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Managing Groundwater Demand through Surface Water and Reuse Strategies in an Overexploited Aquifer of Indian Punjab

Abstract

Groundwater sustainability is one of the most critical issues to the State of Punjab, India. This research employed a numerical groundwater flow model (MODFLOW) to simulate flow and groundwater levels in the Sirhind Canal Tract of Punjab between 1998 to 2030. Historical groundwater patterns were calibrated using reported groundwater data from 1998 to 2013 for aquifer parameters viz. hydraulic conductivity and specific yield. Thereafter, the calibrated flow simulated model was validated for the years 2013-2018. Twelve possible strategies, including three irrigation conditions and four pumping scenarios, were postulated to evaluate the performance of groundwater resources through to 2030. During the study, it was found that if current groundwater abstraction continues, there will be a further steep decline of 21.49 m in groundwater level by 2030. Findings also suggest that canal water supplies will be beneficial to reverse groundwater level decline and help to increase the water level by 11% above that in the year 2018. The projected increases in water level will reduce energy demand leading to reduced CO_2 emissions of approximately 966.6 thousand tons by 2030.

Keywords: Groundwater depletion; Wastewater reuse; Sustainable groundwater management Simulation modelling

1. Introduction

Punjab, “The Land of Five Rivers”, occupies 1.53% of the total geographical area of India, with 82% of the State’s entire land being used for agricultural activities (ESOPB 2020, pp.78-79). The cultivation of high yield crop varieties and the increased utilisation of fertilisers and groundwater reserves has resulted in a significant increase in the agricultural production of Punjab during the last few decades, hence establishing the State as the leading supplier of food grains to the country (Aggarwal et al. 2005; Khosa et al. 2012). The role of the State in ensuring national food security, via leveraging an extended mandi supply network system, is prominent as out of the 7,128 thousand ha of the total area under cultivation for food and non-food crops, rice and wheat cover nearly 81% (ESOPB 2020, 78-79, pp.86-89). Approximately 99% of Punjab’s net agricultural area is sown under irrigation, while surface water resources accommodate only 28% of the total irrigation needs (ESOPB 2020, p.157). The rest 72% of the required water supplies become available through tubewells (ESOPB 2020, p.157). The increased utilisation of groundwater abstraction structures in the State has increased during the past five decades owing to: (i) the implementation of resource development schemes supported by liberal funding from institutional finance agencies; (ii) the increased availability of electric power and diesel; (iii) the provision of quality seeds and fertilisers; and (iv) direct governmental support via subsidies (Ministry of Water Resources 2017, p.15).

However, the economic gains have come at a cost with significant depletion of groundwater resources (Saleth 2004; Shah 2009; Liu et al. 2019). In fact, the current average groundwater extraction rate in Punjab is 165%, with the sustainable threshold being 20 billion m^3 (Central Ground Water Board 2017, p.13; Srivastava et al. 2015), hence resulting in a cumulative groundwater level decline of 10.8 m over the 20 year period, 1998-2018, with an annual fall rate of 54 cm. Based on the Central Ground Water Board (2017), the aquifers in Punjab are projected to run completely dry within the next 25 years if the current groundwater abstraction rate is maintained.

India ranked top in groundwater abstraction in 2010 because of its tenfold increase in groundwater abstraction in the past 50 years, representing twice the annual groundwater abstraction of either U.S. or China (Gorelick and Zheng 2015). Whilst irrigation water may be drawn from ground and surface water sources (Knapp et al. 2000), the current predominance of abstraction at unsustainable levels is alarming.

Overexploitation of groundwater threatens future availability of the most valuable natural resources, increases freshwater resources' pollution, and degrades ecosystems (Jha et al. 2006). The rapid depletion of groundwater resources is a serious national concern regarding agri-food supply networks and food security. Significant threats to water resources around the world have initiated the concern for their sustainable management (Vadiati et al. 2018). The most efficient measure to fight against groundwater pollution is to make a plan for integral prevention (Manos et al. 2010, Esteban and Dinar 2013). In the past decades, many researchers suggested solutions applicable to both upstream and downstream agri-food supply chain operations to promote the restoration of groundwater levels in Punjab, including crop diversification, efficient irrigation options, water conservation practices, groundwater recharge techniques and wastewater reuse (Aggarwal et al. 2004; Aggarwal et al. 2005; Shakoor et al. 2018). From a policy-making perspective, Hira (2009) emphasised shifting subsidies from farming inputs (e.g., subsidised energy to tubewells) to farming outputs (e.g., increase in procurement price or bonus on marketable agricultural produce) to encourage farmers to use irrigation water more efficiently. Furthermore, Kaur et al. (2011) suggested an optimal crop plan that could result in groundwater savings of almost 25% in Punjab. Nevertheless, to the best of our knowledge, very limited research has been conducted on how suggested interventions could impact groundwater behaviour.

Groundwater systems are complex in nature entailing a range of constituents, like surface water, geological media containing water (such as aquifers), flow boundaries, water recharge factors, sinks leading to water withdrawals, heterogeneous distribution of subsurface materials, and transient groundwater fluxes (Chang et al. 2017). To this effect, groundwater systems' analysis generally requires sophisticated mathematical tools/models to analyse the underpinning dynamics (Mayer et al. 1998; Patil et al. 2020). Simulation models can help assess the impact of different controls on groundwater recharge (Li et al. 2017; Tubau et al. 2017), provided that the associated models realistically account for all the involved processes. Thereafter, a calibrated and validated model can help identify the critical depletion and recharge zones, hence informing groundwater management strategies.

Groundwater models allow stakeholders to simulate and predict changes in water tables and determine water reserves' contamination levels. Models such as MODFLOW, FEFLOW, GMS, MODPATH, RT3D, SEEP2D and SEAM3D have been extensively used to inform groundwater resources management (Kori et al. 2013, Gorelick and Zheng 2015).

Indicatively, MODFLOW has been used to inform the management of groundwater reserves via adjusting the current extraction patterns to sustain future water resources (Rejani et al. 2008; Shakoor et al. 2018). Nevertheless, modelling studies focusing on the groundwater levels in Punjab, explicitly using up-to-date data, are sparse. In addition, despite the global water withdrawals of more than 65%, irrigated agriculture contributes 44% to the agricultural production, which represents only 18% of the cultivated area (FAO 2014). This further justifies the need to consider the efficiency of water use and sewage water reuse in the applied research methodologies and approaches (Barbosa et al. 2017). The application of treated wastewater in agriculture increases in water scarce areas of Mediterranean countries to augment water supply (Candela et al. 2006). The utilisation of multi-water resources is deemed essential for sustainable development (Wang et al. 2019). For example, farming and the food processing industries generate large volumes of effluents, rich in organic matter, that can be reused as an environmentally sustainable practice for irrigating plantations (Menegassi et al. 2020). To the best of our knowledge, the impact of wastewater augmentation on groundwater levels has not been examined, particularly via investigating a range of alternative irrigation conditions and pumping scenarios. Vij et al. (2021) investigated wastewater paradigms in India during the last three decades and observed a policy shift towards wastewater treatment from '*water resource to meet basic human needs*' to '*water scarcity and beautification of cities*'. However, the authors further realised a gap between policy recommendations and actual on-the-ground interventions.

Motivated by the scarcity of studies on groundwater modelling in Indian Punjab, and to further address the evident gap about modelling approaches investigating the respective impact of multi-water resources' management, this research contributes to the extant body of literature on groundwater management via: (i) simulating the groundwater system of the Sirhind Canal Tract, one of the most productive aquifer systems at the Indo-Gangetic basin; and (ii) assessing the groundwater level in the region via evaluating alternative pumping and water management scenarios. Following the suggestion of Miglani et al. (2015), this research applied MODFLOW to simulate and assess the future groundwater behaviour of the Sirhind Canal Tract. The novelty of this research is encapsulated to the following: (i) a range of irrigation conditions was considered, including wastewater augmentation from Sewage Treatment Plants (STPs); and (ii) different pumping scenarios were evaluated, resulting in twelve possible strategies for the sustainable management of groundwater resources by 2030. Considering that groundwater behaviour is a dynamic phenomenon and the need to update the respective information regularly, this research used recently gathered data about the region.

