Charles Sturt University

Gulbali Institute
Agriculture Water Environment

Modelling Climate Change Impacts and Adaptation Strategies for Managing Groundwater Resources in Southern Punjab

Abdul Raheem, Muhammad Saifullah, Jehangir F. Punthakey, Ghulam Zakir-Hassan, Irfan Ahmad Baig

Modelling Climate Change Impacts and Adaptation Strategies for Managing Groundwater Resources in Southern Punjab

Abdul Raheem, Muhammad Saifullah, Jehangir F. Punthakey, Ghulam Zakir-Hassan, Irfan Ahmad Baig

Research commissioned by the Australian Centre for International Agricultural Research (ACIAR)

Cataloguing in Publication provided by the Gulbali Institute – Charles Sturt University, Albury, NSW 2640.

Raheem, A., Saifullah, M., Punthakey, J. F., Zakir-Hassan, G., Baig, I. A. (2024). Modelling Climate Change Impacts and Adaptation Strategies for Managing Groundwater Resources in Southern Punjab. Gulbali Institute, Charles Sturt University, Albury, NSW.

1 volume, Gulbali Institute Report No. 5

ISBN: 978-1-86-467458-3

Project	Adapting to Salinity in the Southern Basin (ASSIB)
Funding Research Program Project No.	Australian Centre for International Agriculture Research, Australia Land and Water Resources (LWR) LWR-2017-027
Project Team	Charles Sturt University (CSU) Commonwealth Scientific Industrial and Research Organisation (CSIRO) Ecoseal International Center for Biosaline Agriculture (ICBA) International Union for Conservation of Nature, Pakistan (IUCN) Mehran University of Engineering & Technology (MUET) MNS University of Agriculture, Multan (MNSUAM) Murdoch University Society of Facilitators and Trainers (SOFT) University of Canberra

Disclaimer

The views expressed in this report are solely the authors, and do not necessarily reflect the views of Charles Sturt University or any other individual or organisation consulted or involved in the research.

Acknowledgements

We are grateful to Dr Muhammad Riaz, Punjab Irrigation Department, for his constant support for the Adapting to Salinity in the Southern Indus Basin (ASSIB) project and for providing the flow, head gauge, groundwater level, and quality data used for groundwater development. We also acknowledge the efforts of Mansoor Ahmed Jiskani from Sindh University for providing valuable projected rainfall and temperature data that were used for climate change scenario modelling. We thank Dr Yingying Yu for rainfall datasets, and Dr Mobin-ud-Din Ahmad and Dr Peña-Arancibia from CSIRO, and Dr Mobushir Riaz Khan from Charles Strut University (CSU) for providing the evapotranspiration data used in the model development. We extend our sincere gratitude to Mark Filmer (CSU) for his exceptional professional editing of the groundwater modelling and monitoring reports. We are also thankful to the many staff of the Muhammad Nawaz Shareef University of Agriculture and Charles Sturt University for their constant support of this research project. We also gratefully acknowledge the funding support from the ACIAR and Charles Sturt University for the Adapting to Salinity in the Southern Indus Basin (ASSIB) project. The ASSIB project aims to develop and investigate adaptation options and strategies with people managing and living in salinity affected agricultural landscapes in the Southern Indus Basin. This project is being led by Charles Sturt University (CSU) and key national partners Mehran University of Engineering and Technology (MUET), Muhammad Nawaz Sharif University of Agriculture Multan (MNSUAM), in collaboration with the University of Canberra and Murdoch University in Australia, CSIRO, the International Union for the Conservation of Nature (IUCN, Pakistan), the Society of Facilitators and Trainers (SOFT, Pakistan) and the International Center for Bio-saline Agriculture (ICBA, UAE). This study covers the extensive modelling of the groundwater systems of the Southern Bari Doab Canal Command, Pakistan and its contribution to the ASSIB project in understanding groundwater and salinity dynamics under a changing climate regime in the Southern Indus Basin and simulation of feasible adaptation options.

Executive Summary

Irrigated agriculture has been important in enhancing Pakistan's food security and economic sustainability. Agricultural water requirement is increasing to meet the demand for food and fibre as Pakistan's population increases and the industrial sector expands. While surface water irrigation remains pivotal in agricultural production, in recent decades, the share of irrigation from groundwater has increased exponentially in all four provinces, i.e., Balochistan, Khyber Pakhtunkhwa (KPK), Punjab, and in the freshwater zones of Sindh. Pakistan's irrigation system, which was initially designed for a cropping intensity of 67%, is now experiencing cropping intensities above 150% and up to 180% in some areas (Khaliq et al., 2019). Moreover, surface water scarcity in the lower reaches due to seepage losses in the upper reaches and inequity in canal water supplies due to variability in river water flows have forced farmers to shift their demand towards groundwater. Climatic changes have exacerbated the situation. Because of the increase in groundwater pumping, groundwater levels are declining in Southern Punjab. Significant declines have been observed in Lodhran, Jahanian, and Duniapur tehsils, where groundwater levels have decreased consistently over the past decade (Zakir-Hassan et al., 2022).

Little attention has been paid to the increasing use of groundwater as it is an unregulated resource, and it has been one of the least understood challenges in Pakistan in recent years. Interestingly, Pakistan is facing the menace of waterlogging in some areas, particularly in the lower riparian area of Sindh, as well as overexploitation of groundwater. Groundwater modelling is one of the main techniques being used globally that allows resource managers to test different management strategies and simulate scenarios to understand different stresses, including climate change impacts on an aquifer system.

The groundwater model presented in this report was developed in collaboration with the Punjab Irrigation Department (PID) for Southern Bari Doab in Punjab, which is part of the Southern Indus Basin. Four major districts, Multan, Khanewal, Vehari, and Lodhran, cover an area of 11,348 km2. Three major irrigation canals, Sidhnai/Pakpattan Lower, Mailsi, and the Sidhnai Mailsi Link Canal, as well as several branch canals, are part of the irrigation network in the area.

To evaluate the spatio-temporal impact of different hydrological components on groundwater levels in the study area, a regional groundwater model (MODFLOW) was developed. Different hydrogeological factors, such as seepage from rivers and canals, recharge from rainfall and field application losses, evapotranspiration, groundwater pumping, and aquifer lithology were incorporated to evaluate the groundwater dynamics of the aquifer.

The groundwater model was developed for ten years from October 2010 to September 2020 for 120 monthly stress periods. It has three layers with thickness assigned as 30m, 95m and 180m for Layer 1, Layer 2, and Layer 3, respectively. The thickness of Layer 1 was based on the maximum depth to the watertable in the area, Layer 2 was based on the average maximum depth of bore logs in the area, and Layer 3 on the bedrock of the aquifer.

The water balance for the model indicates that the inflow from river and canal seepage is 1,637.3 MCM/yr, while the recharge from field application losses of surface supplies and pumping return flow was 1,485.8 MCM/yr, comprising 53% and 47% of the total inflow, respectively. Also, the average groundwater extraction calculated by the model is 3,355.5 MCM/yr, amounting to 92% of the total outflow from the model. This also indicates that attempts to limit canal seepage will accelerate the decline in groundwater levels since about 53% of groundwater is replenished by canal seepage. The net storage was found to be -533.4 MCM/yr, which is evidence of high pumping in the area.

The water balance of the three layers shows that groundwater inflows of 3,155.0 MCM/yr occur from Layer 1 to Layer 2, indicating a depletion of Layer 1 in response to pumping in Layer 2. The layer water balance indicates Layer 2 is replenished by downward flows from Layer 1 and by upward movement of 1,442.9 MCM/yr from Layer 3. This suggests that as water levels are depleted in the upper layer, many farmers will have to invest in deepening tubewells, which may result in using marginal quality water.

Given the above, we recommend various strategies for improving groundwater sustainability. One approach would be to regulate and set limits on groundwater extractions, but this would affect livelihoods and food security. Moreover, implementing and enforcing regulations would not be possible in the medium term. We recommend focusing on hotspots where groundwater declines are persistent and causing farmers to increase the depth of their wells and where pumping costs are increasing as groundwater levels decline. We also recommend a change in cropping pattern away from crops like rice, sugarcane and cotton that use a lot of water to so-called low delta crops like mung bean and onion, which use less water and are also suited to the agroclimatic conditions of Southern Punjab. To this end, we simulated a set of three adaptation options up to 2060. One simulation involved gradual substitution of high delta with low delta crops. Another simulated monsoon floods with a return period of 10 years, based on the flood event that occurred in the Chenab and Sutlej Rivers on August 25, 2013. The third option explored a strategy to mitigate the impacts of flash floods by establishing a green barrier of trees along the riverine corridor of the Chenab River. The combined impact of these three adaptation options resulted in net storage of -586.6 MCM as compared with the increased pumping scenario which indicated a net loss in storage of - 939.6 MCM annually. Although the implementation of these three options increased groundwater storage by about 353 MCM/yr, the resulting net storage loss indicates additional adaptation options will be required as impacts from climate change on agricultural water demand increases over this period.

Other improved land and water management strategies can also be implemented by providing an enabling environment for farmers to adopt and adapt to climate smart agricultural practices. In these areas, community facilitators can play a vital role in improving farmer knowledge of groundwater management as a shared resource leading to improved livelihood outcomes under Sustainable Development Goals (SDG 1.3, 2.4 and 6.4). From an institutional perspective, this study provides insights into the limits of groundwater extractions for different areas. This will allow resource managers and agricultural policy makers to develop policies that support the transition to a sustainable irrigation future in Southern Punjab. This model will provide a basis for institutional stakeholders to develop strategies to improve the management of groundwater resources for sustainable use.

Contents

Figures

Tables

Abbreviations

ACIAR	Australian Centre for International Agricultural Research
ADB	Asian Development Bank
AMSL	Above Mean Sea Level
BCM	Billion Cubic Metres
BL	Baseline (scenario)
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DTW	Depth to watertable
EC	Electrical conductivity (1 mS/cm= 1dS/m = 1000 µS/cm = 640 mg/l)
GDP	Gross Domestic Product
MAR	Managed Aquifer Recharge
MNSUAM	Muhammad Nawaz Sharif University of Agriculture, Multan
PID	Punjab Irrigation Department
PS	(Increased) pumping scenario
SDG	Sustainable Development Goal

1. Introduction

Agriculture plays a vital role in Pakistan's food security and economy, which supports a population of approximately 220 million. The agricultural sector contributes about 24% of the GDP and provides livelihood opportunities to around 40% of rural households (Iqbal et al., 2021). Pakistan is a land-rich but water-scarce country with occasional water surpluses during the monsoon season. Increasing agricultural water productivity is a primary concern in fulfilling the rapidly growing population's food and fibre requirements. In Pakistan, irrigated agriculture is predominantly practised in the Indus Basin. The Indus Basin's extensive agriculture is enabled by a sophisticated irrigation infrastructure dubbed the Indus Basin Irrigation System (IBIS). This is one of the largest irrigation systems in the world. The Indus River and its major tributaries, including the Jhelum, Chenab, Ravi, and Sutlej Rivers, provide water for this irrigation system. These rivers run through the provinces of Khyber Pakhtunkhwa, Punjab, Sindh, and Balochistan. According to the Indus River System Authority (IRSA), there was 92.5 MAF (114 BCM) of surface water available during 2021–2022. Comparing this to the average system consumption, which is usually 103.5 MAF (127 BCM), showed a reduction of 10.6%. Notably, the largest decrease was during 2018–2019, reaching 18.5% for total water availability and use (Hamza, 2023). The agriculture sector covers 30.5 million hectares; 47% of the total area, which is higher than the global average of 38%. Out of the total cultivable area (24.1 million hectares), 82% is irrigated, while 18% relies on rainfed agriculture (FAO, 2024). Irrigated agriculture is critical to Pakistan's economy because it uses 94% of available water, produces over 90% of agricultural produce, contributes US$22 billion annually to GDP, and generates 70% of export revenue. It also contributes significantly to employment in the textile and other industries.

Pakistan's climate is classified as arid to semi-arid. The surface water supplies are insufficient and unevenly distributed to meet the basin's irrigation water requirements, mainly due to their spatio-temporal variability. This inadequacy is being addressed through the use of groundwater. The massive freshwater withdrawal severely affects the viable use of groundwater for agriculture, domestic, and industrial purposes. The losses from the irrigation networks create a layer of freshwater of different thicknesses, which have formed on top of the deeper saline groundwater. Fresh groundwater depth is greatest near recharging sources and decreases with increasing distance from recharging sources (Ashraf et al., 2012). Pumping the groundwater from this type of aquifer becomes more complicated. In this case, the volume of water pumped is mainly governed by water quality concerns, as massive pumping results in the upconing of saline water (Saeed et al., 2003).

Despite the critical nature and complexity of groundwater, the country lacks a regulatory framework. Anyone can drill an unlimited number of wells at any depth, capacity, and pump an unlimited amount of water. Thus, well drilling depends entirely on the guidance of local drillers and the needs of farmers. This practice has resulted in groundwater depletion in both quantity and quality. The inadequate design and installation of tubewells results in secondary salinisation and increases the cost of installing and operating these wells (Ashraf et al., 2012).

Compared to the Upper Indus Plain, the Lower Indus Plain, especially Southern Punjab, faces various groundwater management challenges. The availability of fresh groundwater primarily depends on the Indus and Chanab Rivers, seepage from the vast canal network, and soil characteristics. The remaining areas have saline groundwater which limits groundwater exploitation. Additionally, the saline and sodic nature of soils creates significant difficulties in agricultural areas of Southern Punjab (Van Steenbergen et al., 2015).

In the Punjab province of Pakistan, irrigation with marginal quality groundwater is common when surface water supplies are insufficient. The lower and central portion of the Indus Basin has the most pre-eminent saline groundwater zones. Fresh groundwater lenses frequently overlie saline groundwater over large areas of Southern Punjab. Excessive aquifer withdrawals from the freshwater lenses results in transport of dissolved salts from the underlying saline groundwater which can significantly deteriorate the freshwater lens. The lateral intrusion of salt water into the fresh groundwater areas and the vertical upconing of the saline interface are causing aquifer degradation. This nearly irreversible process requires special attention to slow or stop. The use of saline groundwater for agricultural production increases the salinity and sodicity of the soil, which adversely impacts crop production and farmer livelihoods (Post, 2005).

The continuous decline of groundwater levels observed in Southern Punjab suggests there is considerable potential to improve groundwater management in the Indus Basin (Ashraf & Ahmad, 2008). Innovative management strategies are needed to optimise groundwater use more effectively. Also, implementing the National Water Policy 2018 will be managed so that it does not impede crop growth or cause land salinity or underground saltwater intrusion (Nasir et al., 2021). Almost half of Pakistan's irrigation requirements are fulfilled by groundwater; therefore, even a modest increase in groundwater productivity will have significant benefits (Qureshi et al., 2020). Farmers with access to groundwater have been observed achieving 50–100% higher crop yields than those using surface water only (Qureshi et al., 2020). On the other hand, losses result from inadequate land and water management, including groundwater mismanagement. Estimates of the extent of salinity vary, but most researchers refer to the results of substantial surveys late last century when 35–40% of Pakistan's total irrigated area was affected by salinity (Ashraf et al., 2022). There are numerous obstacles to implementing sustainable and effective groundwater management as well as Sustainable Development Goals (including SDG 6.1). These include a lack of policy guidelines with an integrated implementation framework, awareness, institutional arrangements, and capacity for governing the use of surface and groundwater. A lack of resource data, complexity in defining groundwater entitlements, and smart management tools to assist water professionals in managing multiple water sources are also big challenges.

Decision support tools can aid in identifying beneficial technology solutions for redistributing surface water supplies, developing methods to control waterlogging, rationalising groundwater abstraction, and promoting artificial recharge of aquifers. To address issues of sustainable groundwater and surface water use, the quantity and quality of groundwater were determined in response to changes in recharge and groundwater pumping rates using a groundwater model developed for the Southern Bari Doab in Punjab to address SDGs 1.3 and 2.4 for the betterment in livelihood of rural communities as well as food security, respectively.

Computer-based modelling has always been an excellent option for better understanding groundwater systems. Also, modelling enables the development of optimisation and best management strategies by simulating various scenarios before implementation, thereby saving time, money, and resources. Any computational method approximating an underground water system is called a groundwater model (Osman et al., 2022). While groundwater models are, by definition, simplifications of a more complex reality, they have proven to be effective tools for addressing a variety of groundwater problems and assisting in the decision-making process over the last several decades. Groundwater models shed additional light on a complex system's behaviour and, when designed properly, can aid in the development of conceptual understanding (Kumar et al., 2015). Additionally, once they have been shown to reasonably reproduce past behaviour, they can be used to forecast future groundwater behaviour, assist in decision-making, and allow for the exploration of alternative management approaches.

Therefore, this report introduces a project to address the behaviour of the Southern Bari Doab aquifer in response to different hydrogeological parameters explained in the model conceptualisation section. The report has precise and oriented objectives designed to provide valuable insights for researchers and policymakers on how groundwater could be managed sustainably under system and climate stress. A targeted literature review was summarised to give a broader picture of groundwater conditions under conditions similar to those of our study site. The report then covers the detailed development of the groundwater model for the Southern Bari Doab Canal Command under different projected scenarios with their future implications and some practicable recommendations for policymakers.

1.1. Project Objectives and Outputs

This study is a part of the larger ACIAR-funded project "Adapting to Salinity in the Southern Indus Basin" (Project LWR/2017/027). The project aims to develop and investigate adaptation options and strategies with people managing and living in salinity affected agricultural landscapes in the Southern Indus Basin. The expected outcome of the project is to explore how communities can live well in saline-affected areas with improved livelihood outcomes for farming communities in Southern Punjab. This study is one of the major components of the project. It involves the development of a groundwater model of the Southern Bari Doab in Southern Punjab to quantify the historical, current, and future status of groundwater reserves and the behaviour of the aquifer in the area. This quantitative analysis aims to develop an understanding of the key stressors on the aquifer resulting in declining groundwater levels and to estimate the sustainable yield, which can assist the Punjab Irrigation Department and policymakers to co-develop with groundwater irrigators a sustainable groundwater extraction regime for the Southern Bari Doab. As described in the ensuing sections, hotspots identified as part of this study will require careful management of resources to maintain the viability of groundwater irrigated agriculture.

An essential aspect of the groundwater model is establishing a correlation between the changes in storage in the groundwater reserves and regional agricultural practices. The objective is to identify how the aquifer behaves in Southern Punjab in response to the overexploitation of fresh groundwater pumping. Additionally, the groundwater model seeks to conduct scenario analyses to simulate potential future outcomes in the short, medium and long-term. This approach enables the identification of effective interventions to mitigate the impact on groundwater resources. The goal is to develop a predictive mechanism that aids in formulating sustainable water management strategies specifically tailored to the dynamics of the Southern Bari Doab region.

Recognising the influence of climate change on groundwater is another crucial objective of the model. This involves understanding how changes in precipitation patterns and rising temperatures contribute to variations in groundwater recharge and evapotranspiration. Simulating the impacts of climate change on groundwater reserves will allow the development of adaptation strategies for long-term sustainable groundwater management that consider both climatic and agricultural practices.

The groundwater model developed for the Southern Bari Doab covers an area of 11,348 km^2 including parts of the Khanewal, Multan, Vehari, and Lodhran districts. The objectives are:

- Development of a groundwater flow model to evaluate the spatiotemporal response of the aquifer to hydrogeological stresses which will help stakeholders make well-informed decisions using the outcomes of the study.
- Estimation of the impact of groundwater pumping, surface water supplies, and climate change on future groundwater reserves in the area.
- To enhance the institutional capacity of the Punjab Irrigation Department to better understand groundwater modelling approaches for the sustainable management of stressed groundwater resources and to provide guidance on appropriate adaptation options for a sustainable groundwater future.

2. A Review of Groundwater Studies in Punjab

Several studies on groundwater investigations, development, and monitoring have been performed. They have focused mostly on hydrological investigations and monitoring groundwater under different pumping scenarios through tubewells. These studies provide useful background information and data. However, the studies on the development of groundwater models in Punjab province are discussed below.

2.1. Groundwater Model for Bari Doab Canal Command

The study encompassing the districts of Okara and Sahiwal in the Lower Bari Doab Canal (LBDC) Command area indicated that a 20% increase in pumping will reduce groundwater storage by 146 MCM/year, and with a 20% increase in pumping and a 5% reduction in surface water supplies the net change in storage will be 144 MCM/year. Additionally, the study found that groundwater storage will be increased by 163 MCM/year if stakeholders reduce groundwater pumping by 5% (Anjum et al., 2015). The model of the entire LBDC Command by Basharat (2012) and Basharat and Tariq (2015) indicated that groundwater levels in the upper reaches of Balloki and Okara were stable due to sufficient surface water availability in these districts. However, in the lower reaches, in the districts of Sahiwal and Khanewal, the groundwater depletion rate simulated was 0.18mm/year and 0.34mm/year, respectively, driven mainly by inequity in canal supplies to the tail-end of the LBDC, coupled with excessive pumping in the upper reaches due to seepage losses and increased groundwater pumping driven by increasing evaporative demand in the south. The study conducted in the Upper Bari Doab Canal Command depicted the depletion of water levels with a rate of 0.55m/yr and that depletion will reduce the waterlogging problems in the area, with caution of further depletion soon in the case of uncontrolled pumping (Mujtaba et al., 2011).

2.2. Groundwater Model for Rechna Doab, Punjab

The groundwater model developed in Rechna Doab indicated a net storage of 2.542 BCM/yr during the simulation period 2008–2013. The baseline scenario indicates indicated pumping of 10 BCM/yr will not result in significant drawdowns. If groundwater pumping was decreased by 10% with the same canal supply the net storage term increases to 3.567 BCM/yr, while a 10% increase in canal supply with the same pumping would result in an increase in net storage from 2781 GL/yr for the baseline scenario, to 2.900 BCM/yr which is an increase of 0.119 BCM/yr.. If a 10% decrease and 10% increase in canal supply is managed, an additional saving of 0.9 BCM/yr is expected (Punthakey et al., 2015). Based on the above scenarios the authors recommended pumping should be managed around 11 ± 1 BCM/yr depending on the need for pumping in response to drought and or lack of surface water supplies. When surface water supplies are plentiful pumping levels could be decreased so that the groundwater system gets recharged with freshwater. The study conducted in Lower Chenab Canal west, a part of Rechna Doab, indicated a decline in groundwater levels of up to 14m if groundwater pumping is maintained under the Baseline scenario from 2013 to 2030. In addition, the groundwater levels would decline by up to 18 m if pumping increased following the historical increasing trends. The adjustment in canal water supplies and groundwater pattern would recover by 2–3 m in the study area's middle reaches (near Bhawana) (Shakoor et al., 2018).

