Pakistan, groundwater provides over 40% of the total crop water requirements in the densely populated province of Punjab, producing 90% of the country's food (Qureshi and Barrett-Lennard, 1998). India is the largest groundwater user in the world, with an estimated usage of around 230 cubic kilometres per year, more than a quarter of the global total. Groundwater proves to be a vital resource for rural areas in India as more than 60 % of irrigated agriculture and 85 % of drinking water supplies depend on it (Clifton et al., 2010). With an annual growth rate of 1.3 %, India's population is predicted to reach 1.4 billion in another 15 years. The Ministry of Water Resources estimates that by the year 2050, there will be a rise of 56 % in irrigation needs, with double demand of drinking water and increased water supplies to industries and for production of energy. Additionally, the exceptional urbanization in India proves to be energy and water demanding. The groundwater level in India has declined by 61 % between 2007 and 2017 and according to the census. Climate change may further play an intensifying role in dropping water levels in these regions with increased run-off and/or evapo-transpiration (Rodell et al., 2009). North Western and Peninsular India including Punjab, Rajasthan, Maharashtra, Karnataka, Gujarat, Andhra Pradesh and Tamil Nadu have been identified as the critical groundwater regions of India (Shah 2009).

Punjab, a north-western State occupying 1.53 % of total geographical area of country, has about 85 % of its geographical area under agriculture. With high yielding crop varieties, increased use of fertilizer and groundwater, the spectacular increase in agricultural production of Punjab in the last few decades has made it the leading supplier of food grains (rice and wheat) to the country. At present, the state has 99 % of the net area sown under irrigation, of which rice and wheat covers nearly 75 % of the total cropped area. The surface water resources are insufficient to meet the total irrigation needs; only 28 % of the cropping area is irrigated from canals, rest 72 % getting its water from tube wells. Although the economic gains from groundwater use has been enormous (Saleth, 2004; Shah, 2004) yet the rapid extraction of the resource has made it vulnerable to over-exploitation. The number of energized tube wells has increased from 1.91 lakh in 1970 to 14.75 lakh in 2017 (Anon, 2018). Average groundwater exploitation of Punjab is now 165 per cent and is more than two times higher than the sustainable limits of 70 per cent. Consequently, the groundwater levels have registered a steep decline of 10 m in 20 years i.e. from 1998 to 2018 indicating a fall rate of 51.3 cm/year. Up to 1995, this decline was about 23 cm per year (Khepar et al., 2001) which during the next 6 years (1997-2003) increased to 53 cm per year (Hira et al., 2004) and is about 51.5 cm per year during 1998 to 2018. As per the recent report published by Central Groundwater Board (CGWB), the State aquifers will dry by 2030, if the existing abstractions rates continue. This widespread depletion of groundwater resources is a matter of serious concern and strategies need to be identified for its sustainable management. Groundwater models such as MODFLOW, FEFLOW can play an important role (Scanlon et al., 2003) to recognize the critical depletion and recharge zones and to predict its variability in future. Modelling also shows the relative importance of different controls on recharge, provided that the model realistically accounts for the all process involved. The present study aims to simulate groundwater system of Sirhind canal tract using MODFLOW to provide realistic estimates of future groundwater levels under different pumping scenarios in the region.

2. Materials and methods

2.1. Geographic area and climate

Sirhind Canal Tract, one of the most productive aquifer systems of Indo-Gangetic basin and known as Cis-Doab lies south of the perennial Sutlej river between latitude 29º 53′ N and 31º 37′ N and longitude 74º 5′ E and 76º 51′ E (Figure 1).



Canal and drainage network

Figure 1. Location map of Sirhind Canal Tract (shaded portion).

The 2.6 million hectares of area of tract covers entirely the districts of Barnala, Bathinda, Fatehgarh Sahib, Ludhiana, Mansa, Mohali, Moga, Patiala, Ropar, Sangrur with some area of Ferozpur, Faridkot and Muktsar. The elevation of the tract is 340 m in the north east to 190 m above mean seal level (amsl) in southwest. The land slopes are from north-east to south-west with average gradient of 0.68 metre per 1000 metre. Alluvium deposits of Sutlej, Ghaggar and their tributaries are the major form of soil found in the tract. The climatic conditions in the tract are, severely cold winters particularly in the month of December and January, and intense hot summers in April, May and June. Mean monthly air temperature during winter is 5 °C whereas mean monthly air temperature in the summer reaches 40 °C. The mean monthly relative humidity peaks in the months of monsoon (July to September) up to 90 % and troughs down at 30 to 60 % during the summer months. A significant variation of temperature, relative humidity and rainfall is seen across the tract. The eastern side receives normal annual rainfall of 1,000 mm or more and it declines down to less than 400 mm towards the west (Miglani et al., 2015).