The remainder of this research is structured as follows. Section 2 provides a research background by summarising recent studies applying MODFLOW for groundwater modelling. Section 3 details the materials and methods pertinent to this research. Thereafter, Section 4 discusses the research results and findings. In particular, the impact of alternative management strategies on groundwater levels, along with the associated energy requirements and carbon emissions, is presented. Finally, conclusions, policy-making recommendations, limitations, and future research avenues are explored in Section 5.

2. Recent Groundwater Management Studies Using MODFLOW

Groundwater simulation modelling is a valuable analysis approach in regions where groundwater resources' extraction exceeds the natural and induced aquifer recharge rates over long periods, like in the case of the Indian Punjab. To that end, MODFLOW, a three-dimensional finite-difference groundwater flow model developed by the United States Geological Survey, has been extensively used by hydrogeologists for the analysis of groundwater flows due to its easiness, accessibility, and versatility (Kashaigili et al. 2003). Selected studies on groundwater management using MODFLOW are analysed below.

Rejani et al. (2008) used the Visual MODFLOW package and tested five pumping strategies for groundwater management against overdraft and seawater intrusion in the Balasore coastal basin in Orissa, India. Furthermore, the application of MODFLOW in the North China Plain showed that 29.2% reduction in irrigation could prevent groundwater depletion, while an additional 10% reduction in pumping could foster the restoration of the groundwater aquifer to the hydrological conditions of 1956 within 74 years (Hu et al. 2010). Singh and Shukla (2016) employed Visual MODFLOW to project groundwater levels and articulate potential groundwater management scenarios for the Sai Gomti interfluve region in India. Khan et al. (2017) proposed a groundwater policy for the Indus Basin of Pakistan via examining different groundwater modelling scenarios, including: (i) groundwater pumping controls; (ii) improvements to the canal infrastructure; and (iii) precipitation changes. In addition, Sobeih et al. (2017) and Eltarabily et al. (2018) used MODFLOPW to model groundwater flows in the western and eastern Nile Delta to assess different scenarios capturing recharge from nearby canals and discharge from wells. Similarly, Shakoor et al. (2018) quantified the future groundwater depletion under three different pumping scenarios for the Punjab province in Pakistan and found that artificial groundwater recharge and surplus canal water supplies could be beneficial to avoid groundwater depletion. Glass et al. (2018) suggested that local overexploitation of groundwater resources in Hanoi, Vietnam, can be reduced by smart relocation of wells from the main depression cones and via the expansion of riverbank filtration.

In addition, Bouqdaoui and Aachib (2019) focused on managing and restoring groundwater resources of the Berrechid aquifer in Morocco via examining alternative simplified management scenarios such as artificial recharge and reduction of the water volume pumped for irrigation. Furthermore, Chakraborty et al. (2020) used Visual MODFLOW 2000 for analysing the groundwater level in Purba (East) Midnapur, West Bengal, India. Siva Prasad et al. (2020) investigated the groundwater balance for the Kandivalsa River sub-basin in Andhra Pradesh, India, and examined the impact of two scenarios on groundwater levels, namely: (i) increasing the withdrawal rate and keeping the recharge rate constant; and (ii) increasing the recharge rate by 50% while maintaining a constant withdrawal rate. Table 1 summarises representative studies on groundwater modelling using MODFLOW.

Table 1. Groundwater modelling using MODFLOW: An overview.

[Table 1 about here]

3. Materials and Methods

This research followed a multi-step methodological approach for developing the elaborated simulation model (Figure 1). Firstly, in Step #1, the Sirhind Canal Tract was identified as the object of scrutiny. Thereafter, in Step #2, the relevant geographic and climate characteristics were identified while respective data was gathered. MODFLOW-based simulation model of the Sirhind Canal Tract was conceptualised and discretised in Step #3. In addition, boundary conditions were set while groundwater draft and recharge rates were estimated. In Step #4, the model was calibrated and validated to articulate alternative simulation scenarios. Thereafter, in Step #5, alternative simulation strategies were investigated. Specifically, four pumping scenarios under three irrigation conditions were simulated, resulting in twelve alternative strategies that could impact the future groundwater behaviour. The modelling results were summarised and analysed to suggest environmentally sustainable policies for the management of the groundwater behaviour in the Sirhind Canal Tract of the Indian Punjab.

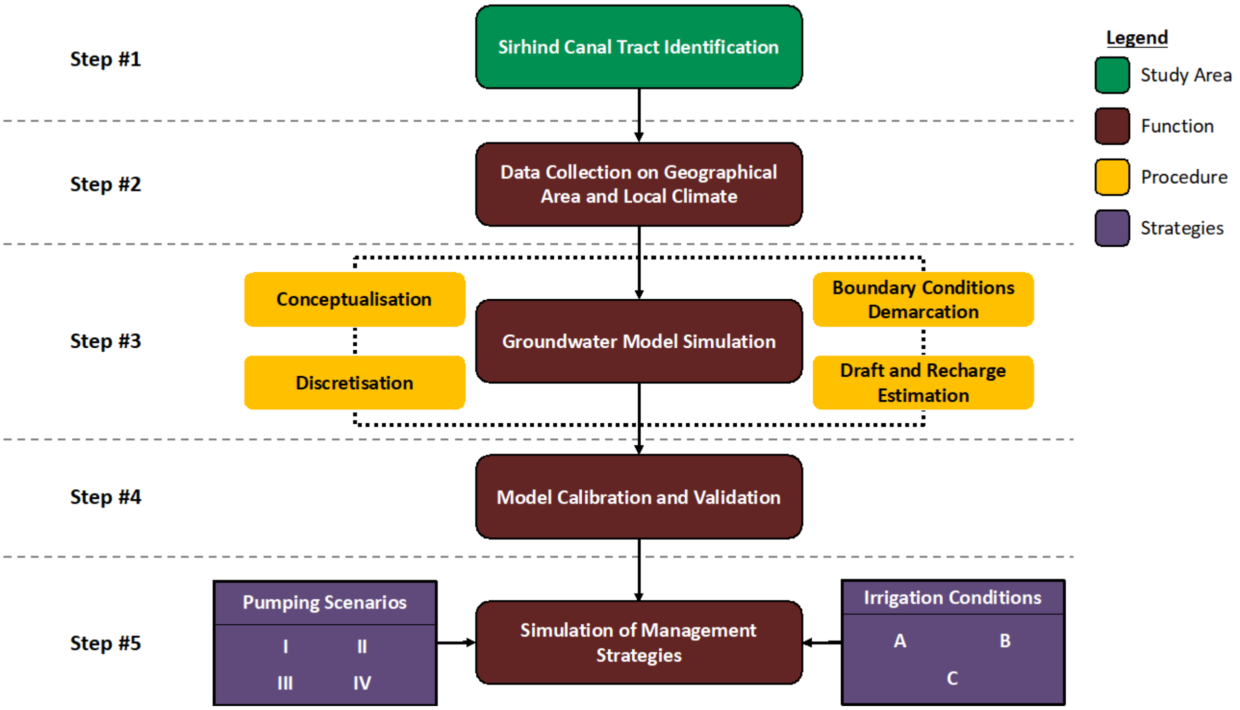

Figure 1. Simulation modelling workflow for the evaluation of alternative groundwater management strategies.

3.1 Case Identification

The Sirhind Canal Tract, known as Cis-Doab, is one of the most productive aquifer systems in the Indo-Gangetic basin. The tract lies to the south of the perennial Sutlej river between latitude 29° 53 ´ N and 31° 37 ´ N, and longitude 74° 50 ´ E and 76° 51 ´ E. The 2.60 million ha area of the tract covers the districts of Barnala, Bathinda, Fatehgarh Sahib, Ludhiana, Mansa, Mohali, Moga, Patiala, Ropar, and Sangrur with some area of Ferozpur, Faridkot and Muktsar (Figure 2) entirely. The elevation of the tract varies from 340 m in the northeast to 190 m above the mean sea level in the southwest (Marok et al. 2000). The land slopes from northeast to southwest with an average gradient of 0.68 m per 1,000 m. Alluvium deposits of the Sutlej River, the Ghaggar River and their tributaries form the principal soil in the tract.