2.3. Groundwater Model for Upper Chaj Doab

A finite difference 3-D numerical model was developed for the Upper Chaj Doab (Ashraf & Ahmad, 2008). The model predicted four scenarios in response to climate change. The first scenario assumed a severe drought condition for four consecutive years 2006–2010. The findings evaluated a 0.6 m depletion in the groundwater level in the area. The second scenario assumed wet conditions for four consecutive years 2011–2015. The model results indicated a 0.42 m depletion expected in these four consecutive years. A third scenario assumed constant pumping of 5000 m^3/day for each of the 33 pumping wells for 2005–2008. This depicted an average decline of 1.63 m. In the fourth scenario, 60% extra pumping was assumed to continue during 2005–2008. The study concluded that higher pumping would reduce waterlogging and salinity in the study domain.

2.4. Lessons Learned from Previous Studies

Some of the key lessons learned from the previous studies are discussed below:

- Increasing reliance on groundwater for irrigation is exploiting the groundwater reserves at an alarming rate particularly in non-perennial canal commands where canal supplies are available only in kharif season.
- There is a significant urgency to improve monitoring of water levels, water quality and groundwater extractions; if you cannot measure it, you cannot manage it.
- There is a significant need to improve equitable distribution of canal water particularly for tail enders that are generally deprived of their fair share of water.
- A focus on managed aquifer recharge projects in Punjab is required to enhance recharge to depleted aquifers.
- The Punjab Irrigation Department guided by the National Water Policy and the Punjab Water Policy is striving to improve resource management however significant capacity constraints exist at the institutional level.
- Specific areas of research is needed to explore and highlight technical as well as management issues and to develop adaptable strategies.
- Groundwater modelling can help in designing well-fields to supply groundwater for drinking water requirements (Zakir-Hassan et al., 2022).
- A network needs to be established to monitor surface and groundwater at the canal command level (Hassan, 2023).

Based on the above, there is a strong need to adopt a comprehensive, integrated approach for sustainable surface and groundwater management development. All concerned stakeholders including researchers, lawmakers, and related departments, must step forward to manage sustainable groundwater development, as prevailing conditions will soon lead to acute water scarcity.

3. Physical Setting

3.1. Topography of the Study Area

The area under study is the southern part of the Bari Doab and is a continuation of the Lower Bari Doab Canal (LBDC) Command area located at the tail of the Ravi and Chenab Rivers on the north and northwest sides, respectively and by the Sutlej River in the southeast containing four administrative districts – Multan, Khanewal, Lodhran, and Vehari. The total area under study is about 11,348 km^2. The study area is a part of the Southern Indus Basin in Punjab. It consists of a network of main, branch, and one-link canals, making it a potentially very productive agricultural zone. A digital elevation model based on the 30m Shuttle Radar Topographic Mission (SRTM) for the Southern Indus Basin was obtained from the United States Geological Survey (USGS) site, which is freely available to download. The surface elevation for the study area ranges between 110 (m AMSL) in the Lodhran district to 156 (m AMSL) in the Khanewal district (Figure 1). Based on the metrological data, the area comes under semi-arid climatic zones with an average annual rainfall of less than 250mm and higher temperatures in summer. Like most Punjab crop areas, there are two cropping seasons, i.e., Rabi (April–Sep) and Kharif (Oct–March). Wheat is the major crop in the Rabi season, while cotton, maize and rice are sown during the Kharif season. Sugarcane is also cultivated as an annual crop on a smaller scale.

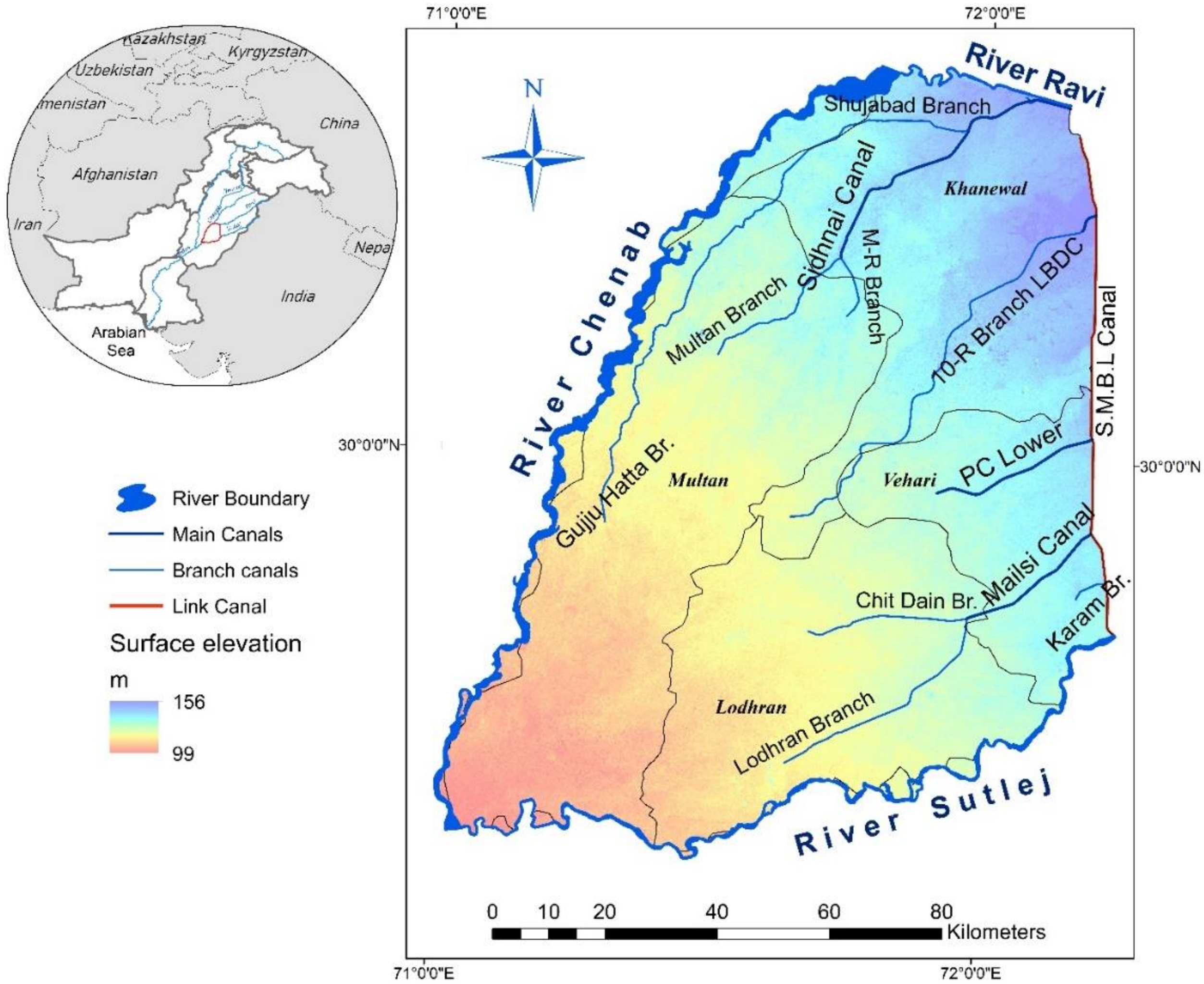


Figure 1. Southern LBDC showing physiography of the study area

3.2. Groundwater Monitoring in the Study Area

The Punjab Irrigation Department (PID) is currently monitoring biannually about 3,300 observation wells to record depth to watertable in seven irrigation zones of the Punjab province. These zones are called the Lahore, Faisalabad, Sargodha, Multan, Sahiwal, Bahawalpur, DG Khan, and Potohar irrigation zones. It has been observed from the data provided by PID that a significant number of monitoring wells are inactive. The total number of water level monitoring wells in the selected study area was 281, of which 42 were inactive or defective from 2010 to 2020. In Figure 2, blue and red points represent active and inactive observation wells, respectively.

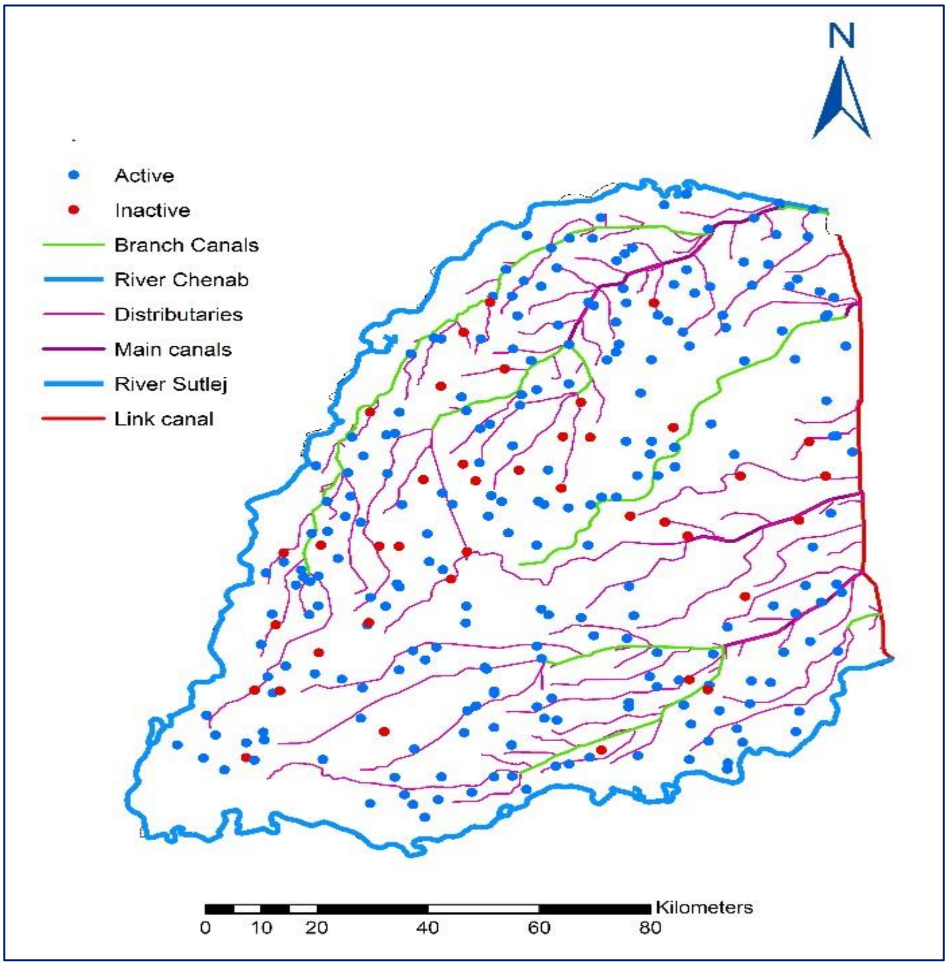


Figure 2. Location of active and inactive observation wells in the study area

3.3. Groundwater Quality Status in the Study Area

The PID is currently monitoring about 4,000 farmer-owned and community tubewells across the seven irrigation zones of the Punjab. The PID records three water quality parameters, i.e., EC, SAR, and RSC. The piezometers/observation wells installed by the PID are used to monitor the groundwater levels, while quality is monitored from existing farmers' tubewells. The monitoring of water quality tubewells was not consistent, a similar situation to water level monitoring wells. Some monitoring wells (observation wells and tubewells) were defective, giving null values or the sample leakage status, which led to inconsistent groundwater monitoring. The number of wells monitored in the study area pre-2010, 2015, and 2019 were 432, 525, and 632, respectively. In addition, the locations of tubewells for water quality monitoring from 2003 to 2013 differed from those of 2014 onwards. Figure 3 shows tubewell locations for 2003–2013 (green) and 2014 onwards (yellow). After removing defective wells and outliers, EC data were interpolated using the Inverse Distance Weighted (IDW) technique in ArcGIS for pre-2010, 2015, and 2019 (Figure 3). The area change from pre-2015 to 2019 is shown in Table 1. About 7% of the area increased under marginal water quality, while less than 1% decreased under relatively fresh and hazardous quality. The PID has three classes of irrigation water quality

– relatively fresh (EC<1.5), marginal (EC= 1.6–4), and hazardous (EC>4) (Ali, 2023). Figure 3 shows a significant area of freshwater zone transitioning to a marginal zone, which will affect future soil and crop health.

Table 1. Area change under different class of EC during pre-2010, 2015 and 2019

Class	EC (dS/m)	Area (km²) Pre-2010	Pre-2015	Pre-2019	2015 to 2019 change (%)
Relatively fresh	<1.5	7,829.8	10,140.5	10,058.5	-0.8
Marginal	1.6–4	3,362.9	1,134.7	1,217.2	7.3
Hazardous	>4	152.7	70.2	69.7	-0.7

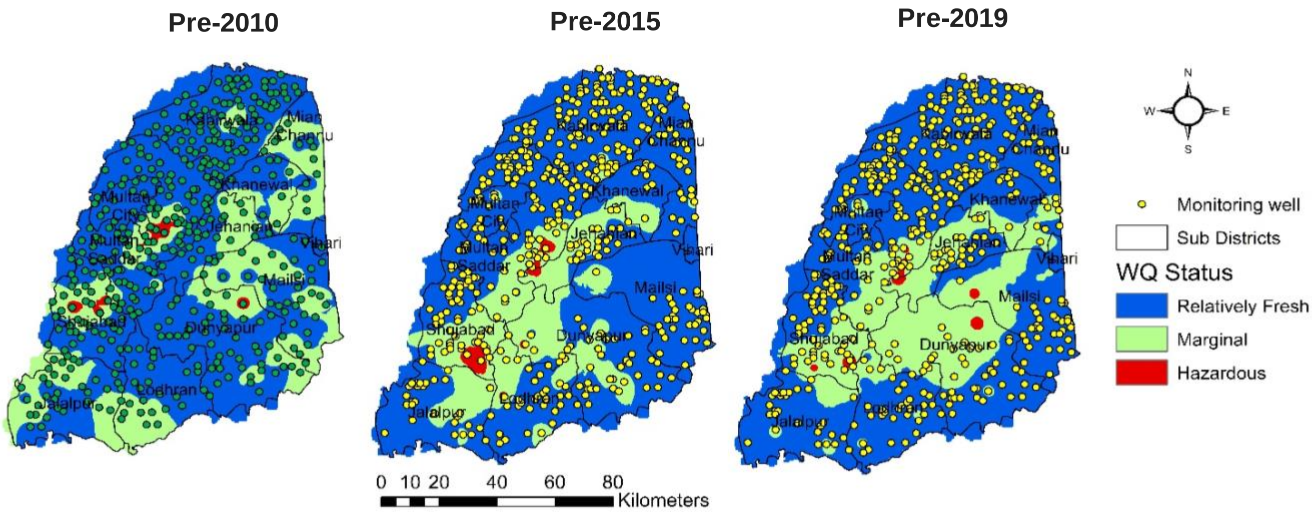


Figure 3. Spatio-temporal variation in EC for Pre- 2010, 2015 and 2019

3.4. Irrigation Network in the Study Area

Sidhnai Canal

About 24 km above its junction with the Chenab, the Ravi River flows almost straight for nearly 13 km, where it is known as the Sidhnai Reach. The width is about 137 metres at the upper end and almost 366 metres at the lower end, near the town Serai Sidhu. The Sidhnai Canal headworks is 5.6 km above that point and the canal on the left bank flows nearly south-west about 60 km. Sidhnai Canal commands an area of 1,111.1 km^2 for agricultural purposes. Near the town of Choparhatta, the Shujabad Branch Canal offtakes from the right bank, which irrigates up to Shujabad. Sidhnai Canal passes through Kabirwala and ends at the Rangu head regulator, where it splits into two branch canals known as Makhdum Rashid Distributary and Multan Branch Canal.

Pakpattan Canal Lower

With the addition of the Sidhnai Mailsi Bahawal Link (SMB link) Canal, the main Pakpattan Canal was divided into two canals named the Pakpattan Canal Upper from RD 0–567 and the Pakpattan Canal Lower (PCL) from RD 568 to 667. Due to this split, the Pakpattan Canal Lower now takes its supply from the Sidhnai Mailsi Bahawal Link (SMB link) with a new head regulator at the SMB link. The design discharge for PCL is 1,160 cusecs.

Mailsi Canal

The Mailsi Canal offtakes from the Sher-Garh head regulator constructed on the Sidhnai Mailsi Bahawal Link (SMB link) Canal. Near Hussain Abad, the Mailsi Canal splits into two branch canals – the Lodhran Branch and the Chit Dain Branch. The Mailsi Canal can carry a discharge of 3,705 cusecs.

Sidhnai Mailsi Bahawal Link Canal

The Sidhnai Mailsi Bahawal (SMB) is a major link canal in Southern Punjab that offtakes from the left bank of Sidhnai Barrage. Three major canals (Pakpattan Canal Lower, Mailsi Canal, and Karam Branch) and 16 distributaries take their supply directly from the SMB link canal and irrigate the areas of Mailsi and Lodhran. The design discharge for the SMB link canal is 11,300 cusecs. Design discharge, full supply depth (FSD), bed levels at upstream and downstream and culture able command areas of the mentioned canals are outlined in Table 2.

Table 2. Salient features of canal network in the study area

Channel	Design Discharge (cusecs)	FSD (feet)	Bed Level U/S	Bed Level D/S	CCA
Sidhnai Canal	4,005	8.7	452.45	431.2	1824.7
Shujabad Br.	1,900	6.75	447.12	388.55	3535.6
Gujju Hatta Br.	700	4.9	388.5	381.72	506.5
Multan Br.	775	5.1	426.94	423.38	6165.6
Makhdum Rasheed Disty.	425	4.4	428.11	405.93	1425.5
10- R Disty	1,236	6.3	469.84	400.46	18,864.0
SMB link Canal	11,300	12	445.87	415.1	-
Pakpattan Canal Lower	1,160	5.8	437.3	423.9	-
Mailsi Canal	3,705	9.3	424.2	413.8	547.0
Lodhran Br.	1,246	6.8	409.3	402.4	2,919.8
Chit Dain Br.	1,819	8.6	404.1	390.7	4,110.1
Karam Br.	630	5.8	430.7	427.6	-

Sub-Canal Commands

According to PID records, the area was divided into three major canal commands, i.e., Sidhnai, Lower Bari Doab, and Pakpattan Canal Lower (Figure 4). The area was manually divided into eleven sub-canal commands based on main and branch canals to define the recharge zones. These eleven sub-canal commands are Sidhnai Canal, Shujabad Canal, Gujju Hatta Canal, Multan Branch Canal, Makhdum Rasheed Branch Canal, 10-R Lower Bari Doab Canal, Pakpattan Canal Lower (PCL), Mailsi Canal, Lodhran Branch Canal, Chit Dain Branch Canal, and Karam Branch Canal (Figure 5).

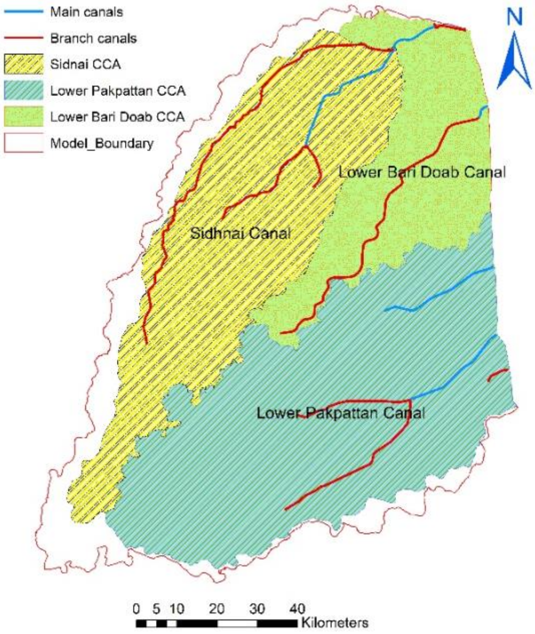


Figure 4. Main canal commands in the study area

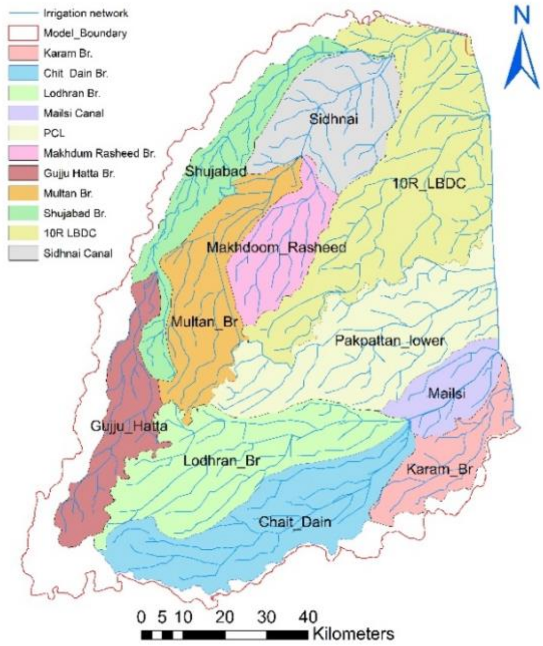


Figure 5. Sub-canal commands in the study area

3.5. Geology

The Southern Indus Basin is in the Indo-Gangetic Plain and is roofed by quaternary alluvium, which likely overlies consolidated and semi-consolidated tertiary rocks or igneous and metamorphic rocks. The area under Multan and Khanewal comprises fluvial deposits of the Chenab, Ravi, and Beas Rivers. The deposits comprise floodplain muds mixed with fine sand and fine-to-medium sand point bars (Hayat, 2003). Some test holes were drilled in the study area at different depths ranging from 243 to 396 m to estimate the thickness of the alluvium and the depth to which the bed rock is located. The bore holes dug by WAPDA show no evidence confirming the thickness of the quaternary alluvium and tertiary rocks and older rocks. The subsurface lithology, which is predominantly sand, revealed the water-bearing characteristics of the alluvial deposits that make up the Southern Indus Basin aquifer in test holes and boreholes. A comparison of lithological logs gave an excellent sense of the texture and structure of the heterogeneous alluvium to a depth of 183 m. Clay, fine sand, fine-to-medium sand, medium-to-coarse sand, sandy silt, coarse sand, and gravel are among the subsurface materials identified in the quaternary alluvial complex (Greenman et al., 1967). The alluvial material surrounding the area under study was thought to be more than 300 m thick and part of the extensive heterogeneous and isotropic unconfined aquifer underneath the Indus Basin. The United States Geological Survey (USGS) confirms that the southern part of Bari Doab is dominated by quaternary sediments (Q), as shown in Figure 6.