2.2. *Groundwater model simulation*

The simulation of groundwater was made with the MODFLOW model (McDonald & Harbaugh, 1988) under a PMWIN environment. The model utilizes the following partial differential equation is used to quantify the three dimensional movement of groundwater in a heterogeneous and anisotropic aquifer

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) \pm w = S_s\frac{\partial h}{\partial t} \qquad (1)$$

Where, Kxx, Kyy and Kzz = hydraulic conductivity along the x, y and z coordinate axes, m/day; h is hydraulic head, m; w is the volumetric flux per unit volume and represents sources and /or sinks of water, m^3/day; Ss = specific storage of the porous material per metre and t is time in days. The tract stretches approximately 220 km in length and 220 km in breadth (north-south). Regionally, the aquifer behaves like a water-table aquifer and was thus discretized with a constant grid spacing of 10 × 10 km considering an unconfined aquifer up to depth of 300 m (Figure 2).

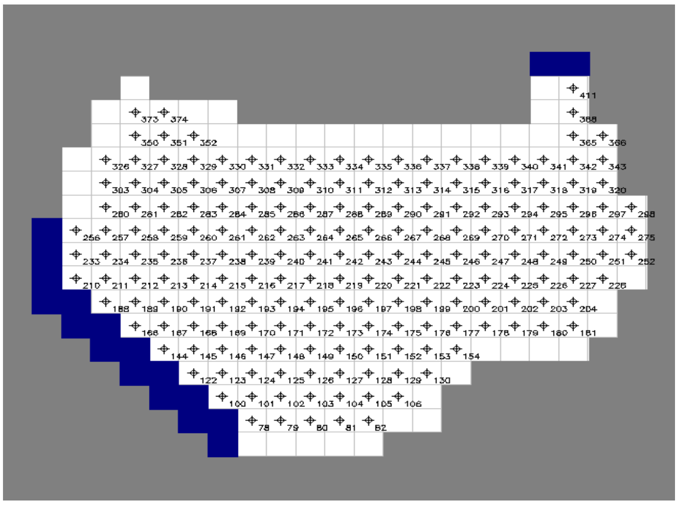


Figure 2. Discretization of the aquifer.

Hydrologically, the region is bounded by Shivalik foothills in the east and north-east, Ghaggar river in the south and south-west, Bhakra Main Line (BML) canal flowing towards south-west and Rajasthan feeder in the west (Figure 1). However, based on the historical annual water level fluctuations, the cells lying to the southwest could only be considered as constant head cells i.e. the storage term was not considered. All other cells lying inside the region were simulated as active cells for which hydraulic heads were computed throughout all time steps of the simulation. The aquifer properties such as such as hydraulic conductivity and specific yield were estimated indirectly (Todd, 1980) from the 500 well logs scattered all across the tract. These were subsequently optimised using automated nonlinear parameter estimator, PEST (Doherty et al., 1994). The model was run in transient state to simulate the annual changes in groundwater levels. The time series pre-monsoon (June) data of more than 200 observation points for Sirhind Canal Tract collected from Department of Agriculture and Water Resources and Environment Directorate, Punjab was used for calibration (1998-99 to 2012-13) and validation (2013-14 to 2017-18) of the model. The temporal parameters i.e. recharge and drafts were simulated using well and recharge flow packages (RCH) for each of the discretized cell. As we didn't have actual locations of the pumping wells, we simulated abstractions with a pumping well positioned in the middle of a MODFLOW cell. Following norms were adopted to estimate recharge and draft.

2.3. *Groundwater abstraction*

The groundwater abstraction during the period 1998-99 to 2017-18 was calculated by multiplying the number of tube wells in each block (smallest administrative unit) with the unit draft values (CGWB, 2015). However, to account for the wet/dry year, the computed values were increased/ decreased by 10 %. The variability of ±19 % or more from normal rainfall was considered for qualifying for wet/dry year.

2.4. *Recharge*

The annual total groundwater recharge for the period 1998-99 to 2017-18 has been computed by the following relation:

$$R_g = \mathrm{R_r} + \mathrm{R}_c + R_{cia} + R_{tia} - E_t \qquad (2)$$

Where,

R_g = Total groundwater recharge (mm)

R_r = Recharge to groundwater from percolation of rainfall (mm)

R_c = Recharge through seepage from the main canals, branches and their distributaries (mm)

R_{cia} = Recharge to groundwater due to return flow from canal irrigated area (mm)

R_{tia} = Recharge due to return flow from tube well irrigated areas (mm)

E_t = Evaporation from shallow water table areas (capillary rise from shallow groundwater into the unsaturated zone and contribution to evaporation) (mm)

and net recharge

$$R_t = R_g - Q_p \pm Q_g \qquad (3)$$

Qg = Groundwater (inflow to) / (outflow from) the area from / to the neighbouring areas (mm)