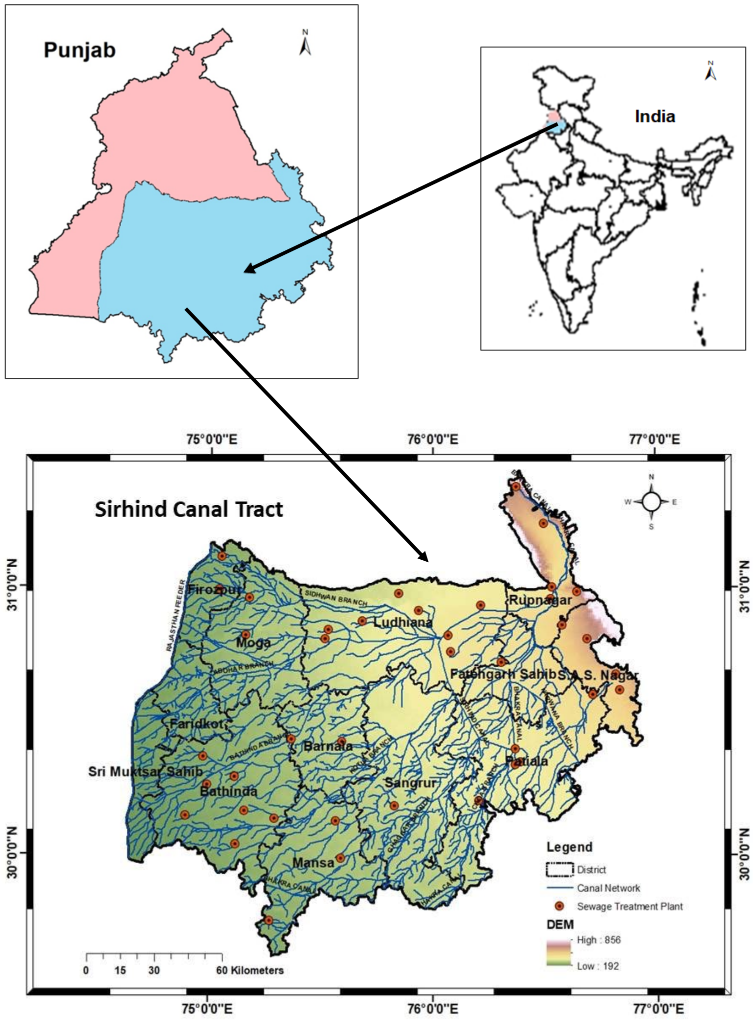

Figure 2. The Sirhind Canal Tract, Punjab State, India [based on data retrieved from the Punjab Remote Sensing Centre, Ludhiana].

3.2 Geographic Area and Climate Determination

There are two main cropping seasons in the tract, namely *Kharif* (summer) and *Rabi* (winter), with rice being the main cultivated crop during the *Kharif* season and wheat the leading crop during the *Rabi* season. Wide seasonal variations in temperature characterise the climate in the region. In particular, summer lasts from April till October with the temperature ranging between 21-51°C, whereas the winter season extends from October till April with the temperature ranging between 7-27°C. The mean air temperature in the tract during winter is about 5°C, while during summer, it reaches 40°C, monthly. In addition, the mean monthly relative humidity reaches 90% during monsoon (i.e., July to September) and varies between 30-60% during summer (Marok et al. 2000). Furthermore, the eastern side of the tract receives a normal annual rainfall of 1,000 mm or more, whereas it declines down to less than 400 mm towards the west (Miglani et al. 2015). Overall, significant variations in temperature, relative humidity and rainfall can be observed across the tract.

The tract comprises an extended canal network, from main canals to distributaries and other inland waterways. The Bhakra Main Line Canal and the Sirhind Canal are the two primary water sources for irrigation in the area. The Sirhind Canal further diverges to the Sidhwan branch, the Abohar branch, the Bathinda branch and the First and Patiala feeders. The First Patiala feeder further bifurcates into the Kotla branch and the Second Patiala feeder. The latter feeder is subdivided into the Ghaggar branch and the Third Patiala feeder (Figure 2). The inter-state canal system of Bhakra Main Line is used to irrigate the eastern and southeastern part of Punjab, along with the northern parts of Haryana and Rajasthan, through the Nirwana branch. The Sirhind Canal system is used to irrigate the central and western parts of the tract (Marok et al. 2000).

3.3 Groundwater Simulation

The groundwater simulation was developed via employing the MODFLOW model (McDonald and Harbaugh, 1988), in a Processing MODFLOW for Windows environment. The

MODFLOW model utilises a partial differential equation to quantify the three-dimensional movement of groundwater in a heterogeneous and anisotropic aquifer (Equation 1):

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

where, K_{xx}, K_{yy} and K_{zz} represent the hydraulic conductivity along the x, y and z coordinate axes in m/day; h is the hydraulic head in m; w is the volumetric flux per unit volume and represents sources and/or sinks of water in m^3/day; S_s denotes the specific storage of the porous material per m; and t is time in days.

3.3.1 Conceptualisation

To create a conceptual model of the tract, data on the lithology of the aquifer (i.e., structural contours, bore logs, aquifer properties), piezometer levels, climatic data, aquifer abstractions, canal data, canal network, and their L-sections were collected. Principal aquifers of sand beds, separated by clay beds at various depths, characterise the lithological heterogeneity in the area. Unconsolidated alluvium of the tract was accounted with beds of gravel and cemented sand in multiple locations (Marok et al. 2000). Phreatic and confined aquifer conditions in the alluvial material comprised of sand, silt, clay and kankar formulate the medium for groundwater storage. The aquifer properties such as hydraulic conductivity and specific yield were estimated indirectly from the logs of 500 wells scattered across the tract (Figure3) using the following analytic descriptions provided by Todd (1980) via Equations 2 and 3:

$$\mathrm{K_h} = \frac{\sum \mathrm{K}_{hi} \times \mathrm{d}_i}{\sum d_i} \qquad \text{Eq. (2)}$$

$$S_y = \frac{\sum S_{yi} \times d_i}{\sum d_i} \qquad \text{Eq. (3)}$$

where,

K_h = hydraulic conductivity,

S_y = specific yield,

K_{hi} = hydraulic conductivity of the layer,

S_{yi} = specific yield of the layer,

d_i = depth of the layer.

The calculated hydraulic conductivity and specific yield were subsequently optimised using the PEST automated nonlinear parameter estimator (Doherty, 2016). Primary time series data describing the water level of more than 200 observation points for the Sirhind Canal Tract for the pre-monsoon period (i.e., June) was collected from the Department of Agriculture and Water Resources and Environment Directorate, Punjab. The data was used to calculate the hydraulic heads of the tract to calibrate and validate the model.