3.6. Hydrogeology

The Water and Soil Investigation Division (WASID) drilled aquifer test holes in the Punjab Plain of West Pakistan at 164 locations in Chaj, Rechna Bari, and Thal Doabs between 1954 and 1963 (Figure 7). All the test holes were made in unconsolidated alluvium, mainly consisting of materials like sand, silt, and clay. The depth of the alluvium was extended from one thousand to several thousand feet in dominating parts of the area, but none of the 164 test holes was drilled beyond a depth of 400 feet (122 m). In Bari Doab, test holes were installed at 19 sites. The results of the test holes showed the lateral permeability in 67% of the test holes ranged between 0.0010 to 0.0020 cfs/ft^2 with an overall average as 0.0026 (Figure 8). Also, 90% of the test holes showed the specific yield value ranged between 0.02 to 0.26, with an average value of 0.14 (Greenman et al., 1967). The average values of specific yield and hydraulic conductivity estimated by Lytton et al. (2021) range between 0.14–0.20 and hydraulic conductivities range from 50–90 m/day in the Southern Bari Doab. The depth of bore logs drilled in Multan and Lodhran are up to 300 m (Figure 9).

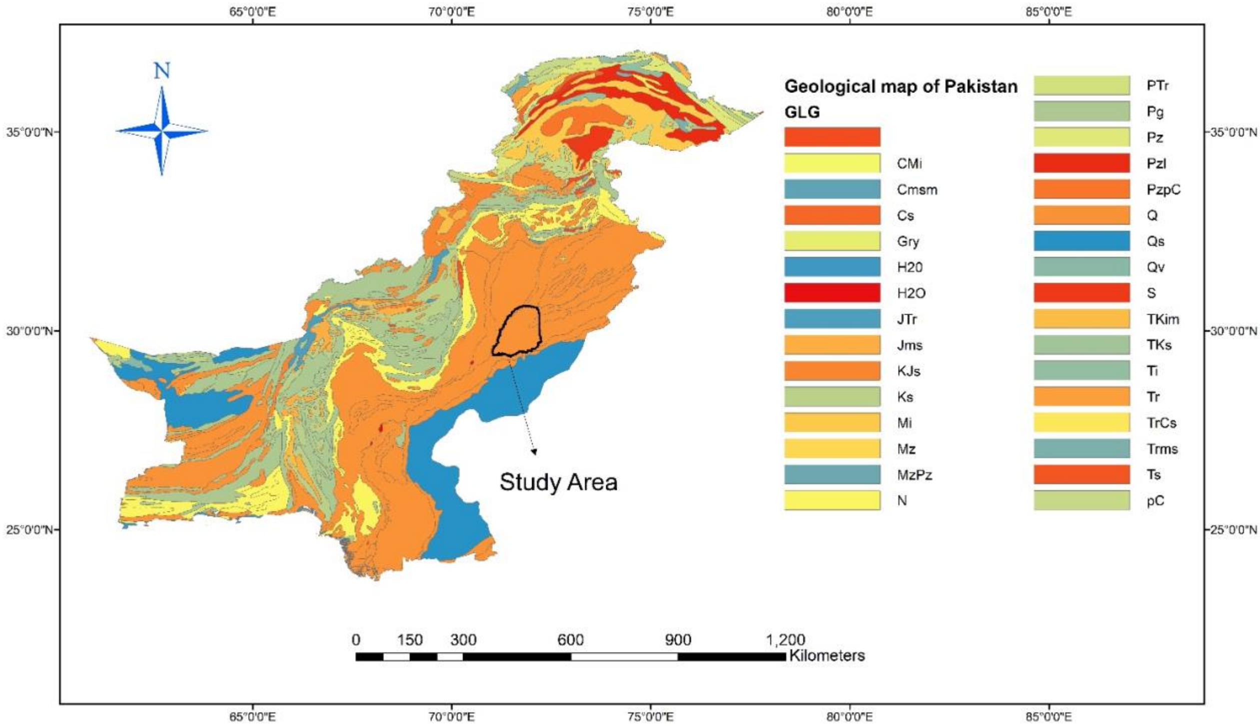


Figure 6. Geological map of Pakistan (source: USGS)

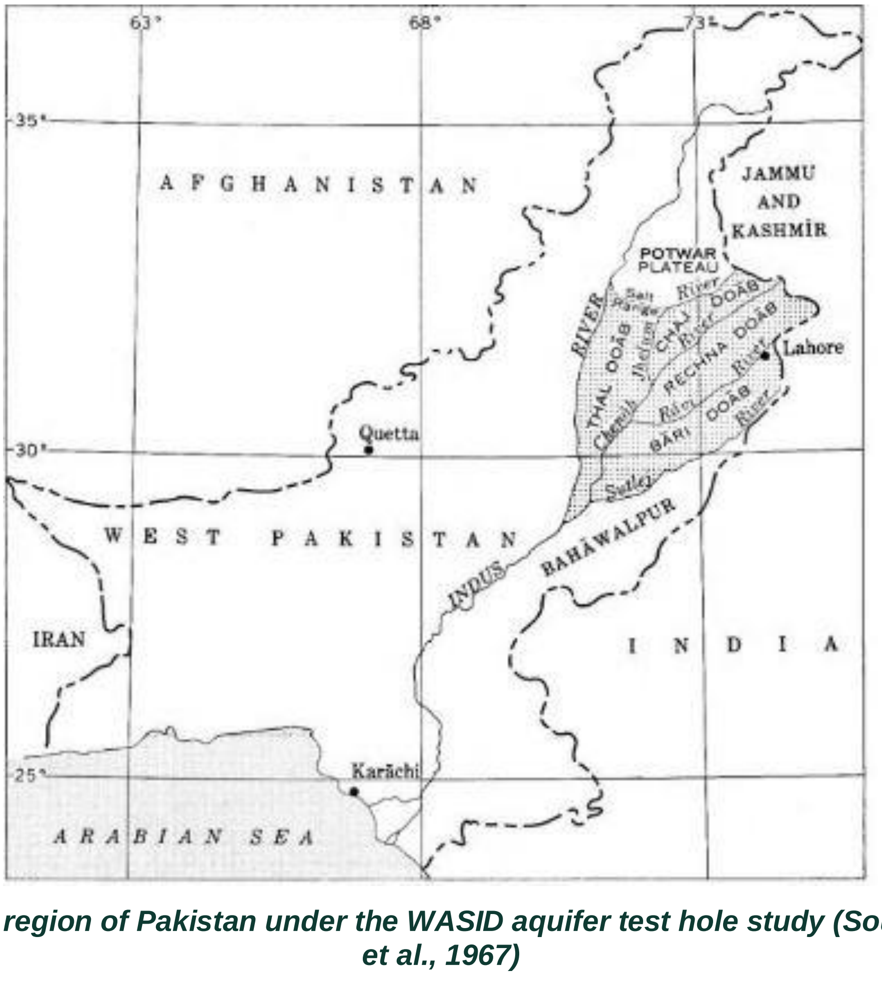


Figure 7. The region of Pakistan under the WASID aquifer test hole study (Source: Bennett et al., 1967)

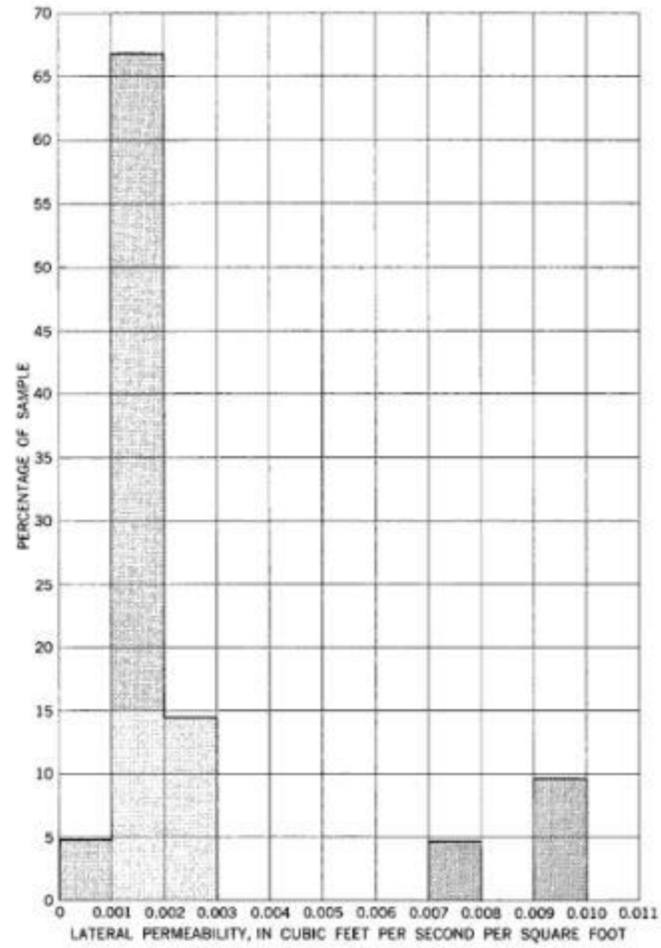


Figure 8. Lateral permeability of test holes in Bari Doab (Source: Bennett et al., 1967)

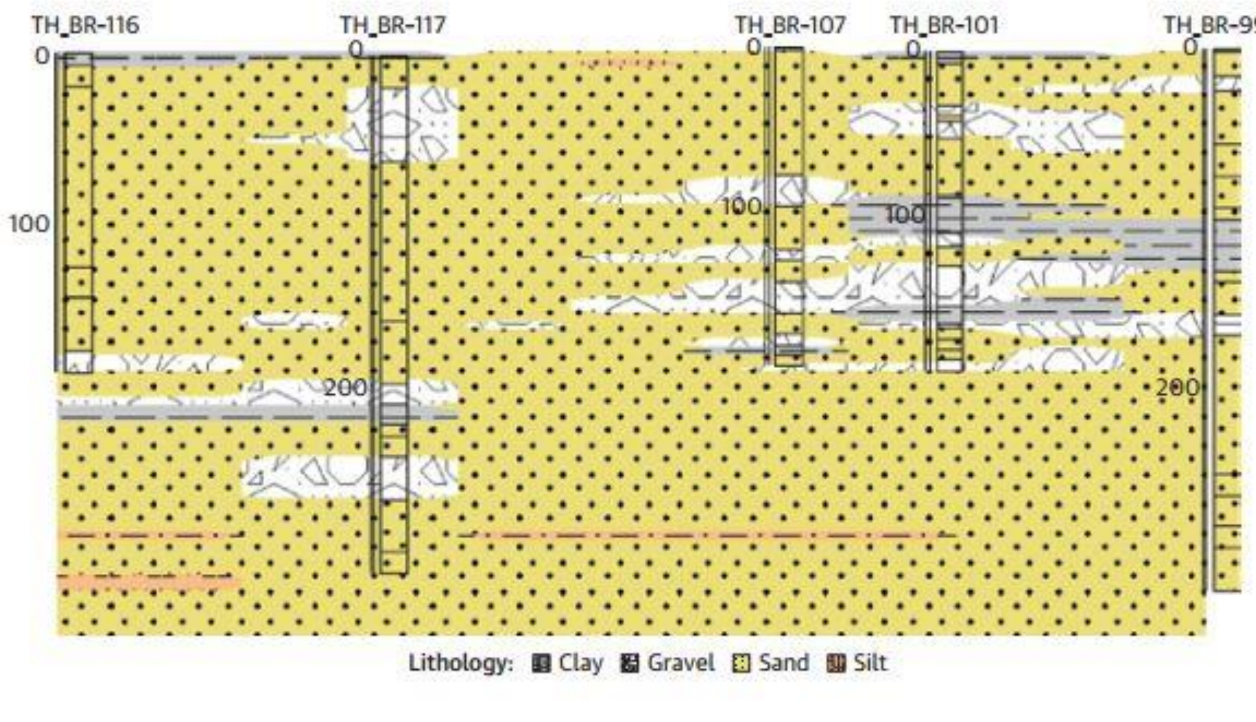


Figure 9. Cross-section through lower traches of Bari Doab in Multan and Lodhran (Source: Lytton et al., 2021)

Akhter and Hasan (2016) covered part of the area under study. Some test holes drilled to a depth of up to 1000 feet (304.8 m) revealed that the lithology of the aquifer consisted of silt, clay, sand, and gravel and the aquifer was unconfined. A pumping test showed the permeability range was 0.0001–0.0047 m/sec and the hydraulic conductivity ranged between 15.3 to 60.9 m/day.

3.7. Soil Map and Fence Diagram of Southern Punjab

The soil map of the designated area reveals distinct layering patterns and material compositions that characterise its geological composition. In the first model layer, clay emerges as the dominant material, shaping the uppermost stratum of the soil profile. Clay soils are characterised by their fine texture and high water retention capacity. The prevalence of clay in this layer suggests that the area might exhibit characteristics such as slow water infiltration and potential challenges for root development.

Moving down to the second model layer, sand emerges as the dominant material, indicating a transition from clay-rich soil to a sandy substrate. Sandy soils have larger particles and thus possess good drainage capabilities. The presence of sand in this layer suggests improved water infiltration rates compared to the clay layer above, allowing for better drainage and potentially lower moisture retention.

In the third model layer, the soil composition transitions again, with gravel taking the lead. Gravel is characterised by its coarseness and relatively large particle size. Gravel soils offer excellent drainage and aeration properties. The presence of gravel in this layer suggests that the area may have had a history of water movement or deposition, which contributes to its unique soil characteristics.

Overall, the soil map portrays a layered composition with clay dominating the uppermost layer, followed by a transition to sand and gravel in the deepest layer. This layering indicates variations in soil properties such as water retention and drainage, which can influence agricultural practices, recharge, and land use planning in the area (Figure 10).

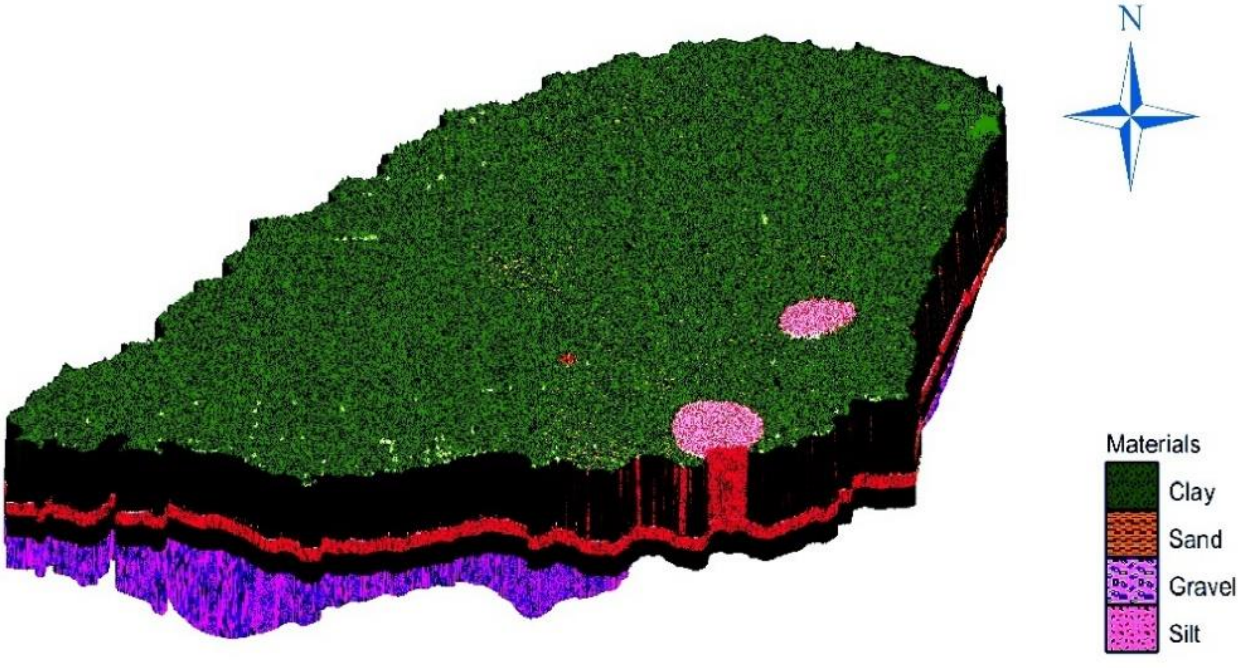


Figure 10. Soil type map based on WAPDA borelog data for the Southern Punjab area

The fence diagram illustrates the vertical distribution of clay, sand, and gravel, highlighting the variation in soil characteristics across the layers (Figure 11). This information provides useful information of the material type at different depth of the aquifer that was used in assigning the layer thickness of middle and bottom layers.

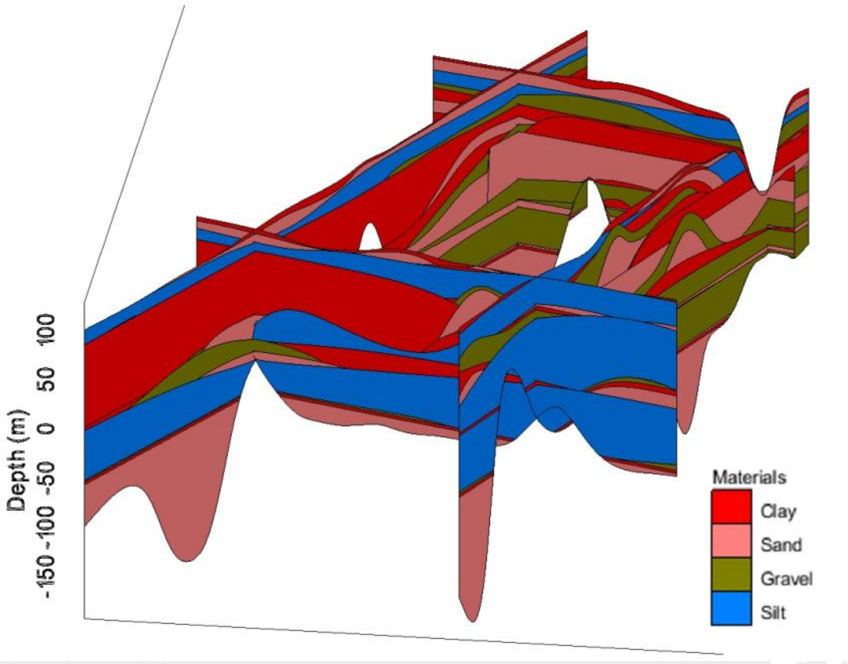


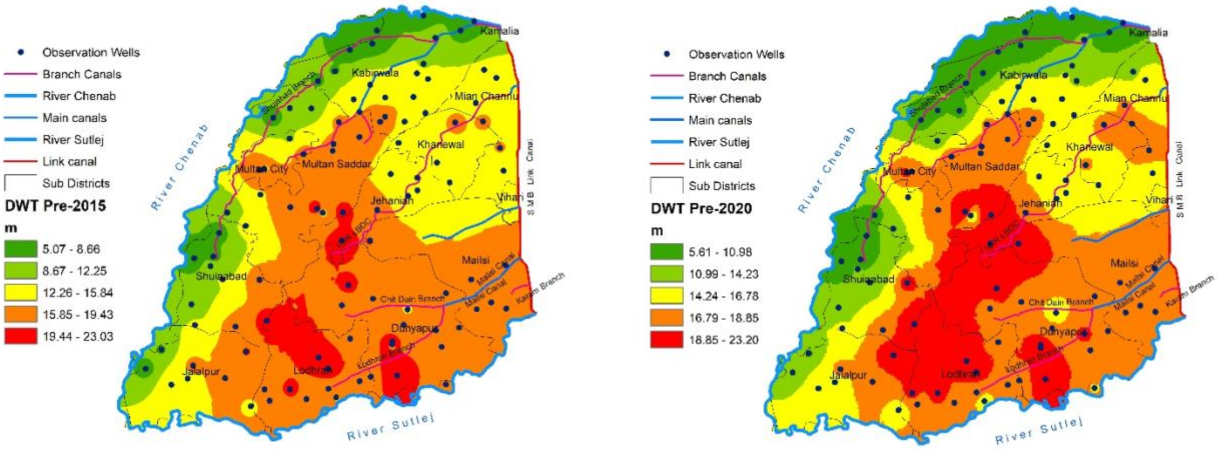
Figure 11. Fence diagram showing cross sectional view of the soil type in Southern Punjab

3.8. Spatiotemporal Analysis of Water level Trends in Southern Punjab

After irrigation began in the Southern Punjab, the watertables started rising due to surface irrigation and leakage from canals and rivers. After the Indus Water Treaty was signed in September 1960, all flows of the Ravi, Sutlej, and Beas Rivers were allocated to India for unrestricted use, removing a major source of irrigation water from Pakistan. At the same time, the cropping intensity and demand for irrigation water increased in Pakistan. As surface water supplies reached their full supply capacity, the shortfall was made up by several thousand shallow wells pumping groundwater for irrigation and domestic needs.

Depth to watertable data were obtained from the Punjab Irrigation Department from pre-2010 to pre-2020 for Southern Punjab. There were many outliers/dead/defective/closed piezometers, which have been removed from the raw data. The remaining piezometric data were digitised and interpolated using the IDW technique in GIS. Furthermore, GIS maps were developed to observe groundwater level trends in 2015 and 2020 for the Southern Punjab groundwater study area model (Figure 12).