Qp = Groundwater abstraction (mm)

Due to negligibility of shallow water tables in the study area, the evaporation from such areas has been considered as insignificant. The recharge from rainfall (R_r) was taken as 25 % of total rainfall. Also, it was assumed that no recharge will take place if monthly rainfall value was less than 50 mm (CGWB, 2015). The seepage from canal network (R_c) for the unlined canal is taken as 18 ha-m/day/106 sq.m. For the lined canals, seepage losses are taken as 20 percent of the above value. Although the region has massive webbed canal system of Sirhind canal and Bhakra Main Line, yet only 263 mm (27 %) irrigation water is applied through it. A value of 20 % of water delivered at the outlet for application in the field was considered as recharge from the canal irrigated areas for the non-paddy area whereas for paddy area 35 % of the water delivered at the outlet was taken as recharge. Similarly, the return flow from tube well irrigated areas is taken as 25 % for non-paddy fields and 35 % of the irrigation water delivered at the outlet is taken as return flow from paddy fields. The knowledge of hydrological heads and hydrological properties on both the sides of the boundaries of the area helped for the estimation of groundwater inflow or outflow. The validated model was then used to predict future groundwater levels in the year 2025 and 2030 considering different pumping scenarios. Scenario-I considered that the recent pumping and recharge rates to continue till 2030. In Scenario-II the number of tube wells was increased in accordance to the past trends of last five years (2013-2018) and accordingly it was reflected in enhanced pumping rates. In Scenario-III the canal water supplies were enhanced by 10 %, without any change in groundwater abstraction and Scenario–IV, the groundwater abstractions were reduced for compensating the surplus canal water supplies.

3. Results and discussions

The groundwater table in SCT was 7.94 m in 1998 which plunged to 18.94 in 2018 a fall of 11 m in 20 years; indicating the region is experiencing an average annual fall rate 55 cm/year. There was significant spatial and temporal variation (due to changes in recharge and draft) in the magnitude of hydraulic head which the model simulated successfully. Hydrographs of simulated and observed hydraulic heads at select points spread across the region are also shown (Figure 3).

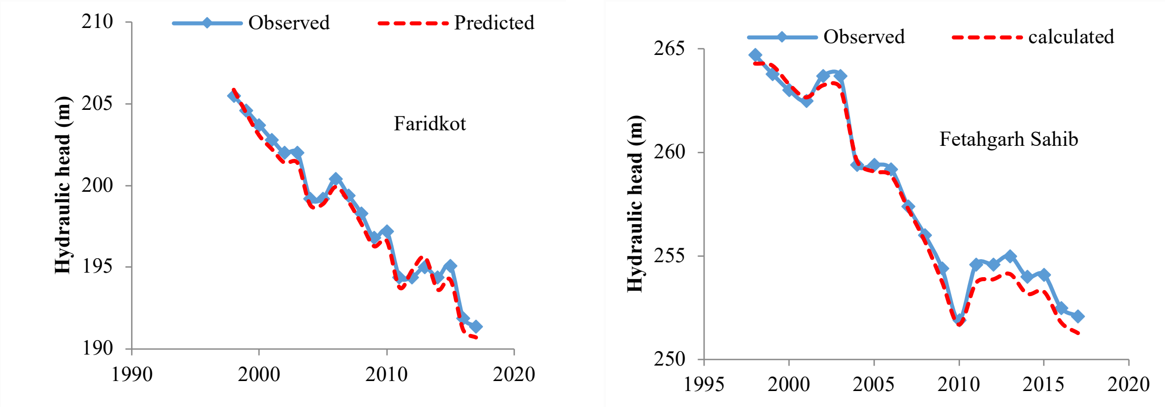


Figure 3. Observed and simulated hydraulic head at different locations.

The average difference between the observed and simulated water levels for most of the internal nodes varied between 0 and 0.75 m. For deviations within these limits groundwater model performance can be considered as satisfactory (Toews and Allen, 2009). Simulation error calculated as RMSE value ranged from 0.41 to 0.56 m for the calibration period and from 0.60 to 0.69 m for the validation period.