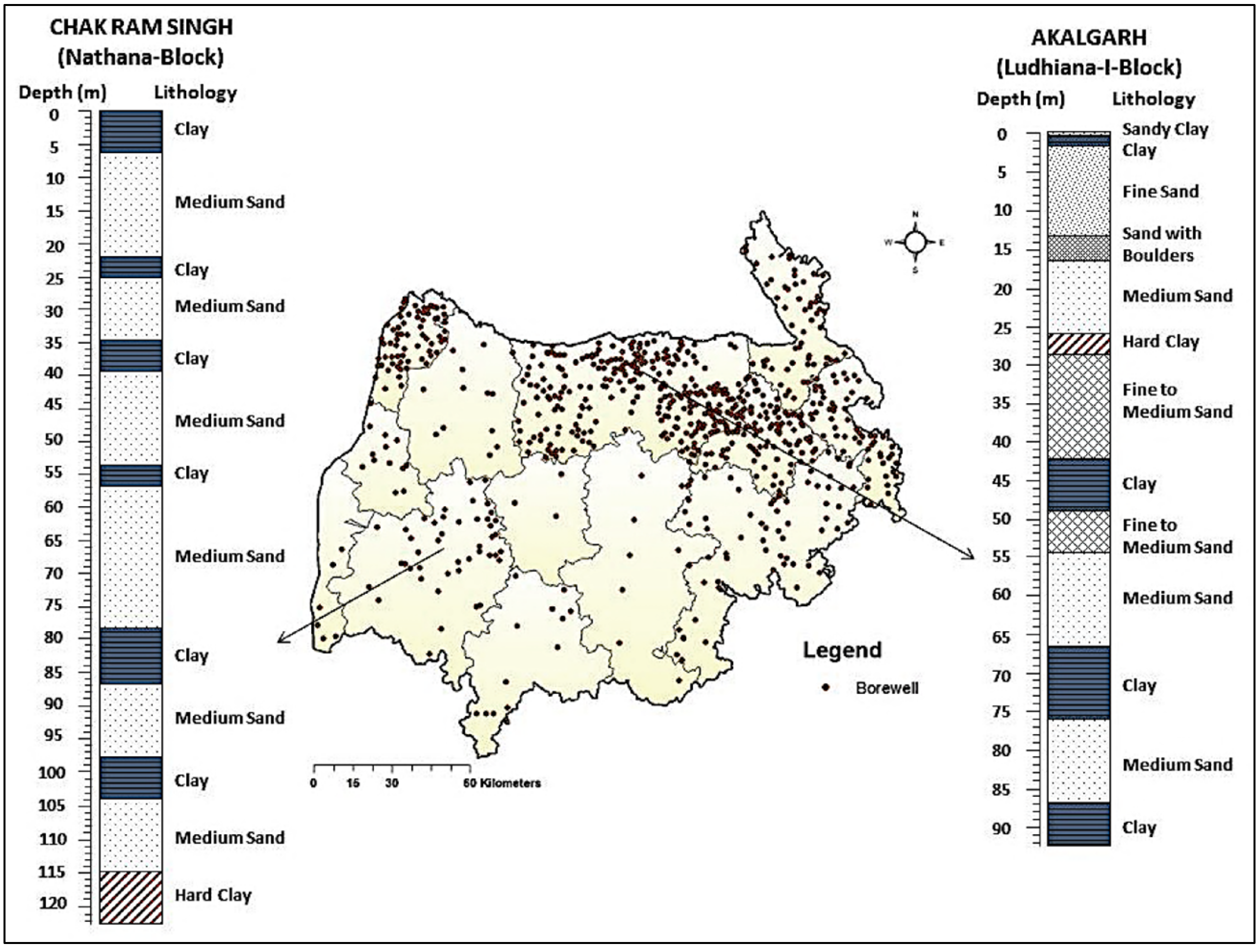

Figure 3. Location and lithological description of observation points [based on data retrieved from the Punjab Remote Sensing Centre, Ludhiana].

3.3.2 Discretisation

Regionally, the aquifer behaves like a water-table aquifer and extends approximately 220 km in length and 220 km in breadth (north-south orientation). After the conceptual model was developed, the area was discretised into 21 rows and 23 columns with a constant grid spacing of 10×10 km, considering an unconfined aquifer up to a depth of 300 m, resulting in a total of 483 discretised cells (Figure 4). The digital map of the area was imported in MODFLOW to represent the real-world location of the study area.

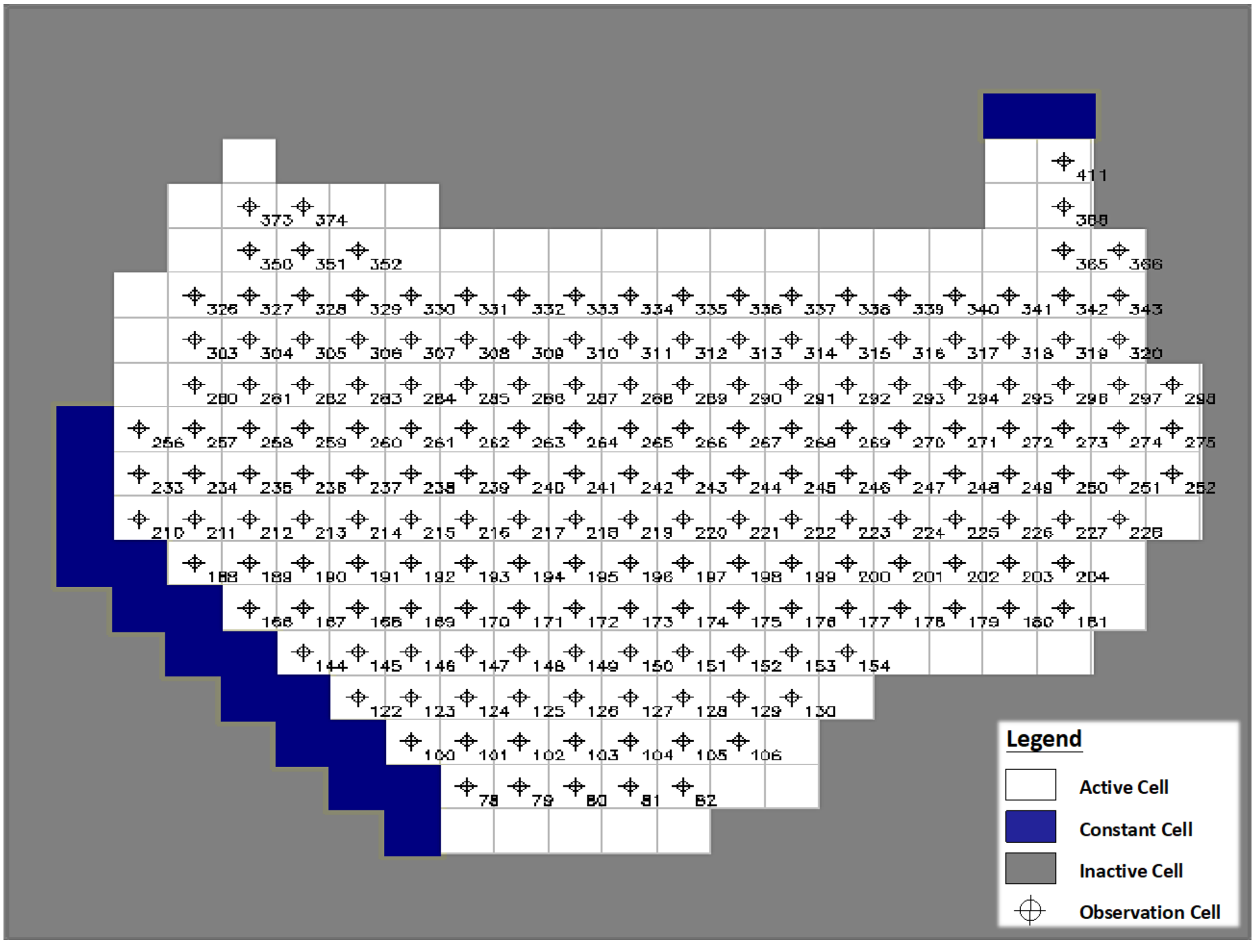

Figure 4. Discretisation of the Sirhind Canal Tract using MODFLOW.

3.3.3 Boundary conditions demarcation

Hydrologically, the Shivalik foothills delimit the tract towards east and north-east, the Ghaggar River flows in the southern boundary, the Bhakra Main Line canal courses towards the south-west and the Rajasthan feeder streams in the west. However, based on historical annual groundwater level fluctuations, the cells lying southwest of the tract were considered constant head cells, i.e., the storage term was not considered, and the head specified in the beginning was kept constant throughout the simulation. 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 flux from/to individual boundary cells was computed using Darcy's law. The cells lying outside the boundaries of the study area were considered inactive or no flow cells meaning that no inflow/outflow of the cell was permitted in any time step of the simulation. Out of the total 483 discretised cells for the model, 226 were marked as active cells, 18 as constant head cells, and 236 as dormant cells. The study area was simulated using 188 cells (observation cells) out of 226 active cells. The model was run in a transient state to simulate the annual changes in groundwater levels. A stress period of 365 days was selected to simulate the annual effects of recharge and draft on the groundwater system. The temporal parameters, i.e., recharge and draft, were simulated using well and recharge flow packages for each discretised cell.

3.3.4 Groundwater draft and recharge estimation

The number of tubewells in each block (smallest administrative unit) was multiplied with their values of unit draft to calculate the groundwater pumped during the period from 1998-1999 to 2017-2018 (Ministry of Water Resources, 2017). However, the computed draft was increased or decreased by 10% while considering the variability of rainfall as ±19% or more compared to average rainfall during wet/dry years. The total groundwater recharge for the tract, during 1998-2018, was estimated using Equation 4:

$$\mathrm{R_g} = \mathrm{R_r} + \mathrm{R_c} + \mathrm{R_{cia}} + \mathrm{R_{tia}} - \mathrm{E_t} \qquad \text{Eq. (4)}$$

where,

R_g = total groundwater recharge (mm),

R_r = recharge to groundwater from percolation of rainfall (mm),

R_c = recharge to groundwater 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 tubewell 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 the net recharge was evaluated via using Equation 5:

$$\mathrm{R_t} = \mathrm{R_g} - \mathrm{Q_p} \pm \mathrm{Q_g} \qquad \text{Eq. (5)}$$

where,

Q_g = groundwater inflow/outflow to/from the area from/to the neighbouring areas (mm),

Q_p = groundwater abstraction (mm).