Watertables are generally shallow along the Ravi River. However, the depth to watertables increases with distance away from the Ravi River. Analysis shows that in 2015, in some parts of the Lodhran and Duniapur and Jahanian sub-districts, the groundwater levels were deep (> 19.7 m) compared to other sub-districts of the study area. By 2020, the depth to watertable had increased to the south (away from the Ravi and Chenab Rivers) by 2–3 metres. In the sub-district Khanewal, water levels decreased by about 3 metres in six years (2015–2020). A similar trend can be observed in the Jalalpur and Shujabad sub-districts in 2020. This means groundwater extraction is exceeding groundwater recharge. The hydrographs of average depth to watertable in sub-units (tehsils) show an overall decline in groundwater levels resulting in a 0.5 m/yr decline in stressed zones within the study area (Figure 13).



2015 ***2020***

Figure 12. Spatial variation of depth to watertable (m) for 2015 and 2020 in Southern Punjab

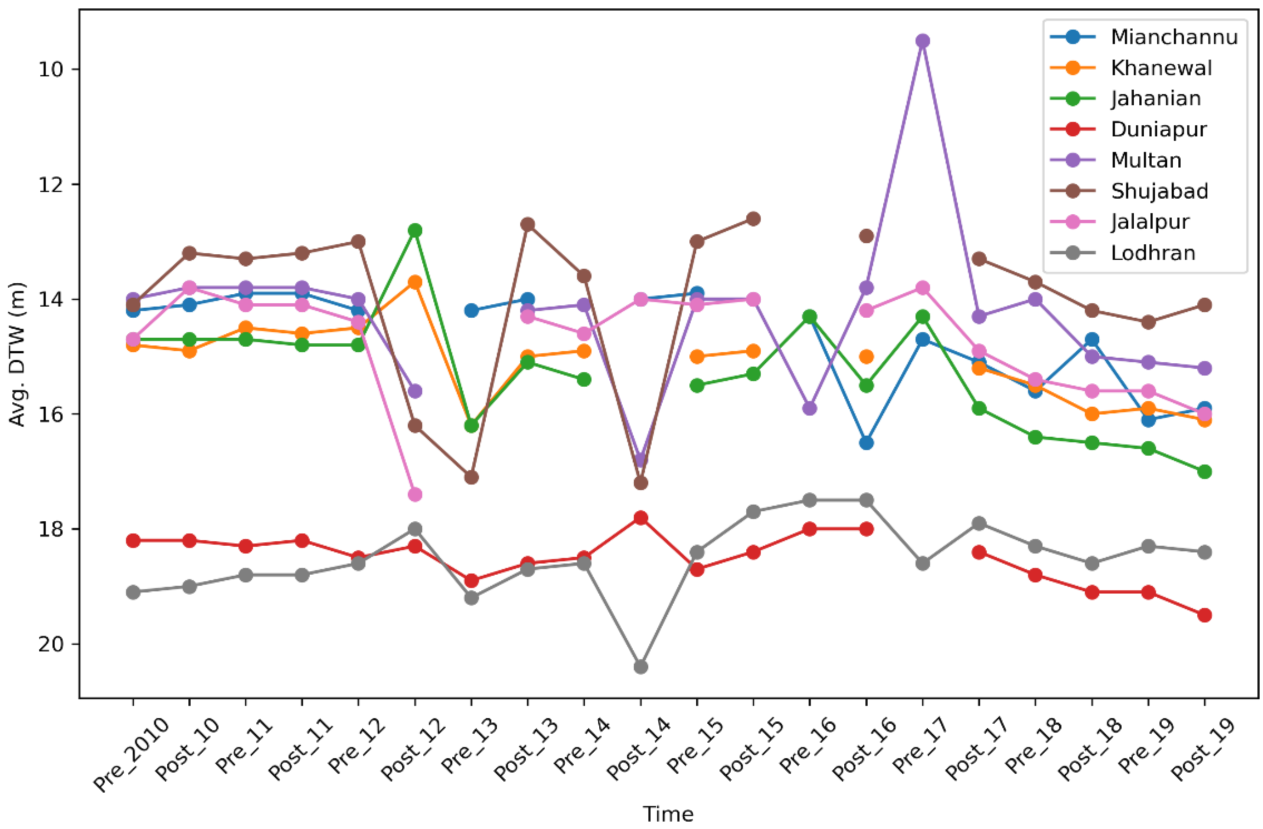


Figure 13. Temporal trends of average depth to watertable (DTW) sub-units

4. Model Development

4.1. Conceptual Model

The most important phase of groundwater modelling is creating an accurate conceptual model. Developing a conceptual model is challenging and occasionally laborious due to the limited and poorly organised data and available information. The quantity of water, the geometric arrangement of water movement, volume, flow direction, and time variations of the key parameters make up the groundwater regime. Each system parameter can be described mathematically as the function of the external elements due to the quantitative relationship between the stresses and the aquifer. If the environmental variables are known, this allows for evaluating a groundwater system and drawing conclusions more precisely. The current groundwater conceptual model was implemented in the Southern Indus Basin (Figure 14). In this model, the following stressors and boundary conditions were used. They are listed below:

1. River/Canal
2. Groundwater Recharge (irrigation and rainfall)
3. Groundwater Abstraction
4. Evapotranspiration

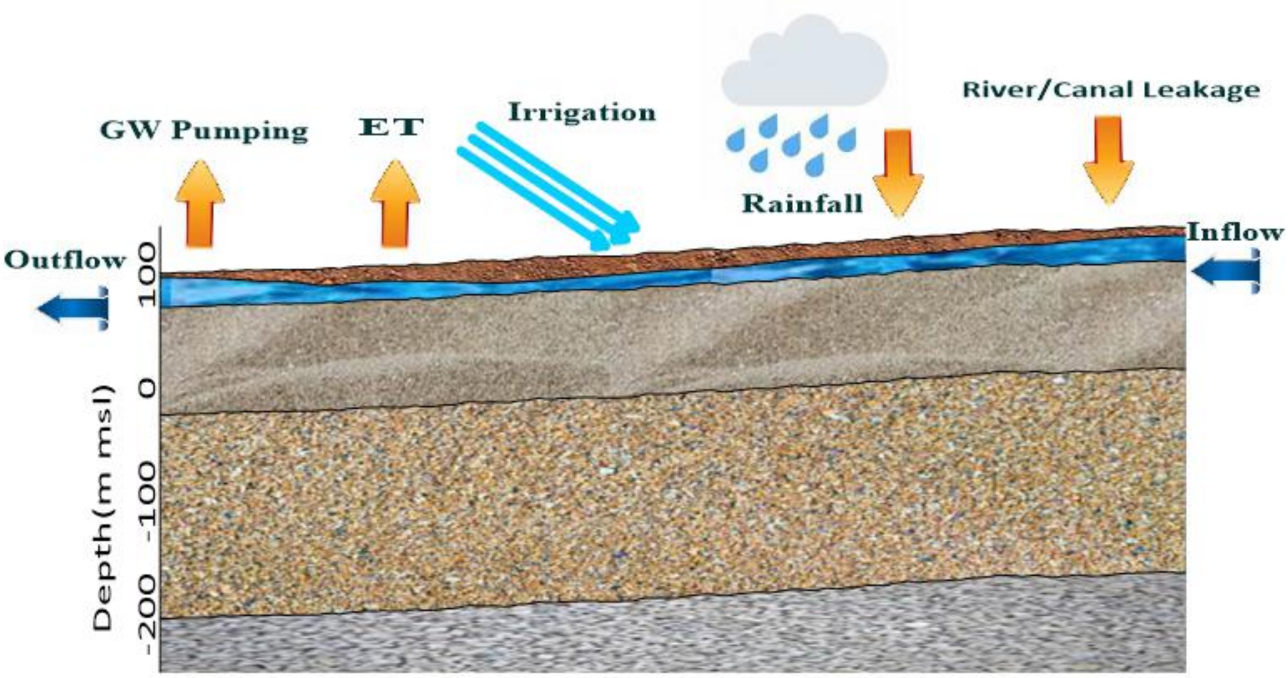


Figure 14. Conceptual groundwater model for Southern Indus Basin

4.2. Aquifer Geometry

The purpose of a numerical groundwater model is to provide a means whereby the inflow parameters, i.e., river and canal leakage and recharge, and outflow parameters, i.e., groundwater pumping and evapotranspiration are used to simulate the groundwater response in an aquifer. The whole area is downscaled in the form of grids of uniform size and the desired hydrogeological parameters are assigned to the model. The model divides the aquifer into three layers, starting from the ground surface elevation.

The numerical groundwater model under study consisted of three rivers: the tail of the Ravi and Chenab Rivers in the northwest, and Sutlej River along the southern boundary. One-link canal, the Sidhnai Mailsi Bahawal (SMB) Link Canal, is east of the model area. The confluence of the Chenab and Sutlej Rivers encloses the model area in the south-west. The model grid was designed based on the Universal Transverse Mercator (UTM) coordinate system using the ArcGIS tool to determine the number of rows and columns for the model area. Based on our conceptual model, the aquifer was divided into three layers: Layer 1 (Top) was assigned the elevation extracted from the digital elevation model (DEM). The thickness of the top (Layer 1) and middle layers (Layer 2) was 30 m and 95 m, respectively, while the bottom layer (layer 3) extended to the bedrock, with a thickness of 180 m. The thickness of the top layer was assigned based on the maximum depth of the watertable, i.e., 24 m; the middle layer depth was based on the bore logs; and the bottom layer, up to the bedrock. Details of the model and setup parameters are shown in Table 3. The grid and cross-sectional view of the groundwater model is represented in Figure 15.

Table 3. Groundwater model setup parameters

Corners	Model extent (UTM)	Model grid size (m)	No. of columns
Right	815,000	1,000	120
Left	694,000		
Top	3,392,000	1,000	143
Bottom	3,249,000		

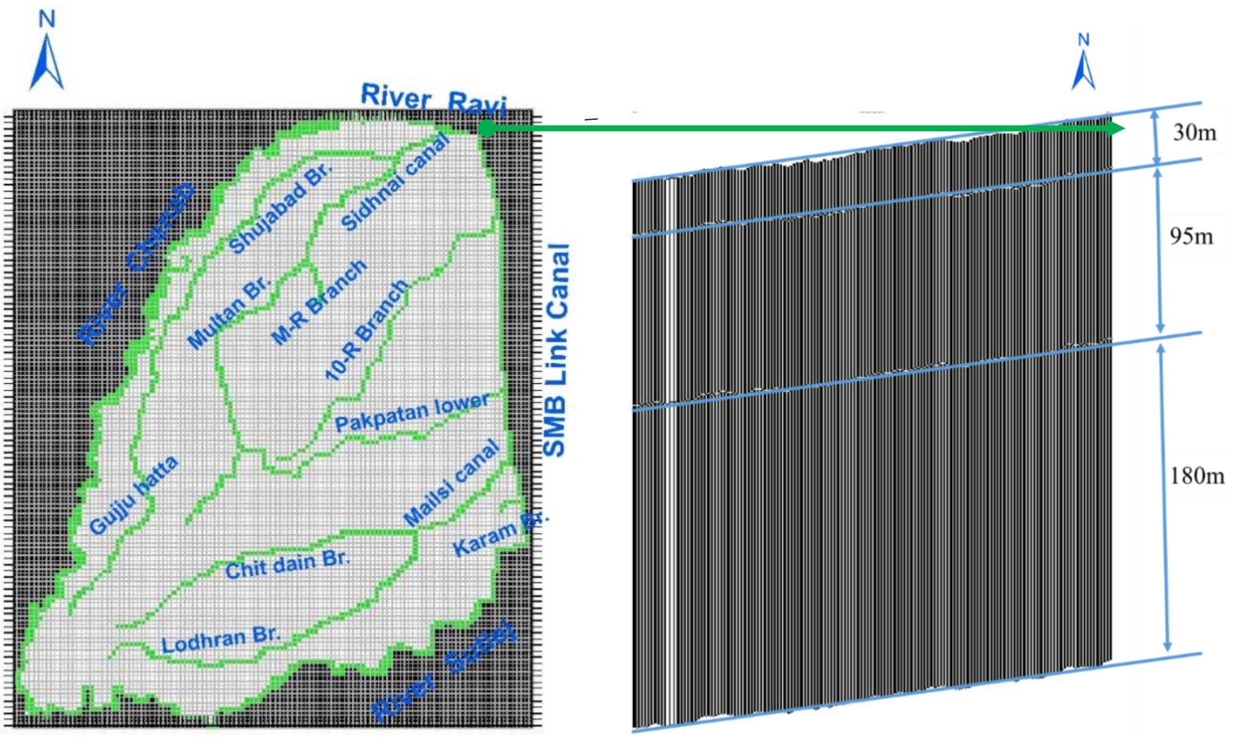


Figure 15. Top and cross-sectional grid design view of the groundwater model

4.3. Aquifer Properties

The bore log data compiled by WAPDA during 1980 was digitised and georeferenced (Schmid et al., 2017), with 62 located in the study area (Figure 16). The soil materials at different depths below the ground surface are shown in Figure 17. The average bore depth for Khanewal, Vehari and Lodhran was 190 m. Clay was observed as the dominating material constituting the top surface, with proportions of sand and silt found to a depth of 30 m (top layer of model), while different combinations of sand, silt, gravel, and clay were present to a depth of 120 m (Layer 2 bottom) in dominating parts of the area. For the bottom layer, the dominant materials were sand, gravel, and clay, found to a depth of 190 m. The average hydraulic conductivity was 69, 74, and 79 m/day for the top, middle and bottom layers, respectively. The average specific storage ranges from 3.5×10-

5 to 3.5×10-4 m^{-1}. Specific yield ranges between 0.11 and 0.15 for the different model layers. In addition, soil porosity ranges from 0.24 to 0.36 (Table 4). Spatio-temporal variations of different aquifer properties (K, Ss, Sy, and porosity) are shown in Figure 18.

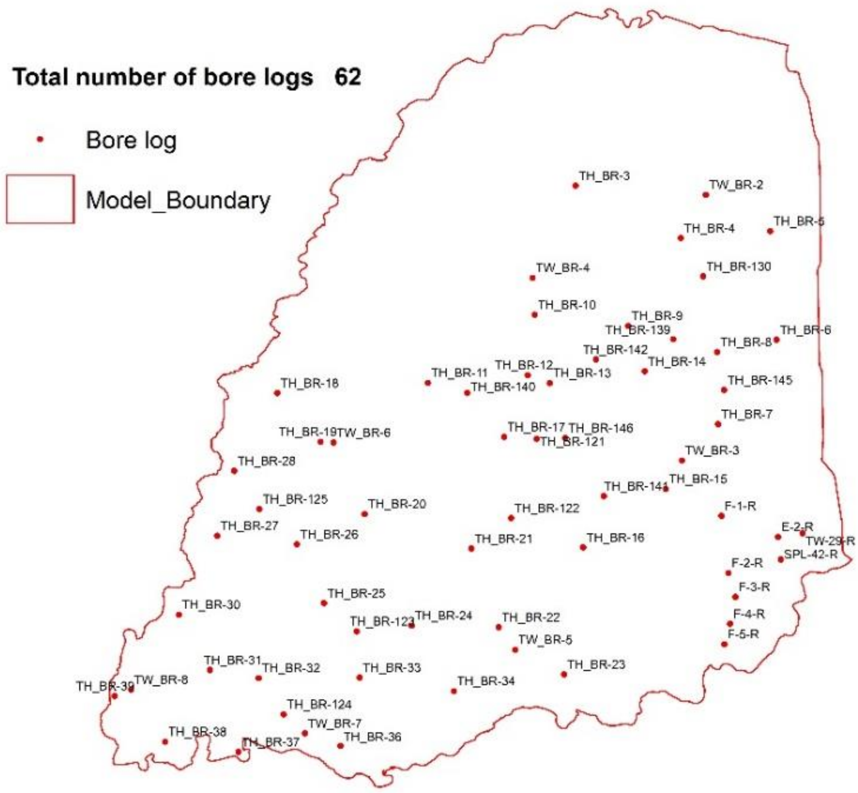
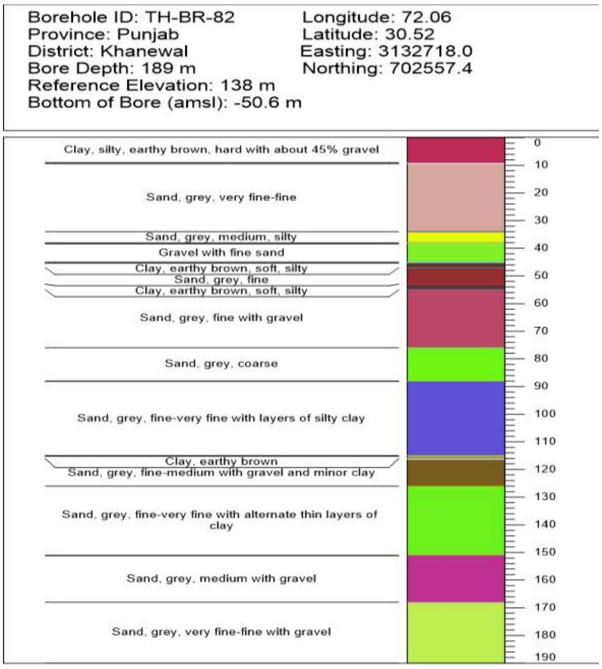


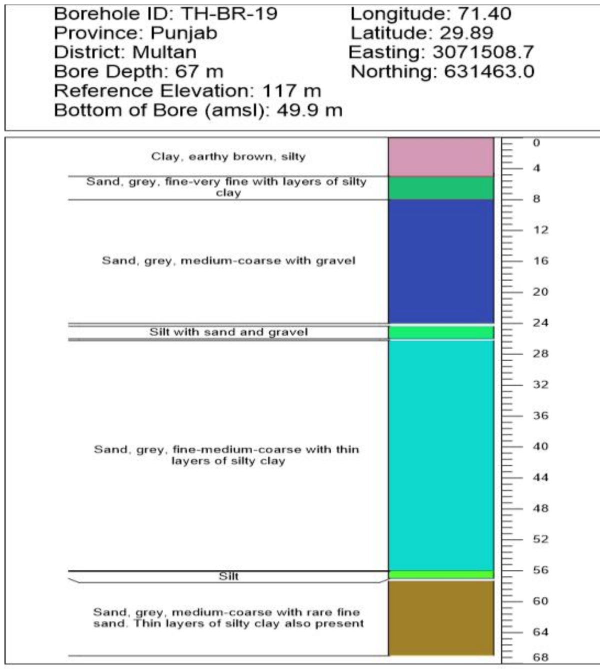
Figure 16. Location of bore logs in the Southern Bari Doab

Table 4. Aquifer lithology or different layers of groundwater model

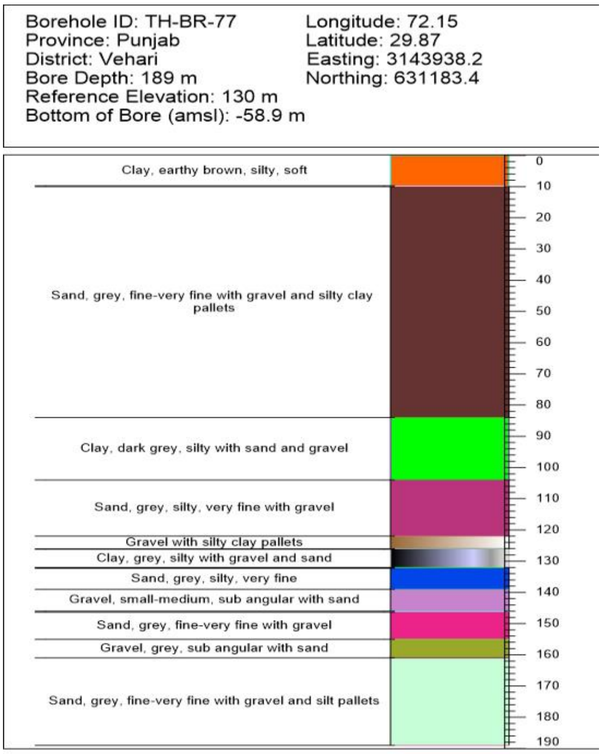
Parameter	Unit	Layer 1	Layer 2	Layer 3
Kx=Ky	m/d	56–82	58–89	15–142
Kz	m/d	1.12–1.64	1.16–1.80	0.30–2.85
Ss	m^{-1}	4.7×10^{-5}–1.5×10^{-4}	2.9×10^{-5}–2.1×10^{-4}	5.7×10^{-5}–4.0×10-4
Sy	-	0.12–0.14	0.10–0.16	0.11–0.17
Porosity	g/cm^3	0.24–0.36	0.24–0.36	0.24–0.36



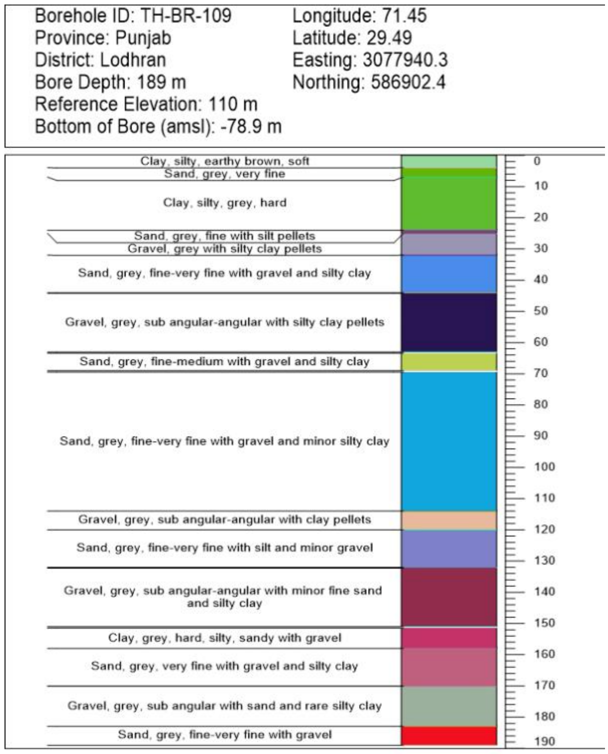
Lithology description of a bore log in Khanewal