The groundwater abstraction of 27.3 BCM and total recharge of 13.8 BCM was computed for the year 2018. The groundwater abstraction was 77 % more in 2018 in comparison to 1998 due to increase in number of tube wells. However, the net recharge being the function of rainfall, irrigation and groundwater storage and abstraction, ranged from (–) 60.0 to (+) 32.4 cm during different years with an average of (–) 10.3 cm. Under the existing abstraction and recharge rates (Scenario-I), the groundwater levels are expected to fall by 3.7 and 6.3 m in the year 2025 and 2030 respectively. Considering the fact, that tubewell density has been increasing in the region; the future groundwater abstraction will increase to 32.6 and 34.2 BCM in 2025 and 2030 causing the water table to decline by 9.0 and 20 m respectively (Scenario- II). In Bhawana, of Pakistan Punjab, depletion of 14 m in groundwater level was reported by Shakoor (2018) under a similar scenario. In Scenario–III, where the canal water supplies are assumed to be enhanced by 10 % with a ban of new tube well drilling, the fall would be of 3.3 m by 2030, nearly half the existing depletion rate as the seepage from canals will contribute to groundwater recharge area. In Scenario–IV the groundwater abstraction is proportionally reduced, as the demand of irrigation water is being compensated by additional canal water supplies (Scenario–III), the simulation suggests, there will be improvement in groundwater levels, with a fall of mere 20 cm in 12 years (2030). The results are summarised in Figure 4.

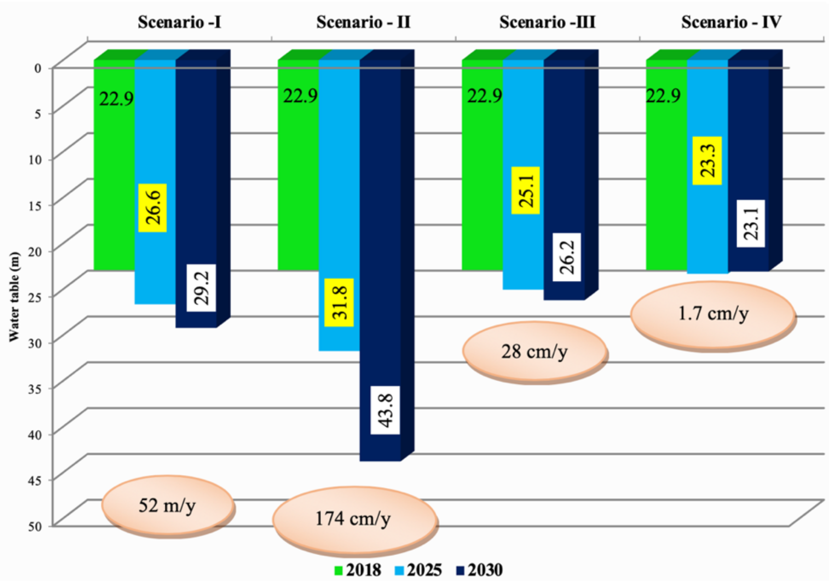


Figure 4. Results.

The depletion of groundwater level has direct and indirect impact on energy, cost and carbon emissions. Kaur et al. (2016) discussed that decline in groundwater levels by 5.47 m (1998–2012) had increased the energy requirements by 67 % resulting in increase in C emissions by 110 %. Dhillion et al. (2017) estimated that 7919.6 MkWh of energy is required for groundwater pumping in central Punjab resulting in C-emissions of 1349.6 ('000) ton. Using the same methodology, we found that the energy requirement vis a vis C- emissions will increase in by 80 % in SCT under Scenario–II (Table 1).

Table 1. Energy requirement and C-emission by 2030 in SCT under different pumping scenarios.

Scenario	Groundwater level (m)	Groundwater draft (BCM)	Energy required (m kW-h)	CO_2 emissions ('000 ton)
I	29.2	27.3	5951.3	1509.5
II	38.9	32.6	10717.8	2718.4
III	26.2	27.3	5416.2	1373.7
IV	23.1	26.3	4685.1	1188.3

4. Conclusions

The study highlights the importance of groundwater models in forecasting the groundwater levels of SCT. The increased dependency on tubewell is the major cause of groundwater decline in Sirhind canal tract. Our findings show that in case the drilling of new tubewells goes unchecked, the groundwater will fall by 20 m in next 12 years, with serious energy and environment consequences. The outcome of the study suggests that the trends of groundwater decline can be reversed in Scenario IV wherein the canal water availability was increased by 10 per cent in blocks with canal network and proportionality groundwater abstractions was reduced. It thus presents a strong case for enhancing the surface water availability in the region. The canal water available in Punjab is 17.54 BCM which can easily irrigate 30.88 lakh ha, out of 42.90 lakh ha . The carrying capacity of the canal network has decreased over time due to lack of repair and maintenance. The Sirhind feeder is running at 138 cumecs instead of 149 cumecs. Over the years, the farmers also have become more reliant on groundwater supplies and have levelled the field distributaries even as the neighboring States are getting their pre-decided share of water. The loser in this case is Punjab. The demand of irrigation water should be met by increasing the availability of canal water. The government should make concentrated efforts to repair the network and restore the field distributaries. This will also result in reduced energy demand and lower C-emissions.

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