Due to the negligibility of shallow water tables in the study area, the evaporation was considered to be insignificant. As per recommended norms by the Ministry of Water Resources (2017), the recharge from rainfall (R_r) was considered 25% of the total rainfall. Also, no recharge was assumed in case monthly rainfall collected in the region was accounted for less than 50 mm (Ministry of Water Resources, 2017). The seepage from the canal network (R_c) for the unlined canal was taken as 18 ha-m/day/106 m^2. Seepage losses were assumed to be 20% of the aforementioned value for the lined canals. Although an extended webbed canal system characterises the region, only 263 mm (around 27%) of 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. In contrast, 35% of the water delivered at the outlet was considered recharge for the paddy area. Similarly, the return flow from tubewell irrigated areas was considered to be 25% from non-paddy fields and 35% from paddy fields.

3.4 Model Calibration and Validation

Long term data is fundamental for the accurate calibration of a groundwater model (Kaur et al. 2015). In particular, the model in this research was calibrated with data for the period 1998-2013; the hydraulic heads predicted by the model were matched with the historic field-measured values by adjusting aquifer parameters within plausible ranges. Thereafter, the calibrated flow model was validated for the period 2013-2018. The degree of fit between model simulations and field measurements was quantified by using the Mean Error (ME) and the Root Mean Square Error (RMSE) given by Equation 6 and Equation 7, respectively:

$$\mathrm{ME} = \frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{h}_o - \mathrm{h}_s) \qquad \text{Eq. (6)}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}(\mathrm{h}_o - \mathrm{h}_s)} \qquad \text{Eq. (7)}$$

where,

h_o = observed hydraulic head,

h_s = simulated hydraulic head,

n = number of observed years.

3.5 Simulation of Groundwater Management Strategies, Energy Requirements and Carbon Emissions

The validated model was then used to predict future groundwater levels by 2025 and 2030. Specifically, four different pumping scenarios were examined in combination with three irrigation conditions (Table 2), resulting in a total of twelve alternative groundwater management strategies (i.e., “Irrigation Condition – Pumping Scenario” combinations).

Table 2. Groundwater management strategies.

[Table 2 about here]

There are 42 STP plants geographically scattered across the Sirhind Canal Tract (Figure 2) which can be used to provide treated wastewater for irrigation (Punjab Pollution Control Board,2017). The wastewater treatment capacity of these operating STPs, which can be exploited for irrigation usage, is tabulated in Table A1 in Appendix I. Acceleration of industrialisation and urbanisation has increased the urban sewage discharge rates at an annual rate of 5%. However, the current capacity for sewage treatment is relatively low (Yang et al. 2017). Notably, the total STPs’ wastewater treatment capacity in the study area is considerably less compared to the potential wastewater generated from the 66 blocks of the area (Table A2 in Appendix I). Although certain progress has been made regarding the exploitation of existing sewage treatment facilities, their geographical dispersion is a challenge (Cheng et al. 2020). To that end, new STPs need to be constructed to address the volumetric gap in wastewater treatment capacity.

While computing groundwater levels under irrigation conditions B and C incorporated wastewater augmentation, groundwater abstraction was reduced from the corresponding cells receiving additional irrigation water. Management of water resources was anticipated by comparing the predicted groundwater levels of the twelve strategies formulated for this research. The groundwater levels projected under the different irrigation conditions and pumping scenarios were finally analysed to determine comprehensive policy-making recommendations for the environmentally sustainable management of the groundwater table in the study area by the year 2030.

Rural electrification reflects upon the fact that the energised tubewells have increased from 0.19 million in 1970 to 1.47 million in 2017 (ESOPB 2020, p.162). Therefore, the depletion of groundwater level directly and indirectly impacts energy, cost, and carbon emissions. Kaur et al. (2016) discussed that a decline in groundwater level by 5.47 m (1998-2012) increased energy requirements by 67% and carbon emissions by 110%. In addition, Dhillon et al. (2018) estimated an energy requirement of 7,919.60 mega kilowatt-hours (MkW-h) for groundwater pumping in central Punjab, resulting in 1,349.6 thousand tons of carbon emissions. In the same vein, the energy requirements and CO_2 emissions were estimated for the tract under the investigated management strategies.

4. Results and Discussion

The groundwater simulation model generated interesting results. The following subsections present the modelling calibration and validation results while discussing the analysis output per investigated management strategy.

4.1 Calibration and Validation

The groundwater model reasonably simulated the significant spatial and temporal variation (due to changes in recharge and draft) in the magnitude of hydraulic heads (Figure 5). The results of the calibrated model, presented in Figure 6, demonstrate a good fit between the simulated hydraulic heads and the real-world observations. Due to the heterogeneous topography and lithology of the region, the calibrated hydraulic conductivity was found to range from 1 m/day to 100 m/day, whereas the specific yield varied from 0.02 to 0.2. The average difference between the observed and the simulated water levels for most internal nodes varied between 0 and 0.75 m. Furthermore, the calculated average ME was 0.227during calibration and 0.341 during validation, while the average RMSE was calculated 0.470 during calibration and 0.662 during the validation period. All the calibration and validation results for the Sirhind Canal Tract are considered reasonable and within an acceptable range. For deviations within these limits, the performance of a groundwater model can be regarded as satisfactory (Toews and Allen, 2009).

The calculated groundwater abstraction in the tract for 2018 was 27.30 billion m^3, and the total recharge was 13.80 billion m^3. Notably, groundwater abstraction in 2018 was higher by 77% compared to 1998 due to an increase in the number of tubewells. Net recharge function of rainfall, irrigation and groundwater storage and abstraction ranged from -60.00 to +32.40 cm in different years with an average of -10.30 cm.

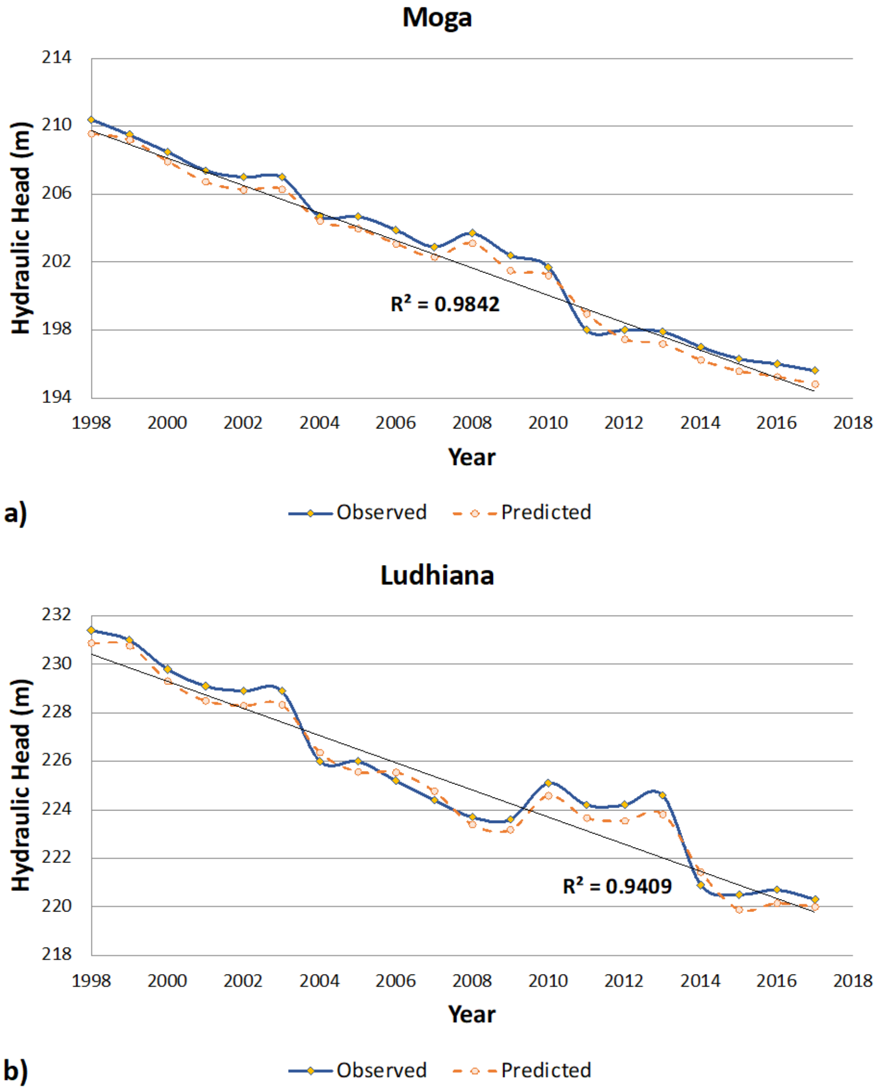

Figure 5. Comparison between observed and predicted hydraulic heads at the Districts of Moga and Ludhiana at the Sirhind Canal Tract, as part of the model calibration process.