Lithology description of a bore log in Multan

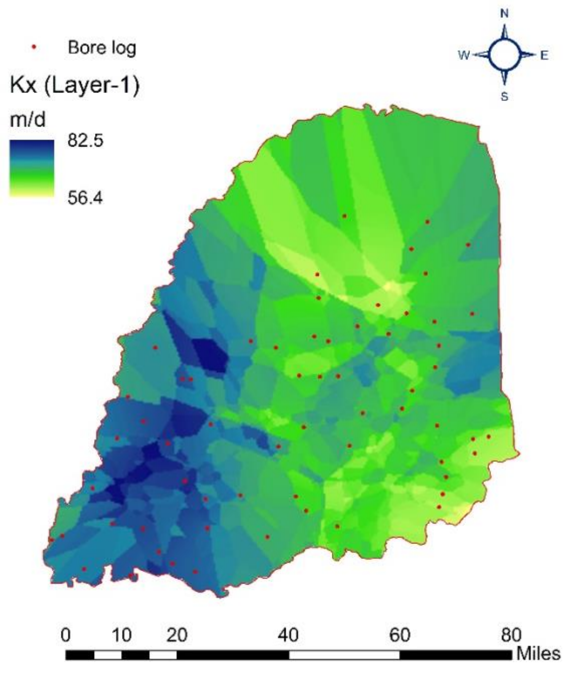


Lithology description of a bore log in Vehari

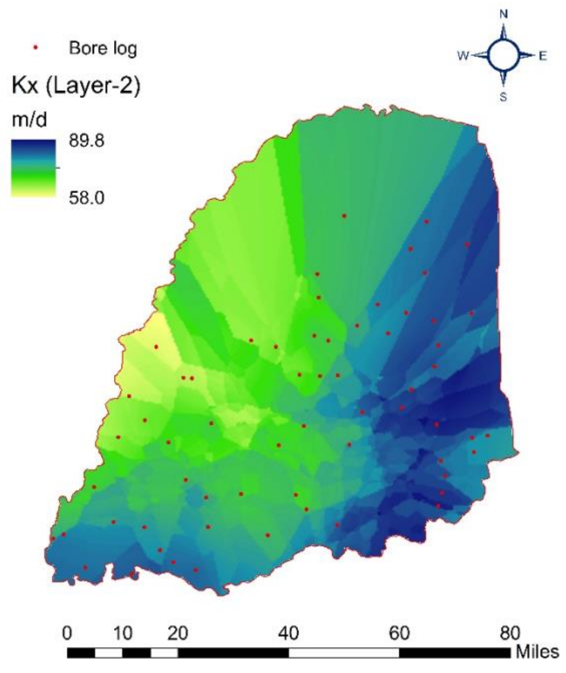


Lithology description of a bore log in Lodhran

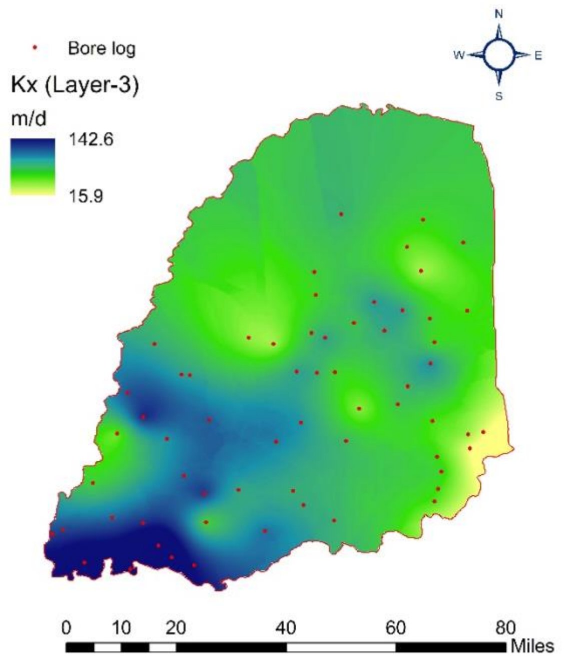
Figure 17. Lithology descriptions of selected bore logs across the study area



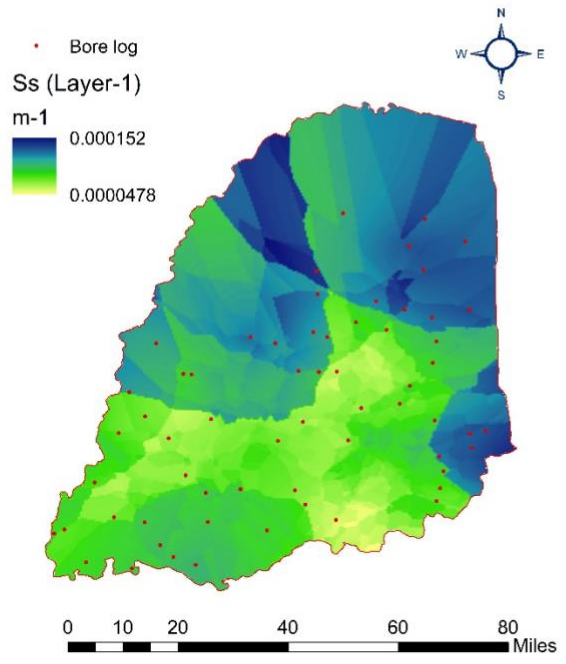
Spatial variation in hydraulic conductivity for Layer 1



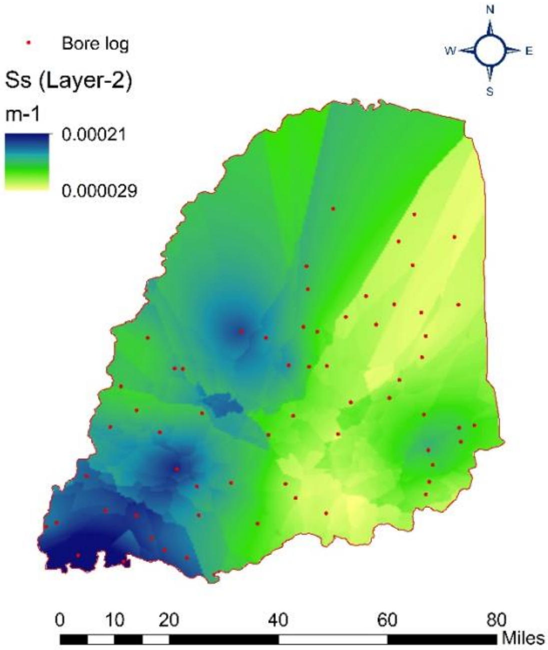
Spatial variation in hydraulic conductivity for Layer 2



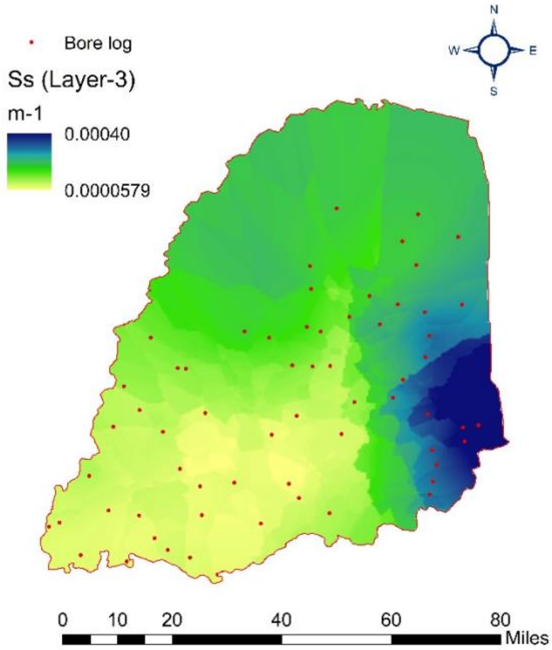
Spatial variation in hydraulic conductivity for Layer 3



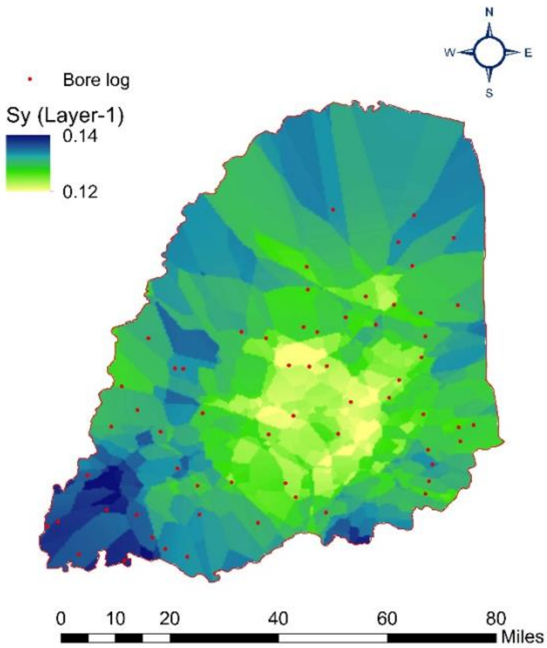
Spatial variation in specific storage for Layer 1



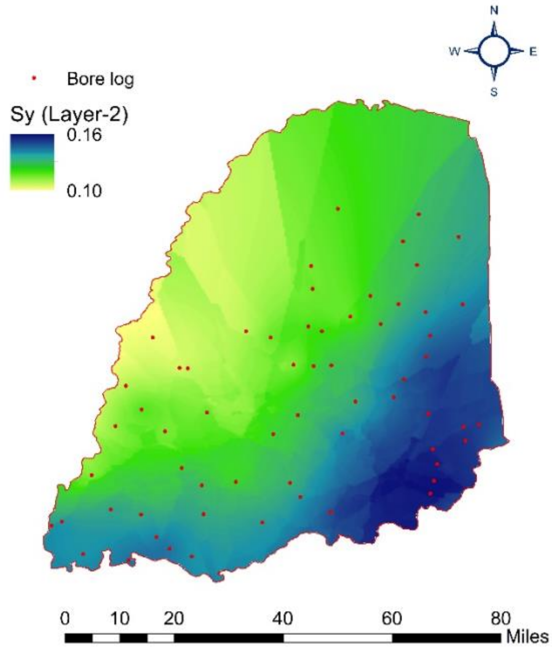
Spatial variation in specific storage for Layer 2



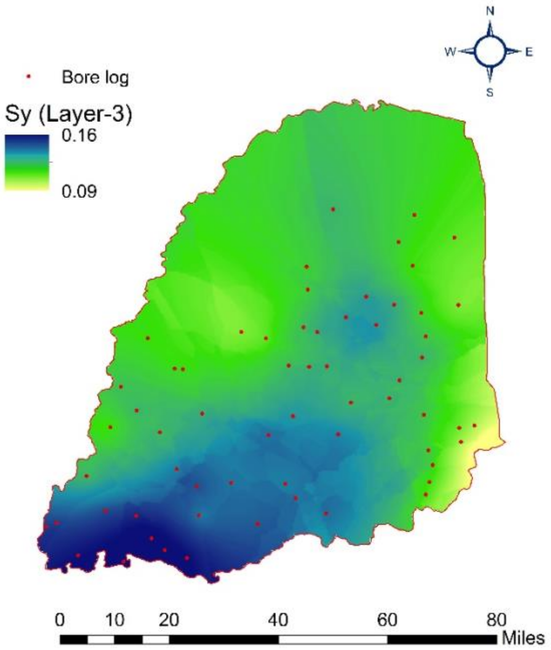
Spatial variation in specific storage for Layer 3



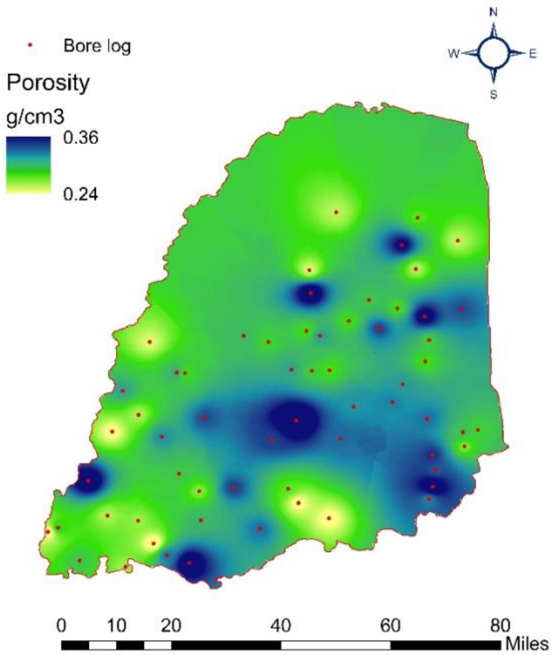
Spatial variation in specific yield for Layer 1



Spatial variation in specific yield for Layer 2



Spatial variation in specific yield for Layer 3



Spatial variation in soil porosity for all layers

Figure 18. Spatial variations of different aquifer properties for different layers

4.4. Rainfall

The study area consisted of four administrative units – Multan, Khanewal, Vehari, and Lodhran. There is only one rain gauge installed by the Pakistan Metrological Department (PMD) in the Multan district, and that is insufficient to estimate the rainfall precisely for the whole study area. Therefore, the Multi-Source Weighted-Ensemble Precipitation (MSWEP) product was used to estimate the rainfall data. The MSWEP is a global precipitation dataset with a 3-hourly (three hour lag with real-time) at 0.1° resolution that is accessible from 1979. The product is unusual in that it combines satellite, gauge, and reanalysis data to produce the most accurate precipitation estimates for every location. A decade mean monthly rainfall record shows that the maximum rainfall was 326 mm/yr during July 2015 (Figure 19). The annual average rainfall record depicts 211 mm/yr with maximum and minimum of 543 and 54 mm/yr during 2015 and 2018, respectively (Figure 20).

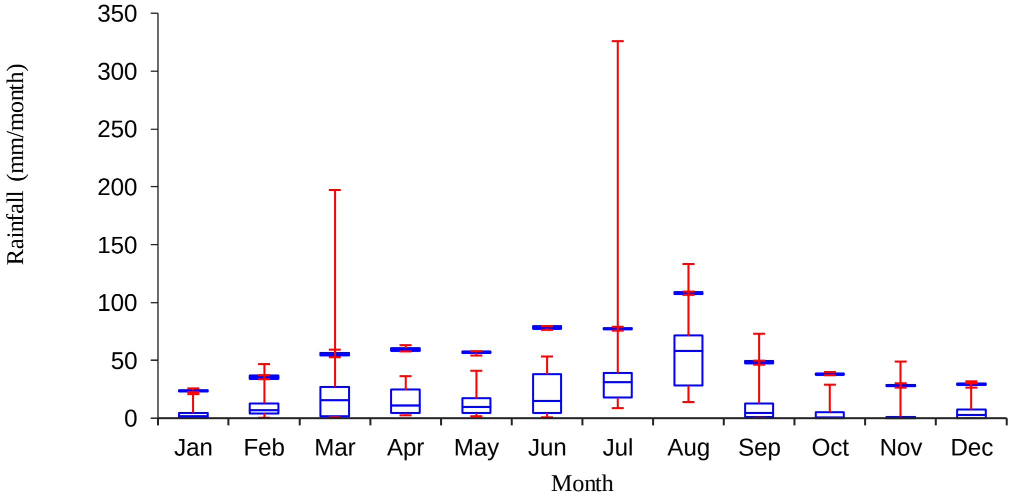


Figure 19. Mean monthly rainfall in the study area

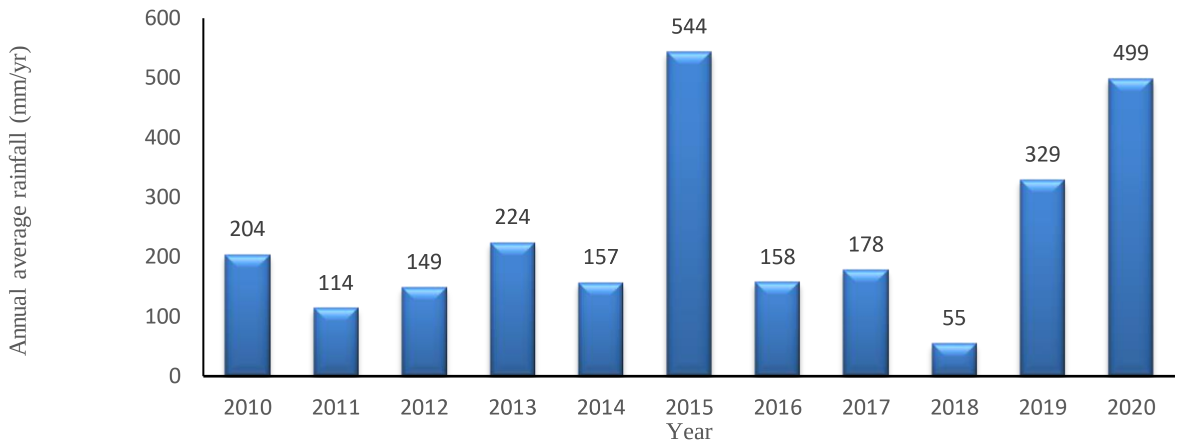


Figure 20. Annual average rainfall in the study area

4.5. Recharge

The groundwater aquifer is replenished by seepage from the river, leakage from the irrigation network, field percolation from return flows from canal and tubewell irrigation, and rainwater percolation. It is recharged mainly by seepage from rivers and canals, and to a lesser extent, through precipitation because the study area falls in the semi-arid climate zone. Seepage losses from the main canal account for 10% of the flow available at the head and 90% of this seepage contributes as groundwater recharge. Distributaries account for a seepage loss of about 15% of the available discharge and 85% of that seepage becomes groundwater recharge. Similarly, 25% of the discharge available at the watercourse head seeps down as losses and 80% of seepage goes to groundwater. The remainder of the available water from the supply system is applied to the field of which 25% of the irrigation applied seeps down and becomes a part of the groundwater system, i.e., return flow. Seepage from the Ravi, Chenab and Sutlej Rivers is generally directed towards the study area, where part of the seepage along the Chenab River evaporates and the remainder contributes to the aquifer as groundwater recharge. Part of the river leakage goes out of the system as lateral outflows. Similarly, field application losses from the main canals, branch canals, and distributaries also contribute to groundwater recharge (Table 5).

Table 5. Seepage losses and groundwater recharge through the irrigation system

System component	Q at head	Losses (L) %	Recharge to groundwater (factor applied to losses)
Main Canal	Q main	10	0.90
Distributary	Q d	15	0.85
Watercourse	Q w/c	25	0.80
Field	Q f	25	0.70

$$Rch_{i,j} = f_1 \times R_{i,j} + f_2 \times Ic_{i,j} + f_3 \times Ip_{i,j} \quad (1)$$

Where f_1, f_2, f_3 are the percentage factors which were adjusted during calibration, $R_{i,j}$ = Rainfall in the model cell, $Ic_{i,j}$ = Canal irrigation return to the model cell, and $Ip_{i,j}$ = Pumping irrigation return to the model cell.

4.6. Crop Water Requirements

The evapotranspiration (Eta) data were computed based on the CSIRO MODIS Rescaled Evapotranspiration (CMRSET) model that integrates Global Vegetation Moisture Index (GVMI) and Enhanced Vegetation Index (EVI) data on a 500 m resolution. Evapotranspiration data were initially computed on a 10 daily basis and then aggregated on an average monthly scale. Reference evapotranspiration (ETo) was calculated using the Hargreaves method. The crop factor (Kc) was computed using 10 daily cloud free composites of EVI and GVMI obtained from the Google Earth Engine (GEE) from the MODIS product (Ahmad et al., 2023).

Five major crops – wheat, maize, cotton, sugarcane, and rice – are being sown in Southern Punjab. Cotton, rice and forage are cultivated during the Kharif season, while wheat is the main Rabi crop. Sugarcane is also cultivated as an annual crop from March to Feb. A 10-year annual average of crop evapotranspiration data shows that the annual average crop water requirement in the area is 1010 mm/yr with maximum and minimum values of 1086 and 942 mm/yr, respectively (Figures 21 and 22).

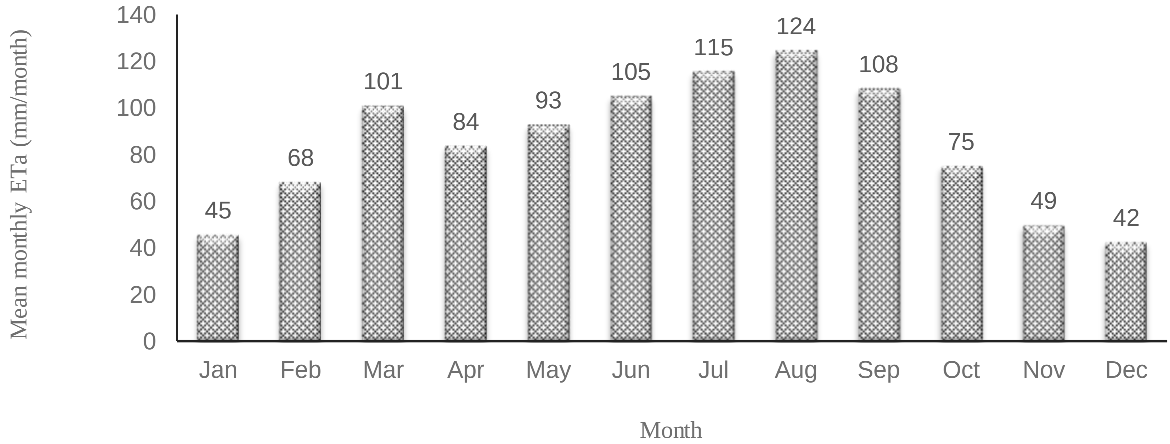


Figure 21. Annual average crop water requirement during the Rabi season

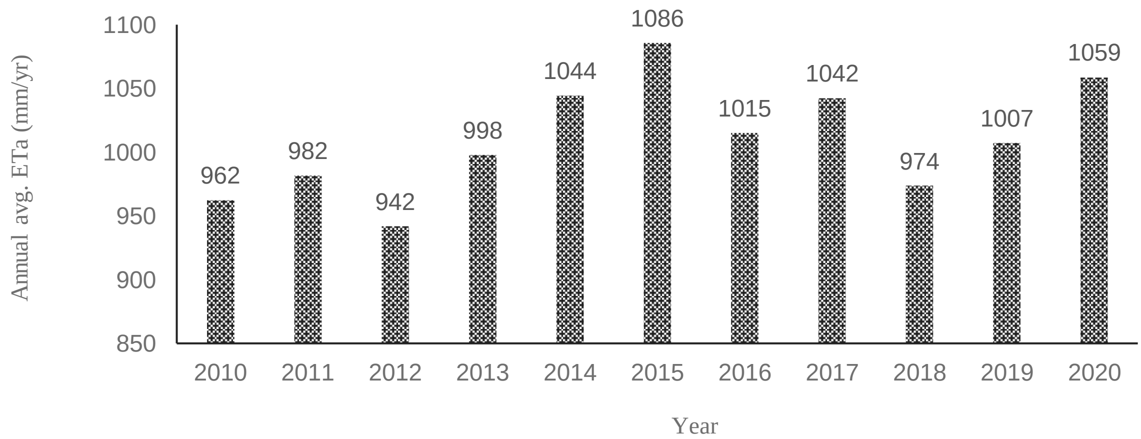


Figure 22. Annual average crop water requirement during the Kharif season

4.7. Tubewell Pumping

According to the Punjab Bureau of Statistics, there were 44,687 tubewells in 2010, which increased to 52,782 in 2020 in the study area (Figure 23). The uncontrolled increase in the number of tubewells over these 10 years is responsible for the declining watertable in the area.

Total groundwater pumping was estimated using a utilisation factor approach and calculated each month based on the monthly crop water requirements. This approach was adopted as tubewells are not metered and the volume of groundwater extraction in the area is an unknown. The utilisation factor depends on operational hours in a day, working days in a year, and the type of tubewell, i.e., diesel or electric (Table 6). Groundwater extraction for a single tubewell and total pumping for the total number of tubewells were calculated. The average monthly groundwater pumping was then estimated based on the monthly variation in evapotranspiration. This approach allowed for temporal variation in pumping being included in the model. The utilisation factor was computed using the equation below:

$$UF\ (\%) = \frac{\text{number of tubewell operation hours in a year}}{\text{the total number of hours in a year}} \times 100$$

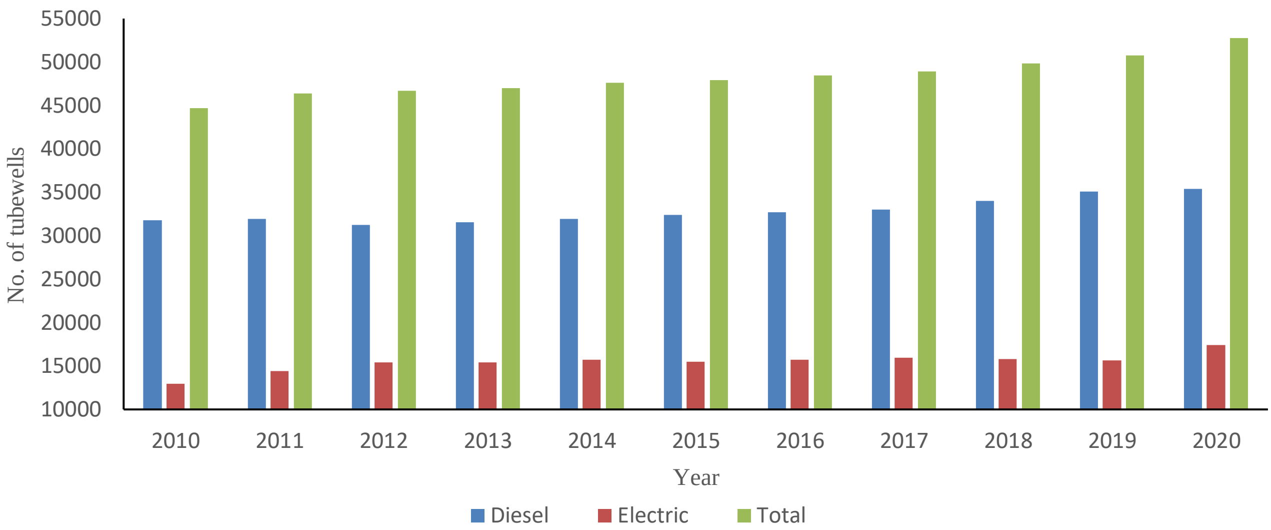


Figure 23. Number of tubewells in the study area (2010–2020)

Table 6. Utilisation factor as influenced by the tubewell type and growing season

Type	Days/yr	Hours/day	Q (cfs)	Utilisation factor (%)
Diesel	124	4.5	0.7	19
Electric	183	6	1.5	25

4.8. Climate Data Projections

Under the Coupled Model Intercomparison Project Phase 6 (CMIP6), the Shared Socioeconomic Pathways (SSPs) offer a framework for evaluating potential future global development pathways depending on various socioeconomic aspects (O'Neill et al., 2016). The SSPs comprise five discrete scenarios, each depicting a distinctive narrative of future socioeconomic conditions (Gidden et al., 2019). Climate model simulations use these scenarios, which range from SSP1 (sustainability-focused) to SSP5 (high obstacles to mitigation and adaptation), as a framework to evaluate the possible effects of various societal decisions on climate change (Akinsanola & Kooperman, 2022). These scenarios are used by researchers to explore a variety of conceivable futures, enabling a thorough grasp of the probable climate consequences under various socioeconomic trajectories.

A widely used method for bias reduction in climate data is quantile mapping. To correct biases in the model outputs and ensure a more precise representation of historical climate patterns, this statistical technique entails matching the cumulative distribution functions of observed and model-simulated data (Maraun, 2013). The significance of the CMIP6 dataset for impactful assessment and planning for adaptation is enhanced by this correction technique (Qian & Chang, 2021).

This approach used the observed data of the Multan district for a significant duration, i.e., thirty years from 1991–2020, obtained from the Pakistan Metrological Department (PMD). The Global Circulation Model (GCM) climate data were obtained and extracted for the same spatial and temporal extent for intermediate and extreme climate change scenarios, i.e., SSP2-4.5 and SSP5-8.5, respectively. These data are freely accessible on the Earth System Grid Federation (ESGF). Through quantile mapping, the data for rainfall and T_{mean} were then bias-corrected for 2021 to 2100 under both climate change scenarios.

The projected rainfall data showed the maximum rainfall under the SSP2-4.5 and SSP5-8.5 scenarios will be 453.1 and 498.5 mm/month during September 2095 and September 2088, respectively (Figure 24). The annual average and maximum rainfall under the SSP2-4.5 and SSP5-8.5 scenarios will be 206.6, 793.1 and 196, 579.2 mm/year in 2088, respectively, showing the relatively lower rainfall under the SSP5-8.5 scenario. Similarly, the projected mean temperature (T_{mean}) data showed a maximum T_{mean} under the SSP2-4.5 and SSP5-8.5 scenarios will be 41.5 °C and 46.9 °C during July 2098 and July 2095, respectively (Figure 25). The annual average T_{mean} data under the SSP2-4.5 and SSP5-8.5 scenarios will be 28.7 °C and 30.6 °C, respectively, showing a higher average temperature under the SSP5-8.5 scenario.

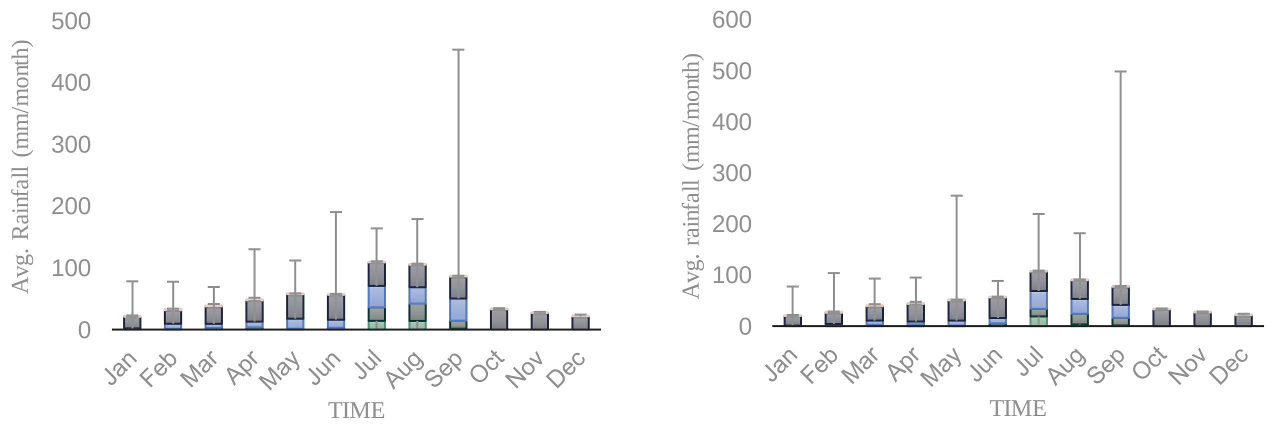


Figure 24. Average monthly rainfall under SSP2-4.5 and SSP5-8.5 scenarios (2021-2100)

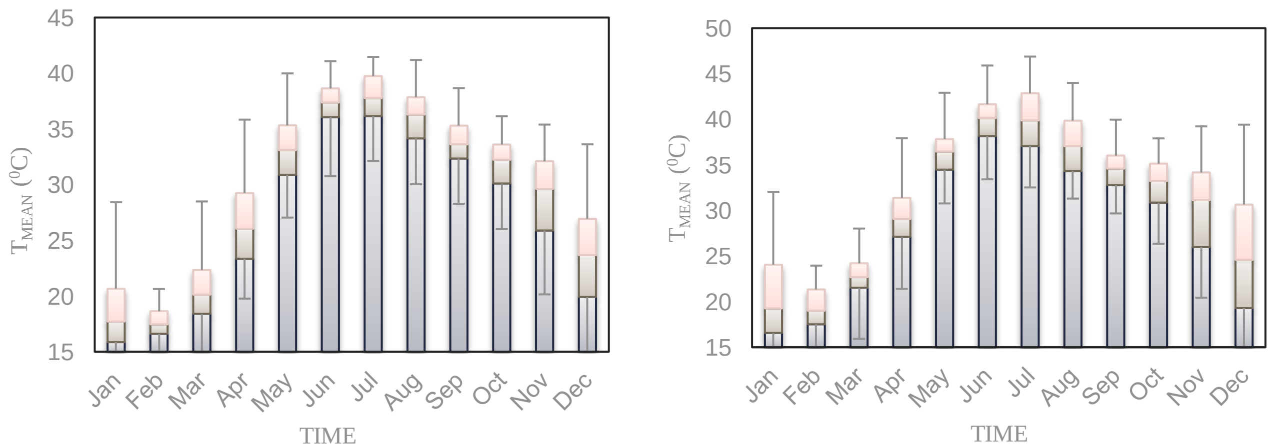


Figure 25. Average monthly mean temperature (T mean) under SSP2-4.5 and SSP5-8.5 scenarios (2021-2100)

5. Sensitivity Analysis

Accurately depicting groundwater systems is essential in hydrogeological modelling for making informed decisions on managing groundwater resources. Groundwater models are valuable for modelling the complex interconnections among geological, hydrological, and hydraulic elements affecting subsurface water flow behaviour. However, such models are susceptible to a variety of uncertain parameters, which can have a substantial impact on their projections. Sensitivity analysis helps to systematically assess the influence of parameter alterations on model outputs. Decision-makers and hydrogeologists can acquire deeper insights into the behaviour of the groundwater system, identify key causes of system behaviour, and improve the dependability of model-based forecasts by investigating the model's sensitivity to diverse input parameters. This study explores a thorough sensitivity analysis of critical parameters inside a groundwater model, revealing their relative importance and paving the path for more precise and realistic hydrogeological simulations.

The parameters hydraulic conductivity (K), specific yield (Sy), specific storage (Ss), and recharge were used to run the sensitivity analysis using the multipliers 0.25, 0.5, 1.0, 1.5, and 2.0. The permissible limits of aquifer parameters (K, Sy and Ss) were counter verified with the literature and field values. It was found that hydraulic conductivity and specific yield were the most sensitive parameters. The sensitivity analysis results shown in Figure 16 indicate the calibration is best at the lowest absolute mean.

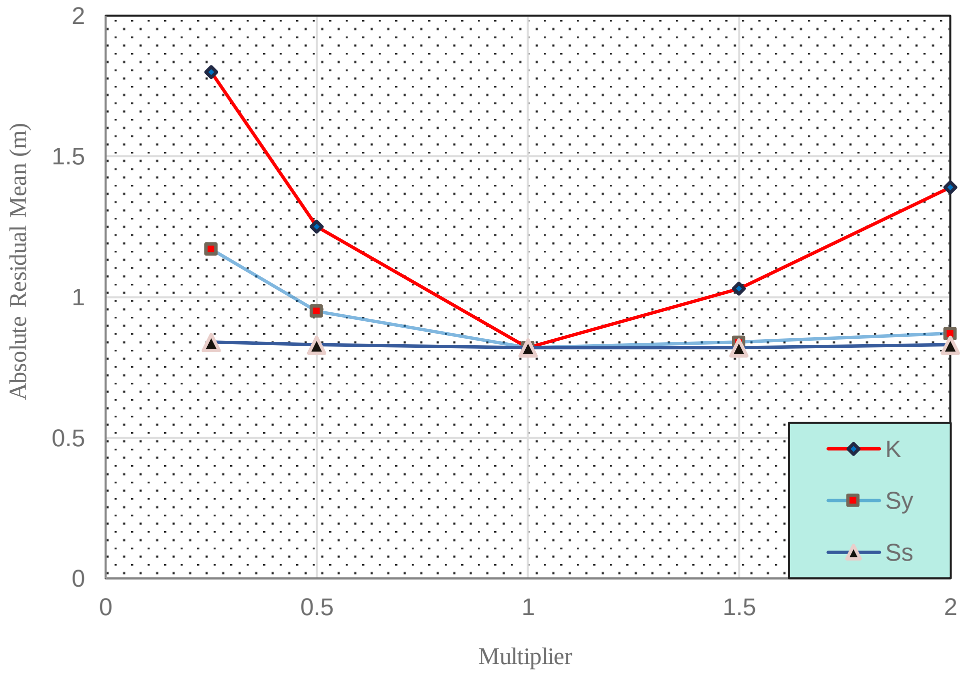


Figure 26. Sensitivity analysis plots of hydraulic conductivity, specific yield and specific storage of aquifer

6. Model Calibration

Calibration is an important step in groundwater modelling since it entails meticulously adjusting model parameters to obtain an appropriate correspondence between the modelled and observed values. This iterative process improves the model's description of hydrogeological processes, enhancing predictions and encouraging a better understanding of subsurface systems. Calibration entails adjusting variables such as hydraulic conductivity, specific yield, specific storage, and recharge rates to minimise differences between simulated and actual data points such as groundwater levels and flow rates. Several statistical indicators are typically applied to logically analyse the calibration performance. They are discussed below:

Root Mean Square Error (RMSE) measures the square root of the difference between observed and simulated average values. It is calculated as:

$$\sqrt{\frac{1}{n}\sum_{i=1}^{n}(h_0 - h_s)^2}$$

Mean Absolute Error (MAE) measures the average absolute deviations between observed and simulated values. It is calculated as:

$$\frac{1}{n}\sum_{i=1}^{n}|h_0 - h_s|$$

Mean Error (ME) measures the average deviations between observed and simulated values. It is calculated as:

$$\frac{1}{n}\sum_{i=1}^{n}(h_0 - h_s)$$

Before calibrating the model, a sensitivity analysis was performed to assess the model's sensitive parameters. Then, the values of different parameters like riverbed conductance, recharge and pumping rates, and aquifer lithology (K, Sy and Ss) were adjusted to minimise the difference between simulated and observed head as much as possible.

6.1. Steady State Model Calibration

The steady-state model was developed and calibrated to provide initial heads for October-2010. A total of 23 target points representing the whole study area with the water levels of post-2010 period were selected for the model calibration. A comparison of observed and simulated heads is shown in Figure 27.

6.2. Steady State Calibration Statistics

Most target (15) points showed residual ranges of less than 1 m, while nine observation wells ranged from 1 to 1.4 m. The model was calibrated with an absolute residual mean of 0.89, a residual mean of -0.50, and a root mean square value of 0.94, which was considered acceptable.

6.3. Transient Calibration Statistics

The model was simulated from Oct-2010 to Sep-2020 with 120 stress periods. The absolute residual mean (ARM) was 0.85m using 363 observed values that were spatially distributed, indicating that the model is calibrated reasonably well. The calibration statistics for transient-state conditions against different statistical parameters are shown in Table 7. The plot between observed and simulated head values is represented in Figures 28 and 29 respectively indicate good calibration results.

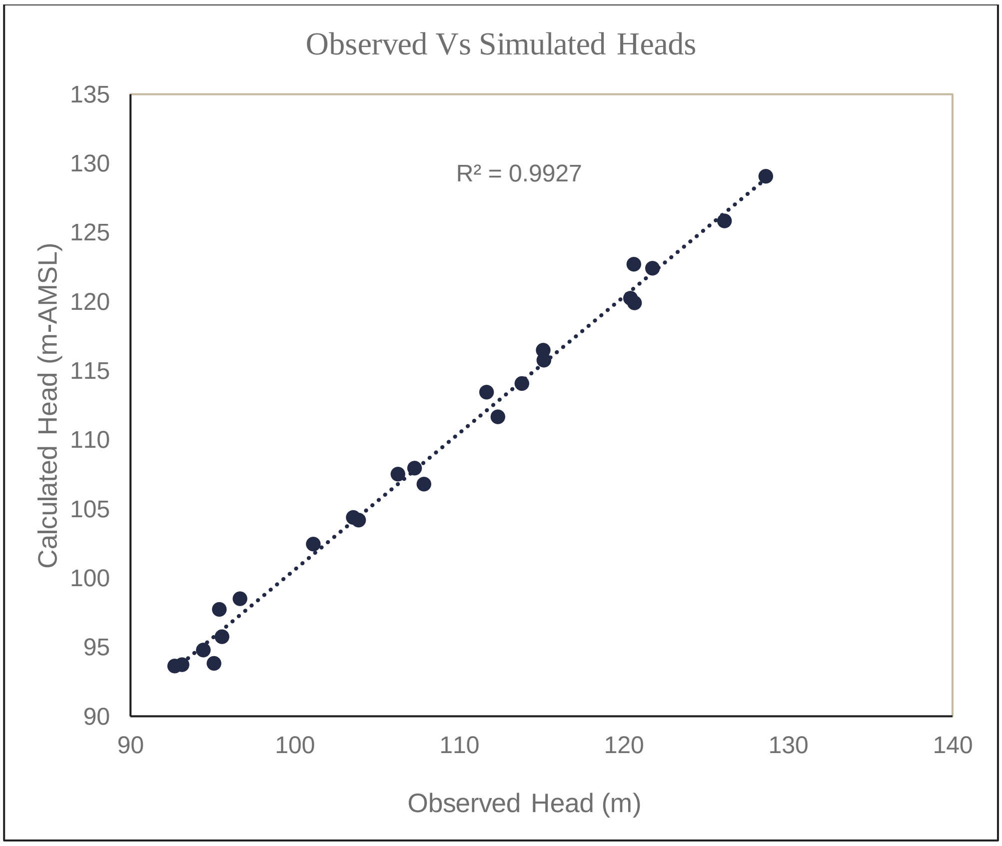


Figure 27. Simulated versus observed head (metres above mean sea level) values for steady state calibration

Table 7. Statistical parameters for transient state model calibration

Parameter	Calibrated statistics
Res. Mean	0.03
Abs. Res. Mean	0.95
Res. Std. Deviation	1.14
Sum of Squares	473
RMSE	1.14
Min. Residual	-4.20
Max. Residual	3.73
No. of Observations	363
Range in Observations	37.75

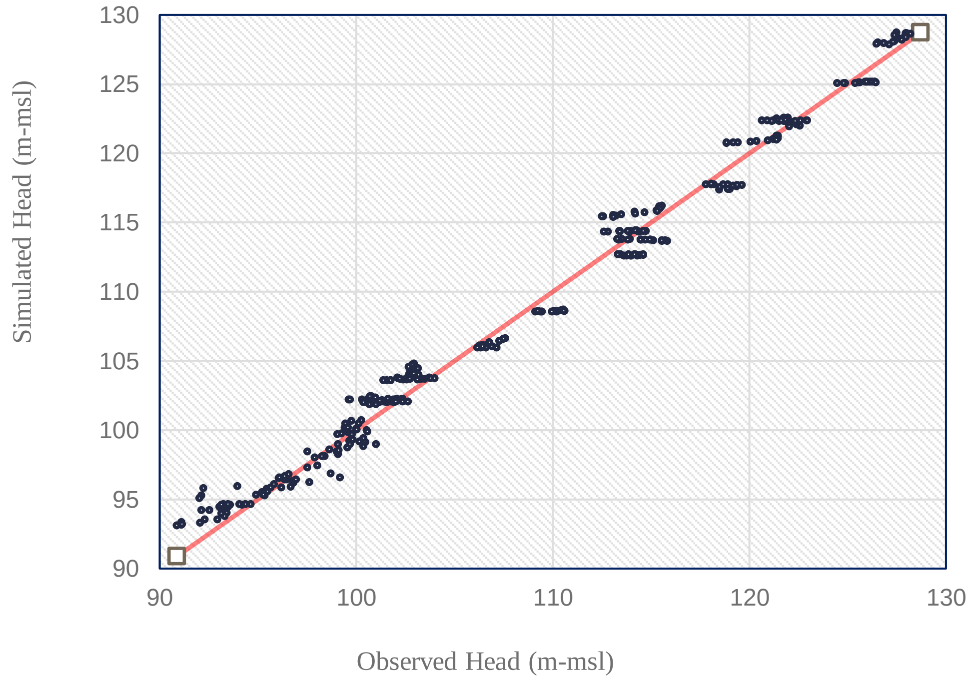


Figure 28. Model output showing observed versus calculated head (m-msl is metres mean sea level)