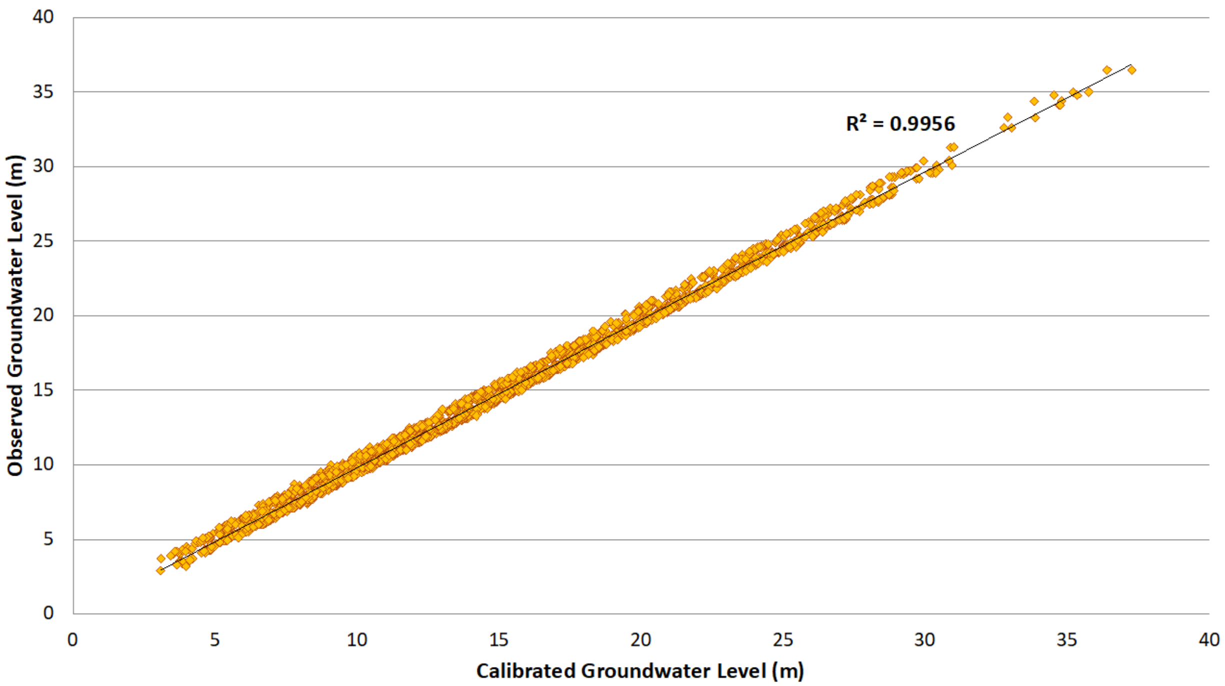

Figure 6. Measured and calibrated groundwater levels at the Sirhind Canal Tract.

4.2 Simulation

The water table at the Sirhind Canal Tract, observed to be 23.20 m in 2018, was simulated for the years 2025 and 2030 under three irrigation conditions, namely: (i) normal irrigation without any augmentation; (ii) augmentation of irrigation with treated wastewater from existing STPs; and (iii) augmentation of irrigation with potentially treated wastewater. The research findings in terms of projected groundwater level under the considered pumping scenarios and irrigation conditions are summarised in Figure 7 and exemplified below.

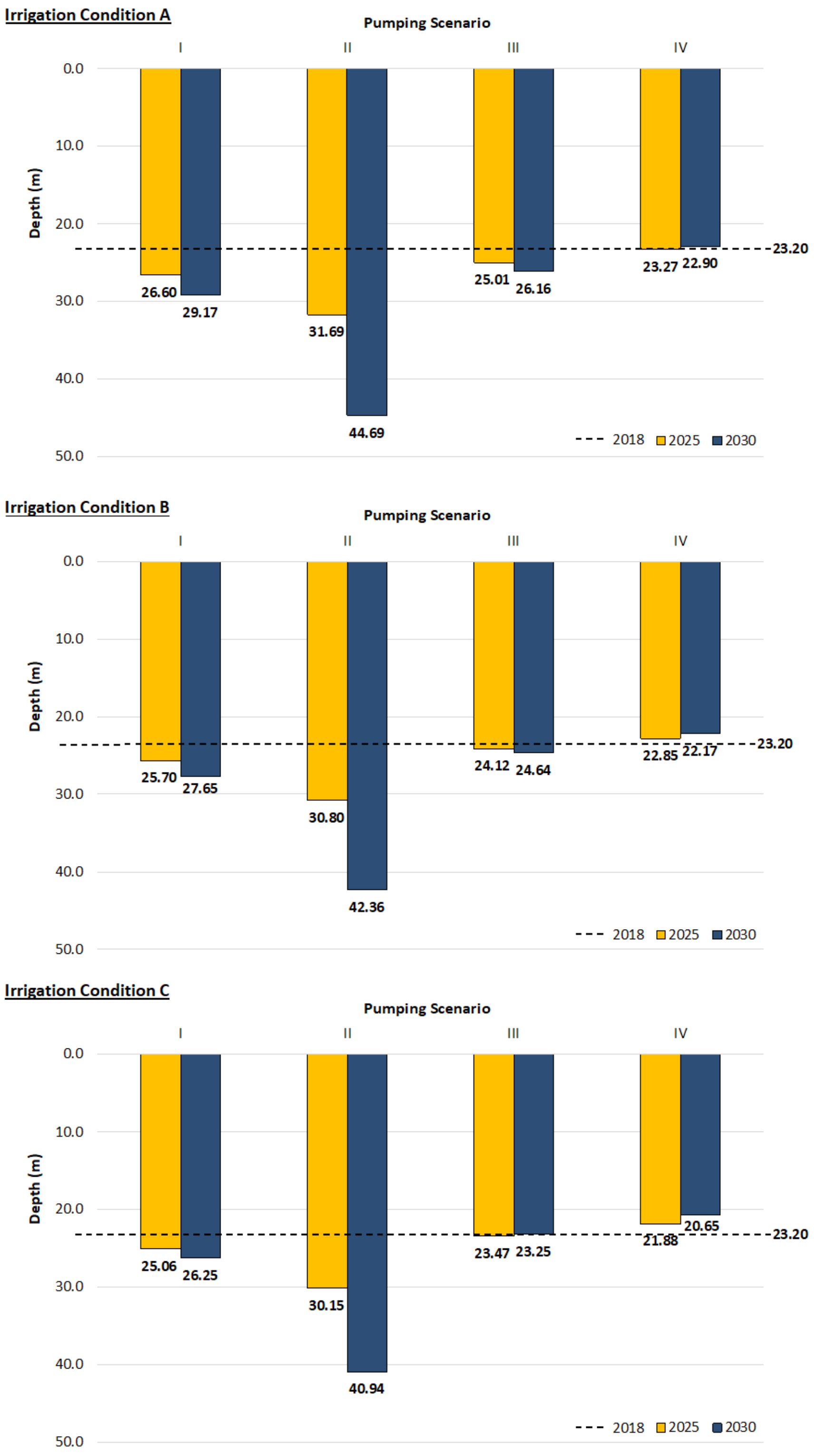

Figure 7. Projected groundwater levels under alternative pumping scenarios and irrigation conditions.

4.2.1 Irrigation Condition A: Normal irrigation without any augmentation

In the normal irrigation condition, groundwater levels are expected to fall by 3.40 m and 5.96 m in 2025 and 2030, respectively, under Scenario I. Furthermore, because tubewell density has been increasing in the region, the future groundwater abstraction of 33.2 billion m^3 in 2025 and 34.9 billion m^3in 2030 under Scenario II will increase to 32.60 billion m^3 and 34.20 billion $m^3$by the years 2025 and 2030, respectively, causing the water table to decline by 8.49 min 2025 and 21.49 m in 2030. In a similar scenario by Shakoor et al. (2018), depletion of 14.00 m in groundwater level was reported for the District of Bhawana in Punjab, Pakistan. In Scenario III, with increased canal water supplies, the predicted fall in groundwater level would be 2.95m by 2030. In Scenario IV, where groundwater abstraction is proportionally reduced, demand for irrigation water is being compensated by additional canal water supplies; thus, it is predicted to make groundwater table rise by 0.30 m in 2030.

4.2.2 Irrigation Condition B: Augmentation of irrigation with treated wastewater from existing Sewage Treatment Plants

In irrigation Condition B, the groundwater level under Scenario I is projected to fall by 2.50 m in 2025 and 4.44 m in 2030. The fall in the water table estimated for the management strategy “Condition B – Scenario I” is 3.37% and 5.19% less than the water table expected to fall by 2025 and 2030, respectively, under “Condition A – Scenario I”. Although the tubewell density is considered to increase in Scenario II, the augmentation with treated wastewater from STPs would decrease the groundwater abstraction approximately by

5.17%, and the water table is expected to fall by 2.82% in 2025 and 5.22% in 2030 compared to the water levels estimated in strategy “Condition A – Scenario II”. In Scenario III of surplus canal water supply along with no additional tubewell drilling, the water table would experience a fall of 0.92 m in 2020, resulting in an improvement of groundwater levels until 2030. Under pumping Scenario IV, reduced groundwater abstraction, additional canal water supply and wastewater augmentation from existing STPs would produce a rise in the groundwater levels by 1.51% in 2025 and 4.43% in 2030 compared to the reference value of 23.20 m observed in the year 2018. Moreover, the estimated levels are 1.80% and 3.18% higher than the levels estimated under strategy “Condition A – Scenario IV” by 2025 and 2030, respectively.

4.2.3 Irrigation Condition C: Augmentation of irrigation with potentially treated wastewater

The results estimated under irrigation Condition C could be regarded as the promising groundwater levels produced by exploiting wastewater along with diverse pumpage and canal water utilisation. Notably, in Condition C, the water table level would fall by 1.85 m in 2025 and 3.05 m in 2030 under the pumping Scenario I. These levels obtained in the management strategy “Condition C – Scenario I” are 5.80% and 9.99% higher than the levels estimated for the years 2025 and 2030, respectively, during the strategy “Condition A – Scenario I”. Under Scenario II, groundwater abstraction of 30.72 billion m^3 in 2025 and 32.3 billion m^3in 2030 would cause the water table to rise by 4.87% and 8.39% by 2025 and 2030, respectively, compared to the predicted values under management strategy “Condition A – Scenario II”. Furthermore, in Scenario III, the water table after possible augmentation of wastewater would fall by only 1.16% in 2025 and 0.29% in 2030 from the reference water table in 2018, which is 6.14% and 11.12% higher than the groundwater levels predicted for the years 2025 and 2030, respectively, under the management strategy "Condition A – Scenario III". In pumping Scenario IV, potential wastewater augmentation along with increased canal water supplies and decreased groundwater abstraction could cause the water table to rise by 5.67% and 10.97% by 2025 and 2030, respectively, compared to the water table depth of 23.20 m calculated for the year 2018. These results are5.95% and 9.80% higher than predicted levels for 2025 and 2030, respectively, under the management strategy "Condition A – Scenario IV".

4.3 Groundwater Levels under Alternative Management Strategies

A comparison across pumping scenarios and irrigation conditions indicates that it is feasible to completely reverse the falling groundwater trend by 2030 in Scenario IV (Figure 8). Indeed, incorporation of all the strategies (i.e., enhanced canal water supplies, decreased groundwater abstraction and potential wastewater augmentation with irrigation under condition "Condition C – Scenario IV") could uplift the groundwater level at 20.7 m in 2030, which is 10.97% higher than the level at 23.20 m predicted for the year 2018. In Scenario II, which can be considered the worst-case scenario, none of the proposed management strategies will be effective for environmentally sustainable groundwater management. Augmentation of irrigation supplies with treated wastewater from existing STPs (i.e., Condition B) seems to be a realistic option and could ensure an improvement in the groundwater levels in the year 2030 by 5.19%, 5.22%, 5.80% and 3.18% under pumping

Scenarios I, II, III and IV, of the management strategy “Condition A”. Additionally, in case all wastewater generated in future is treated (i.e., Condition C), groundwater levels are expected to improve by 9.99%, 8.39%, 11.12% and 9.80% in 2030 under pumping Scenarios I, II, III and IV, compared to the management strategy “Condition A” (Figure 8).

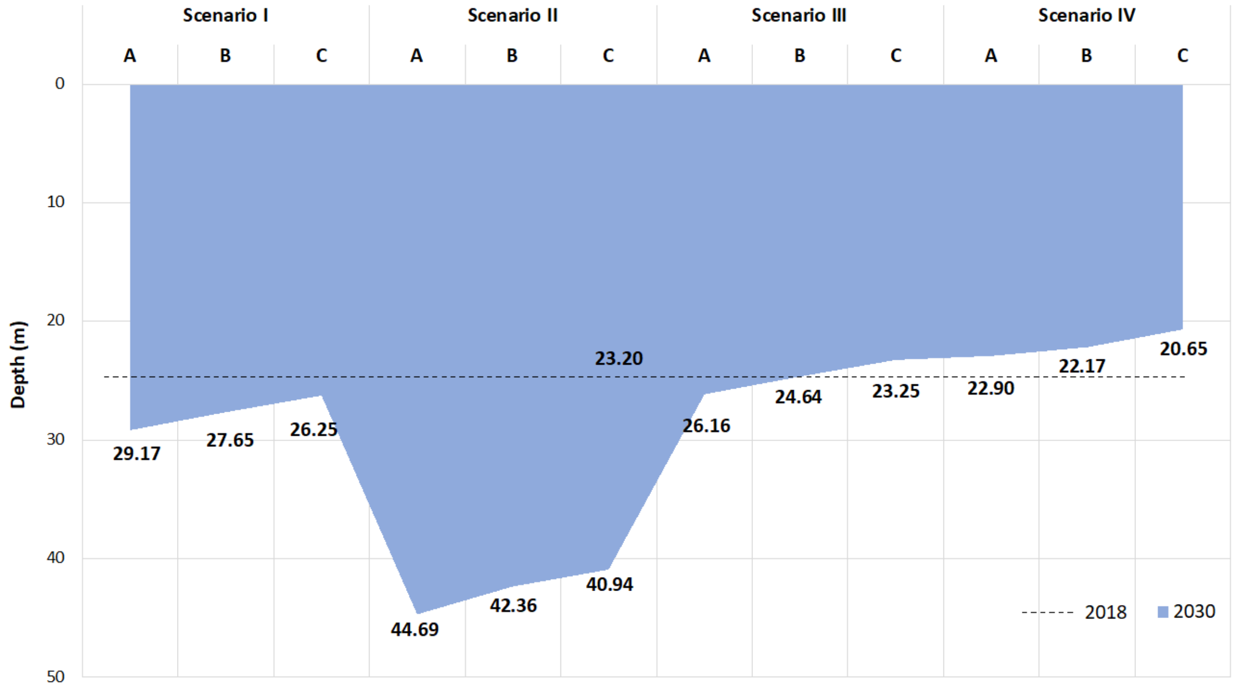

Figure 8. Comparison of expected groundwater levels in 2030 under the investigated management strategies.

4.4 Energy Requirements and Carbon Emissions

Groundwater pumping in Punjab interacts with energy consumption, thus dictating the need to include energy in relevant studies to promote integrated resources management and policy coherence (Wichelns, 2017). In this regard, the energy requirements and CO_2

emissions estimated for the tract under the different investigated management strategies are summarised in Table 3.

Table 3. Energy requirements and CO_2 emissions under the investigated groundwater management strategies.