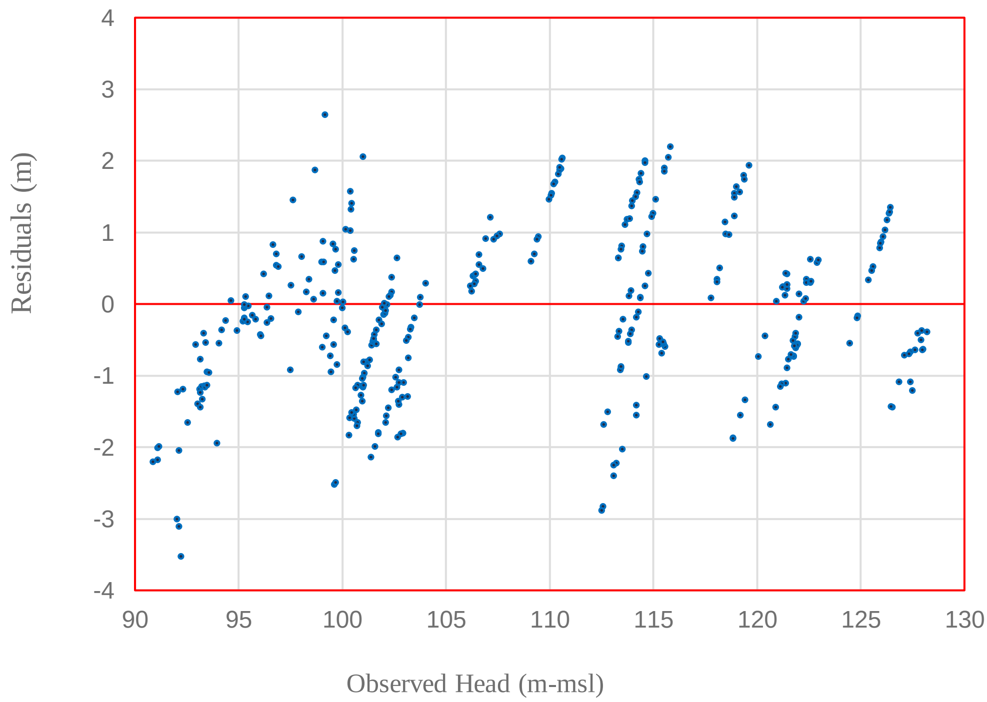
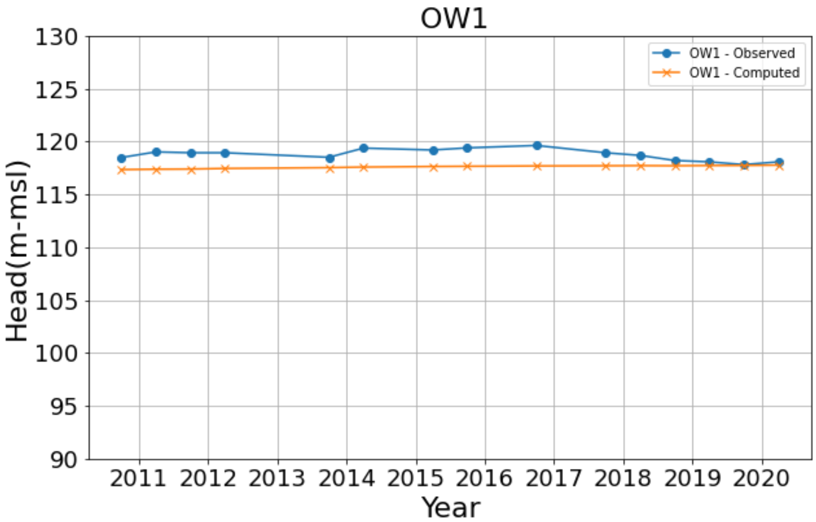
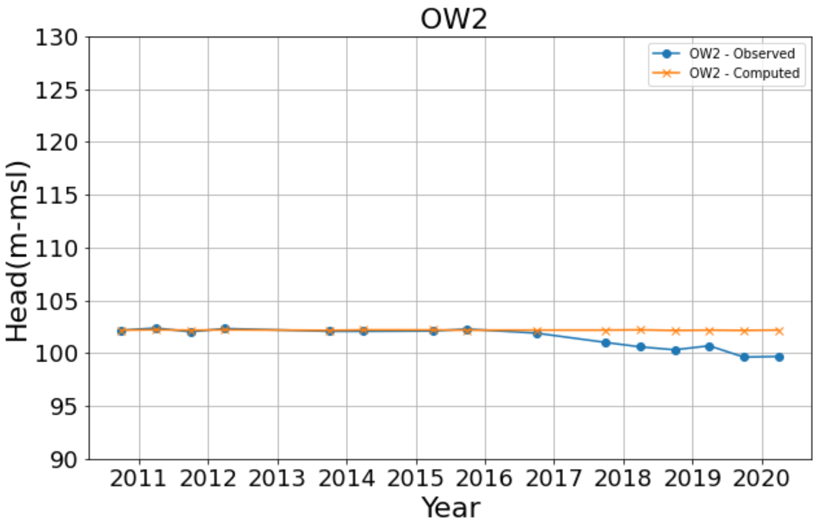


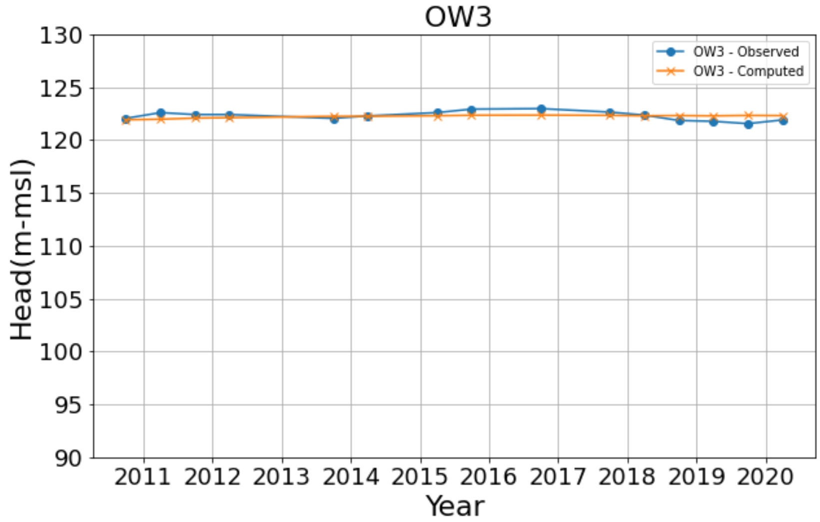
Figure 29. Model output showing observed versus residual values

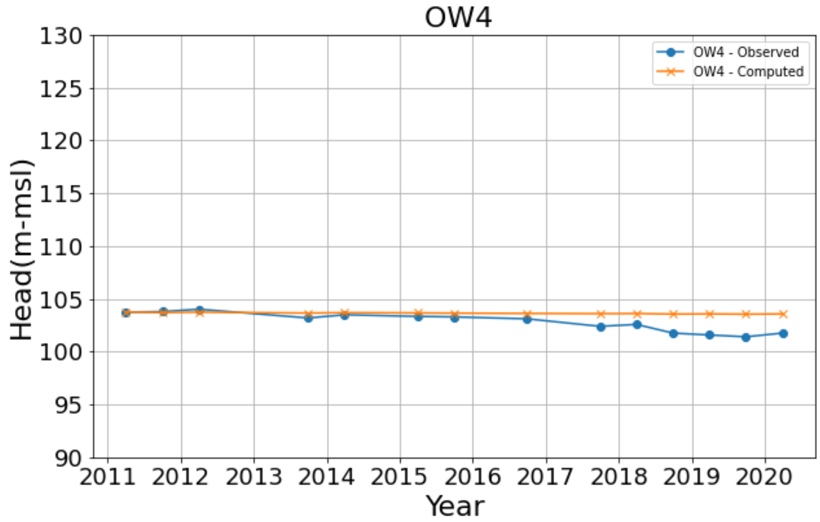
6.4. Hydrographs

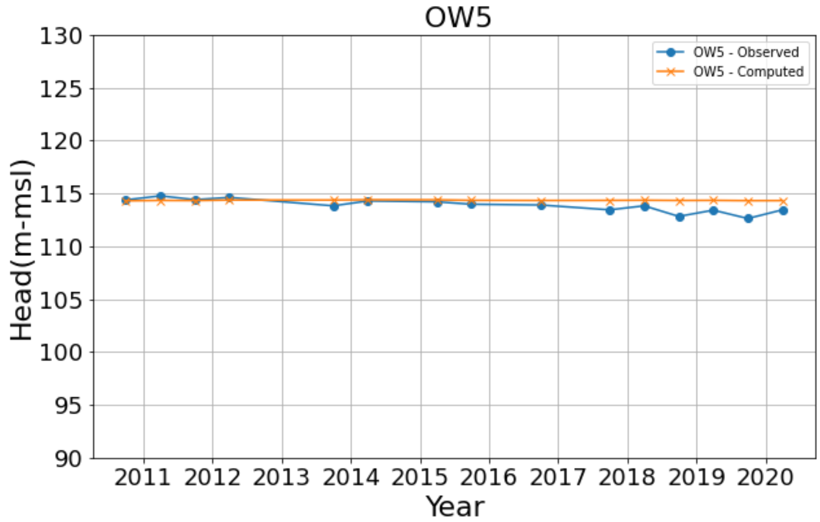
As discussed above, the PID measures the piezometers twice yearly – pre-monsoon (April) and post-monsoon (October) – while the model simulates heads monthly. Each observation well selected for target values contains an average of 15 measurements because measurements for four seasons were not present in the PID's database. The simulated hydrographs show reasonable agreement with observed data, indicating the temporal calibration is reasonable. Hydrographs for two piezometers, OW8 and OW18, located in the LBDC and Gujju Hatta sub-canal command, show the starting model head is slightly on the higher end; however, the trend is reasonable. Many of the piezometers showed declining observed and model head trends, except OW13 and OW15, which are located along the Sutlej River in the Lodhran sub-canal command, which showed a rising temporal trend in water levels. The selection of 23 observation wells has been represented below (Figure 30).

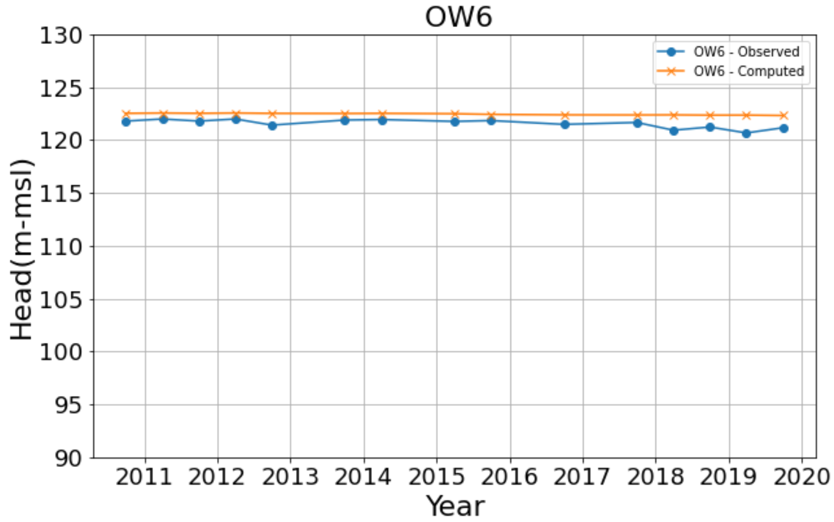


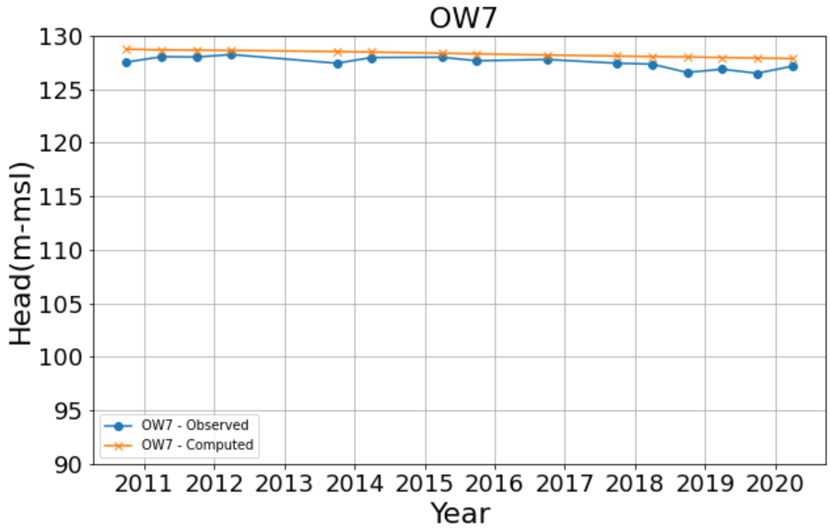


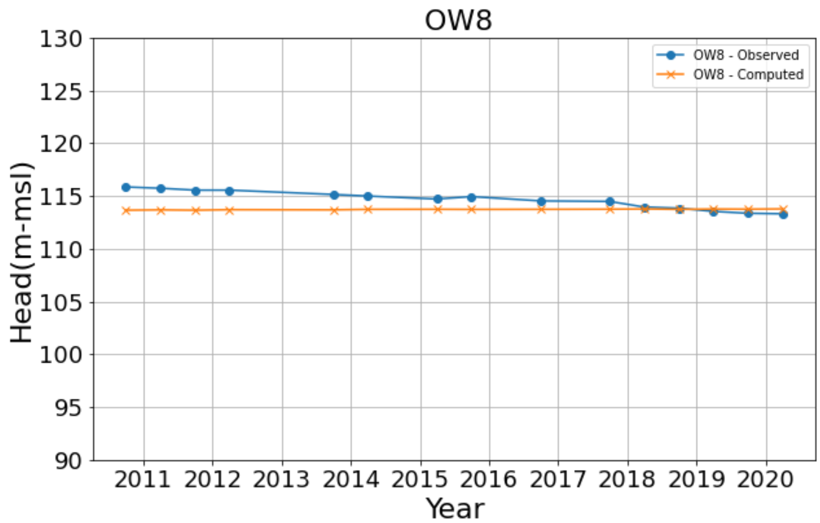

OW3
OW3 - Observed
OW3 - Computed
Head(m-msl)
130
125
120
115
110
105
100
95
90
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Year

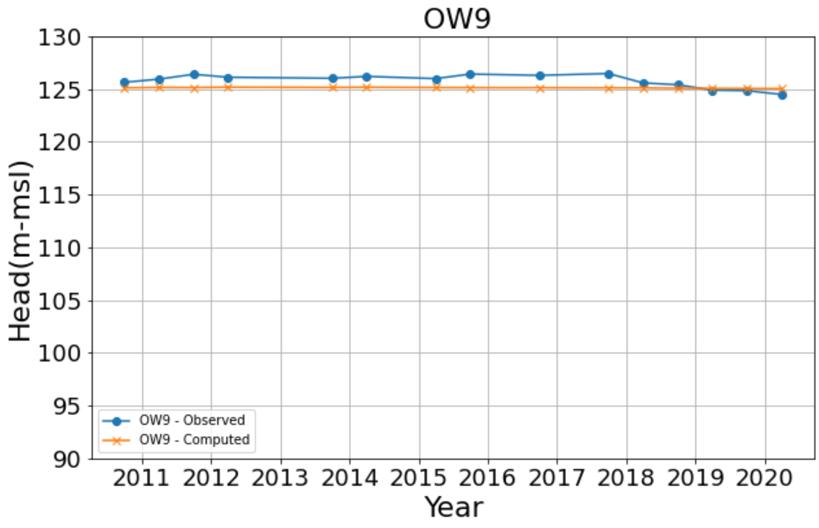

OW4
OW4 - Observed
OW4 - Computed
Head(m-msl)
130
125
120
115
110
105
100
95
90
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Year

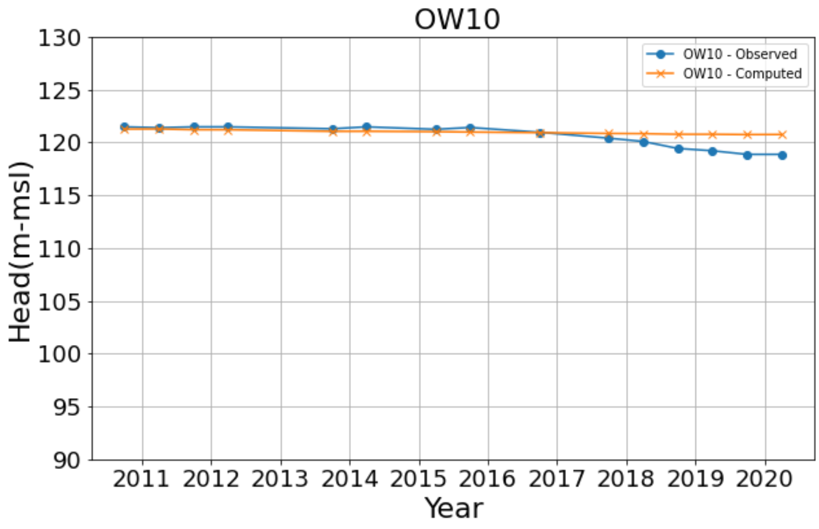

OW5
OW5 - Observed
OW5 - Computed
Head(m-msl)
130
125
120
115
110
105
100
95
90
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Year

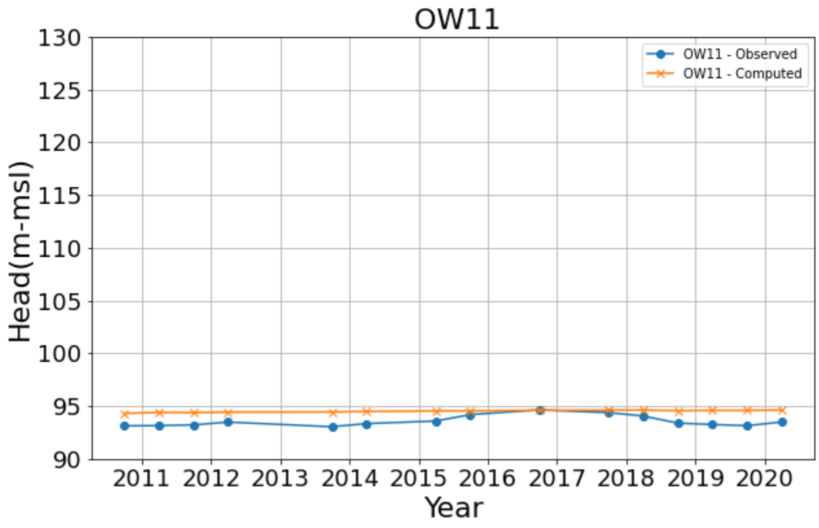

OW6
130
125
120
115
110
105
100
95
90
Head(m-msl)
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Year
OW6 - Observed
OW6 - Computed

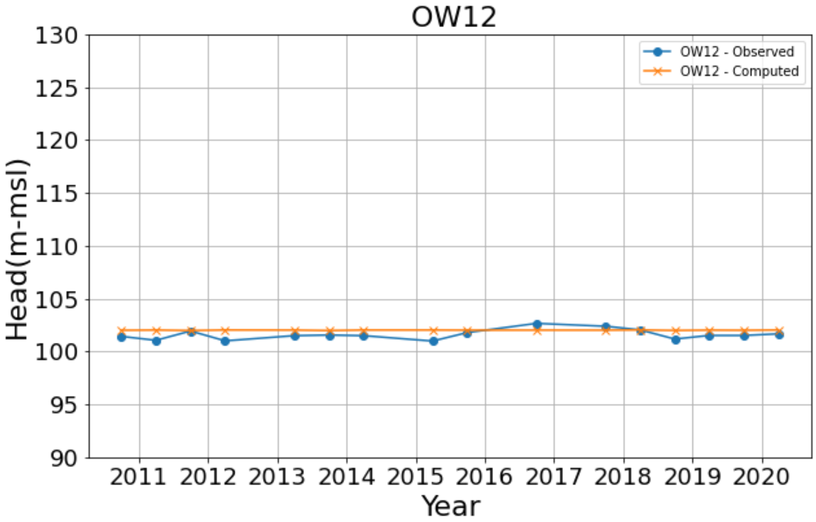

OW7
130
125
120
115
110
105
100
95
90
Head(m-msl)
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Year
OW7 - Observed
OW7 - Computed

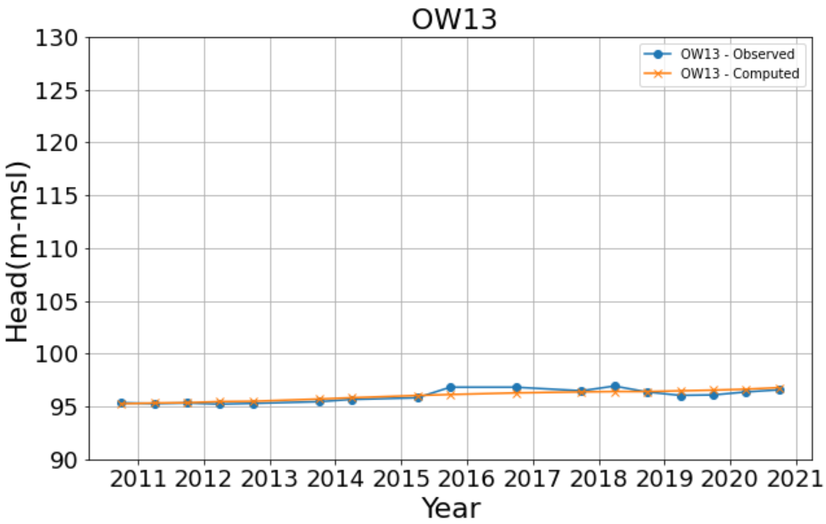

OW8
130
125
120
115
110
105
100
95
90
Head(m-msl)
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Year
OW8 - Observed
OW8 - Computed