[Table 3 about here]

In this research, it was estimated that 5,945.1 MkW-h of energy is required to pump 27.3 billion m^3 of groundwater which resulted in 1,507.9 thousand tons of CO_2 emissions in the year 2018 for the Sirhind Canal Tract. During the simulation of the alternative management strategies, it was found that the energy requirement vis-a-vis CO_2 emissions would be the highest (i.e., 2,825.7 thousand tons) under the strategy “Condition A – Scenario II”. The carbon emissions estimated for the tract during the other strategies would vary by 11-17% from the highest emissions strategy.

5. Conclusions

The increased reliance of farmers in the Indian Punjab on groundwater supplies for irrigation purposes has been the major cause of groundwater decline in the Sirhind Canal Tract. Nearly 99% of the State’s net agricultural area is sown under irrigation, while surface water resources accommodate only 28% of the total irrigation needs and the balance abstracted through tubewells (ESOPB 2020, p.157). This research highlights the importance of groundwater models for predicting groundwater levels under alternative management scenarios. Overall, the findings of this research indicate that new tubewells for farm irrigation purposes should be avoided and surface water exploitation promoted.

5.1 Academic Contributions

This study contributes to the extant body of literature by investigating alternative irrigation, distribution and abstraction strategies through validated simulation models using both primary and secondary datasets. This is one of the first studies in the Punjab region that confirms the severity of current and projected groundwater levels with quantified analysis of the Sirhind Canal Tract in terms of potential mitigation through alternative irrigation, distribution, and abstraction strategies. Specifically, the Sirhind Canal Tract MODFLOW simulation model suggests that canal water supplies could be beneficial to reverse groundwater level decline and help increase the water level by 11% above that in the year 2018. Furthermore, the usage of treated wastewater in irrigation and the different groundwater pumping scenarios provides promising scenarios that reverse recent declines in groundwater water resources in the tract. In addition, in terms of energy consumption involved in tubewell abstraction, the suggested alternative approaches would reduce water abstraction leading to reduced CO_2 emissions of approximately a million ton by 2030. The originality of this research lies in the integration of primary and secondary data over an extensive geography highly exposed to overexploitation, the strength of model validation, the generation of quantified alternative groundwater management strategies and the consequent Environmental, Social and Governance (ESG) impact.

5.2 Policy-making Implications

The simulation modelling investigation successfully captured the spatial and temporal groundwater behaviour, and the analysis of the results focused on the decrease in groundwater abstractions. Specifically, the developed MODFLOW model was applied to predict future groundwater levels by 2030 under twelve management strategies. The research findings can help articulate recommendations to inform pertinent policy-making decisions based on investigating the impact of alternative instruments, as proposed in the literature (Moors et al. 2011).

Firstly, as per the historical trend of groundwater abstraction, the model's findings suggest a steep decline of 21.49 m in groundwater level by 2030. During any examined irrigation conditions, an increase in the number of tubewell scan results in a higher water table fall. Even in case the existing tubewells are allowed to continue operating with prohibitions on developing new tubewells, the State will be facing a decline of 5.96 m in 2030, which is still not considered a sustainable pumping scenario.

Secondly, the findings further suggest that an increase of 10% in canal water supplies can prove beneficial to reverse groundwater level decline. The canal water available in Punjab can be easily exploited to irrigate 3.08 million ha, out of the total 4.29 million ha of the State's land area. This is rational in a way that the canal irrigated area has been reduced by 10% (see Appendix II).

Thirdly, in alignment with policy findings from Vijet al. (2021), this research argues that the many STPs which exist in the vicinity of cities/towns for providing environmentally safe sewage water can augment substantial portions of irrigation water supplies. Substantiating the irrigation water supplies with treated wastewater from existing STPs reduces the surplus groundwater abstraction by 3-4%, which can be further enhanced up to 7-11% by potentially treating the entire volume of wastewater generated in the region. This would prove beneficial to restore the groundwater level by 10.97%. Moreover, deficit groundwater abstraction and surplus wastewater augmentation and canal water supplies under "Condition C-Scenario IV" will reduce energy demand and lead to reduced CO_2 emissions of approximately 966.6 thousand tons by 2030.

5.3 Limitations and Future Research

This modelling research should be considered as a first step to quantify the environmental sustainability of groundwater resources via leveraging surface water and reuse options. In the study, it is assumed that canal water supplies may increase in the future; however, the decline in area under canal irrigation could decrease the water flow in the rivers. This needs to be scientifically assessed if there is a decrease in the river water flow and can be crucial material evidence for Punjab's case in the river water dispute pending in the Supreme Court (Singh 2018) and accordingly, share allocations to neighbouring states may be proportionately reduced. The analysis focuses exclusively on groundwater quantity issues without considering the groundwater quality component due to a lack of timeseries data. Also, certain aspects like reduced crop water demand through crop diversification, improved field water use efficiency as in direct-seeded rice and micro-irrigation techniques, and managed aquifer recharge programmes, which significantly impact groundwater allocation for irrigation and recharge, were not considered in this study. Including such parameters provides research avenues for future studies to guide an integrated groundwater policy-making agenda in the region. Incorporation of groundwater modelling to end-to-end food supply networks that consider the water footprint of products could further provide a more comprehensive view of the sustainability impact of both upstream and downstream operations (Aivazidou et al., 2018). Such a comprehensive systems view could further inform governance decisions for ensuring equitable groundwater extraction in support of marginalised and small farmers (Hoogesteger and Wester, 2015).

The number of installed tubewells provided a reasonable estimation of groundwater use for agricultural purposes. The model was able to effectively capture the annual trends of groundwater levels, which can be utilised for a broader policy formulation. However, this method does not adequately address domestic and industrial groundwater usage. Improved data availability (through mass monitoring and telemetry systems) would allow modelling at a more granular spatial and temporal resolution to give insights into the groundwater flow and recharge processes.

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Appendix I

Table A1. Wastewater treatment capacity of Sewage Treatment Plants located across the Sirhind Canal Tract [Source: Punjab Pollution Control Board (2017)].

[Table A1 about here]

Table A2. Wastewater generation in the Sirhind Canal Tract [*Source*: Punjab Pollution Control Board (2017)].

[Table A2 about here]

Appendix II

Table A3. Canal irrigated area in Punjab.

Area	**Canal irrigated area (‘000 hectare)**			**Remarks**
	1970	**1990**	**2018**	
• **Bist Doab** (Hoshairpur, Kapurthala, Jalandhar, Nawanshaher)	40	53	4	Decreased by 36 thousand hectares
• **Eastern Malwa** (Ropar, SAS Nagar)	2	2	7	Increased by 5 thousand hectares
• **Central Malwa** (Ludhiana, Barnala, Sangrur, Patiala, Fatehgarh Sahib)	224	186	138	Decreased by 86 thousand hectares (40%)
• **South-Western Malwa** (Ferozepur, Moga, Fardikot, Muktsar, Bhatinda, Mansa)	786	975	976	Increased by 190 thousand hectares (25%)
• **Upper Bari Doab** (Gurdaspur Amritsar, TarnTaran)	249	276	51	Decreased by 198 thousand hectares (80%)
• **Punjab State**	**1,301**	**1,492**	**1,176**	Decreased by 125 thousand hectares (10%)

The share of reduction in canal irrigated area is highest in Central Malwa (~23%) of which Sirhind Canal Tract is a part. On the contrary, the canal water supplies have increased in southwestern districts. This has led to water-logging issues in the south-western region as farmers avoid utilizing groundwater for irrigation, owing to its poor quality. In the central region, farmers have become highly dependent on groundwater, and many of the canal water courses are no longer in use or have disappeared. The canals and distributaries in the region have merely become conveyance canal to transport water from Bhakra dam to southwestern districts and neighbouring states. In an article by Singh (2018), out of the total 14.54 MAF of allocated river water, Punjab is using eight MAF less water, while the share to the neighbouring states has remained constant. Also, due to a lack of repair and maintenance, the carrying capacity of the canal network has decreased over time. A decline in the area under canal irrigation could reduce the water flow in the rivers. A concrete canal water redistribution policy and concentrated efforts to repair the network and restore field distributaries can significantly sustain the declining groundwater table. The recent findings by Kaur (2019) for the region point towards increasing rainfall trends by 2050 under Representative Concentrated Pathways 4.5, which may also contribute to the increase in canal water supplies.