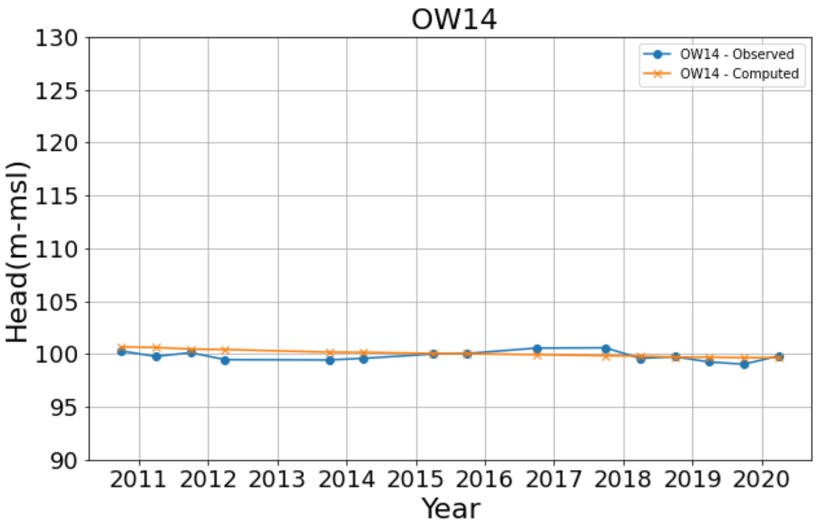

OW9
130
125
120
115
110
105
100
95
90
Head(m-msl)
OW9 - Observed
OW9 - Computed
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Year

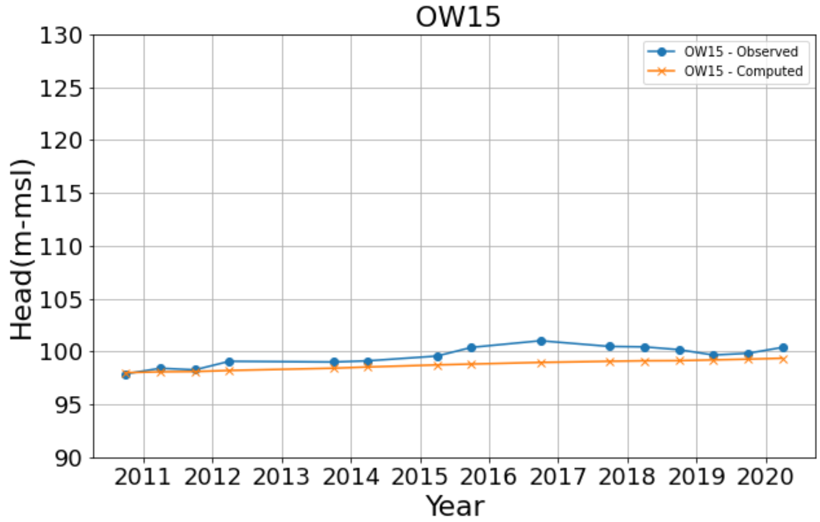

OW10
130
125
120
115
110
105
100
95
90
Head(m-msl)
OW10 - Observed
OW10 - Computed
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Year

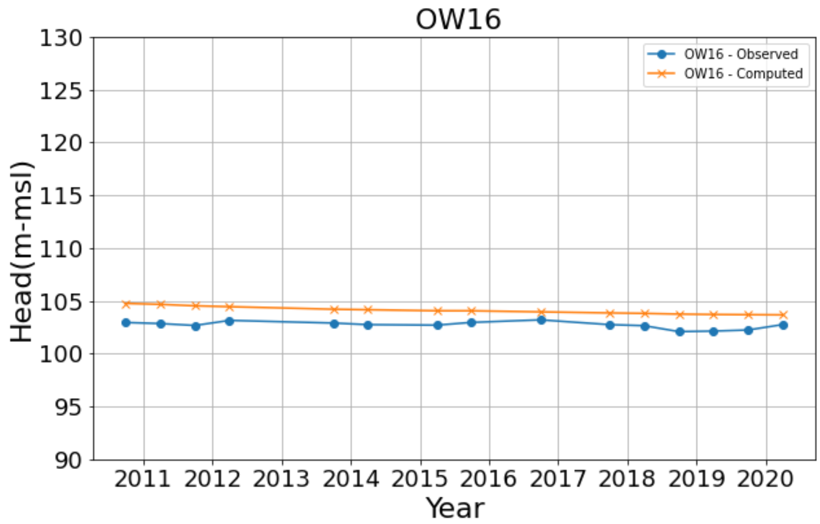

OW11
130
125
120
115
110
105
100
95
90
Head(m-msl)
OW11 - Observed
OW11 - Computed
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Year

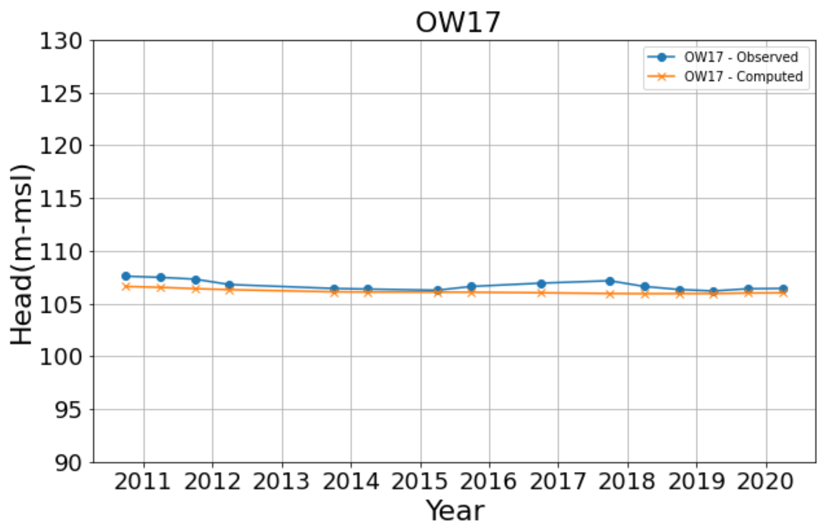

OW12
OW12 - Observed
OW12 - Computed
Head(m-msl)
130
125
120
115
110
105
100
95
90
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Year

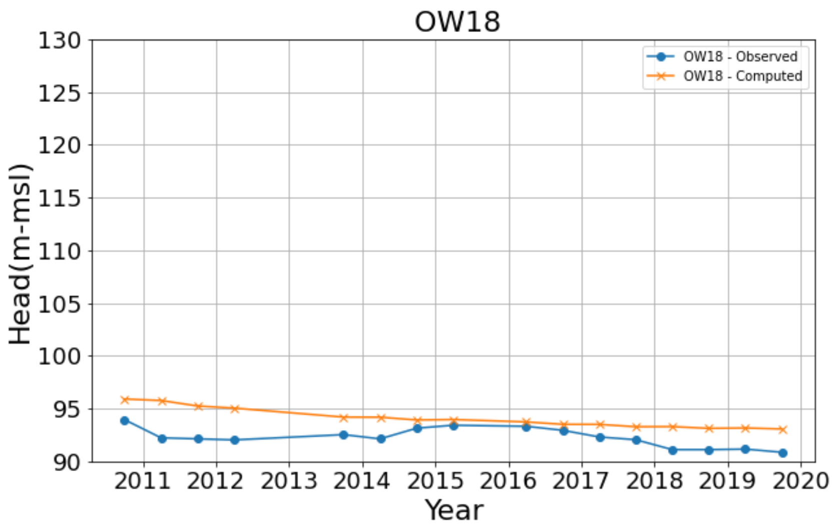

OW13
OW13 - Observed
OW13 - Computed
Head(m-msl)
130
125
120
115
110
105
100
95
90
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021
Year

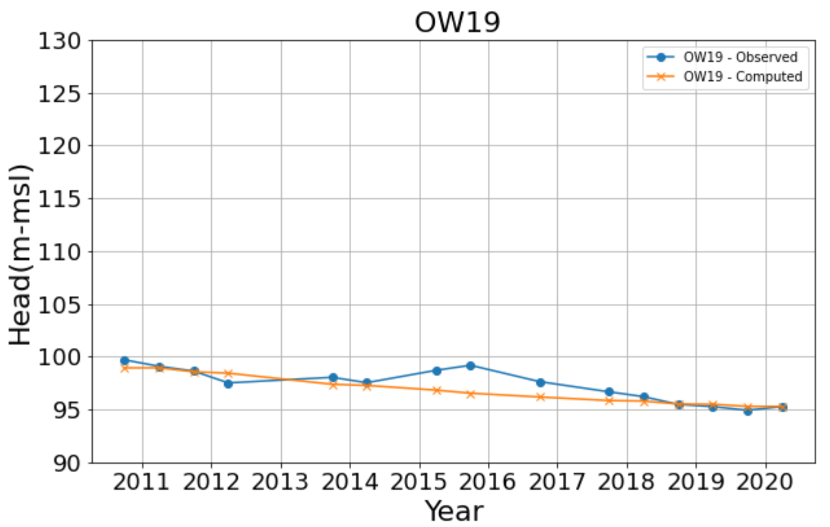

OW14
OW14 - Observed
OW14 - Computed
Head(m-msl)
130
125
120
115
110
105
100
95
90
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Year

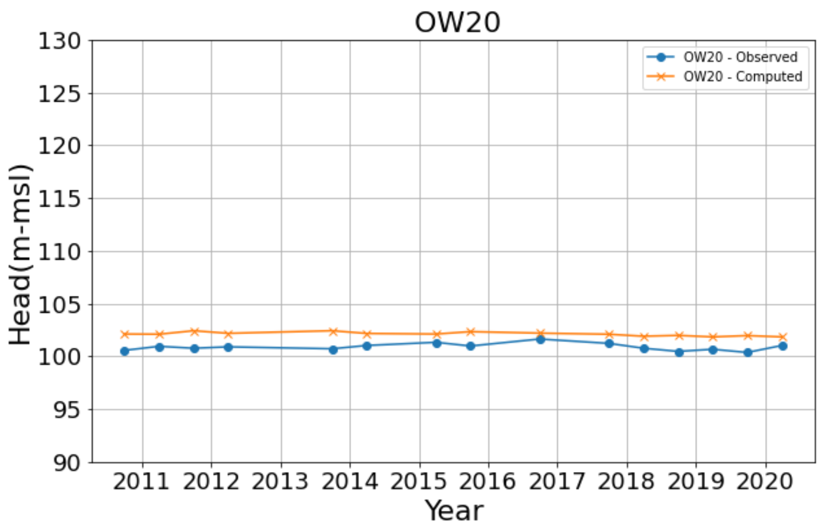

OW15
OW15 - Observed
OW15 - Computed
Head(m-msl)
Year


OW16
OW16 - Observed
OW16 - Computed
Head(m-msl)
Year


OW17
OW17 - Observed
OW17 - Computed
Head(m-msl)
Year


OW18
OW18 - Observed
OW18 - Computed
Head(m-msl)
Year


OW19
OW19 - Observed
OW19 - Computed
Head(m-msl)
Year


OW20
OW20 - Observed
OW20 - Computed
Head(m-msl)
Year

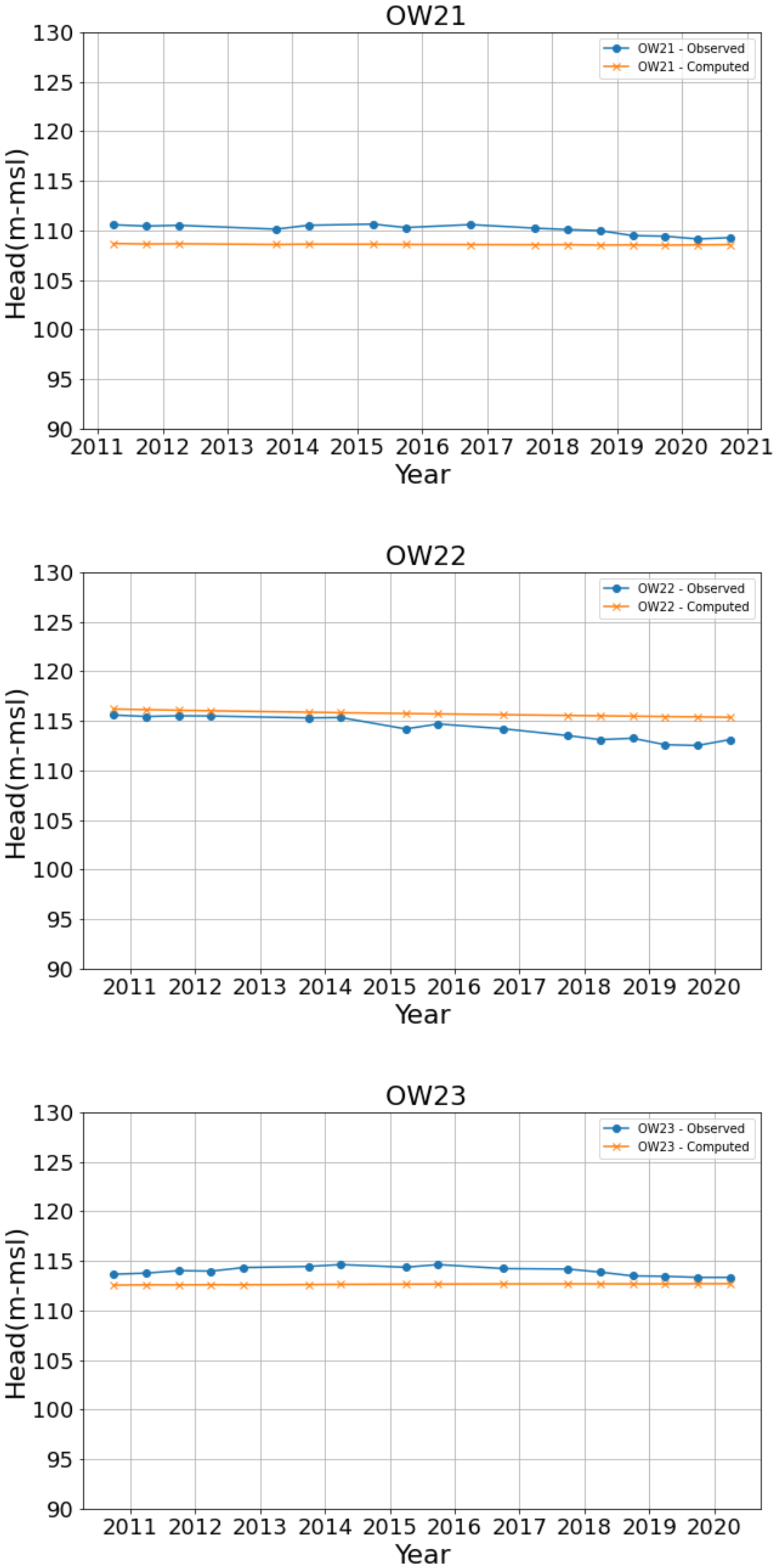


Figure 30. Simulated versus observed head (m-above mean sea level) for piezometers in the study area

6.5. Water Balance for the Southern Bari Doab Command

The water balance in the Southern Indus Basin provides useful insights into the impact of stressors on the underlying aquifer. The leakage of surface water channels, such as canals and distributaries, inflows from the river systems, and recharge from rainfall and field application losses, are the primary source of groundwater recharge in this basin. On the other hand, extraction through pumping wells is the major groundwater discharge source. All the recharging sources including rivers, main canals, branch canals and recharge were assigned in Layer 1. The pumping was assigned in Layer 2 based on the field observations that the average bore depth was more than 30m in dominating parts of the study area. The evapotranspiration rate was assigned to the top layer (Layer 1) with an extinction depth of 5m based on soils along the riverine areas where most of the evapotranspiration losses occur.

The model was developed for October 2010 to September 2020 with 120 stress periods (one stress period = one month). The water balance for the whole model states that total inflow from river and canal leakage is 1,637.3 MCM/yr while recharge from other mentioned sources was 1,485.8 MCM/yr. On the other hand, groundwater extraction was estimated at 3,355.5 MCM/yr. The level of evapotranspiration is very small i.e., 1.9 MCM/yr because of the deep watertable in the area. The net loss in aquifer storage is -533.4 MCM/yr for the calibration period (Table 8).

Table 8. Annual average groundwater balance of model (2010-2020)

Source	Inflow (MCM)	Outflow (MCM)	Net (MCM)
Recharge	1,485.8	0	**1,485.8**
River	1,637.3	-299.2	**1338.1**
Well	0	-3,355.5	**-3,355.5**
ETa	0	-1.9	**-1.9**
Net	**3,123.1**	**-3,656.6**	**-533.5**

Water enters through three sources in the top layer (Layer 1). There is river leakage, which comprises seepage from the Ravi, Chenab and Sutlej Rivers and from the extensive network of canals (1,637.3 MCM/yr), recharge (1,485.8 MCM/yr), and also from the middle layer (Layer 2) by upward flow (253.6 MCM/yr). The major outflow from Layer 1 to Layer 2, which is largely due to pumping concentrated in Layer 2, is gradually dewatering Layer 1. Other outflows, such as from the aquifer to the river (294 MCM/yr) and evapotranspiration (1.9 MCM/yr), are relatively small in comparison. The net storage for Layer 1 was -75.69 MCM/yr.

In the middle layer (Layer 2), the inflows from the top layer (Layer 1) were 3164.6 MCM/yr and from the deeper Layer 3 were 1,436.5 MCM/yr, while outflows to Layer 1 and Layer 3 were 258.3 and 1,034.5 MCM/yr, respectively. The most significant outflow was pumping at 3,355.5 MCM/yr. The net storage in Layer 2 was -50.4 MCM/yr, indicating water levels in both layers are declining gradually over time. However, Layer 2 attempts to balance the pumping stress by enhancing flows from the top and bottom layers.

In the bottom layer (Layer 3), the total volume of inflow from Layer 2 was 1,034.5 MCM/yr and outflow was 1,442.9 MCM/yr, with a net storage of -408.4 MCM/yr, as shown in Figure 31.

The above water balance indicates good connectivity between the three model layers, as evident when the aquifer is stressed, as shown by significant outflows from the top to the middle layer. As groundwater pumping occurs from the middle layer, it enhances flows from the top to the middle layer (Layer 2), gradually dewatering Layer 1. Additionally, the inflows into Layer 2 from the deeper Layer 3 will likely mobilise salinity from the deeper layers. Over time, this will result in increasing soil salinity.

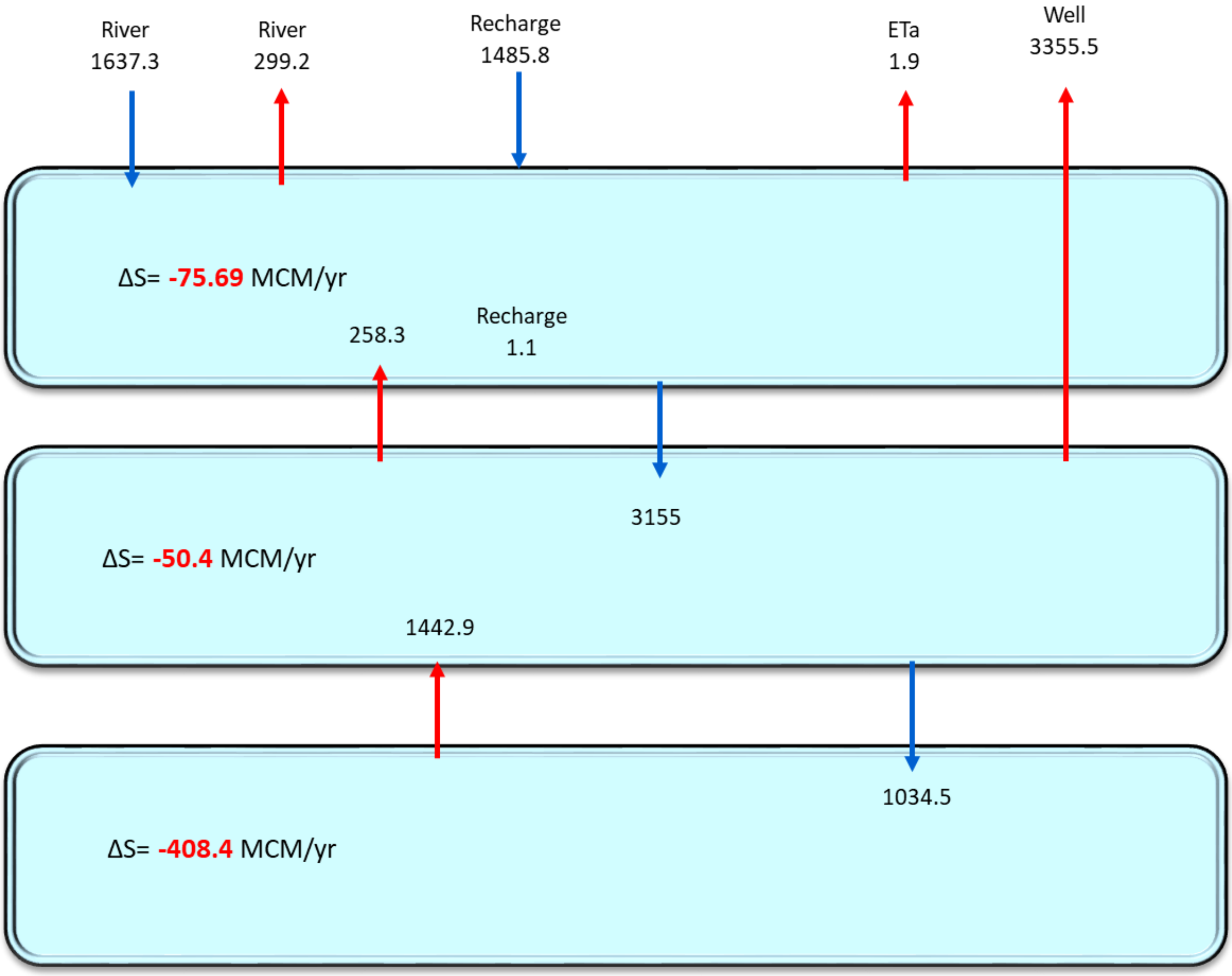


Figure 31. Groundwater balance for the transient-state model (2010-2020)

7. Scenario Modelling

Scenario modelling helps understand the impact of stresses on the groundwater system, which can guide the sustainable use of groundwater resources. It also guides policymakers in formulating a sustainable framework for groundwater management. The following scenarios were developed in consultation with staff from the PID, considering the socioeconomic and climate change impacts on the overall future demand for groundwater (Table 9). The first two scenarios were run from October 2010 to September 2060, while climate change scenarios SSP2-4.5 (intermediate greenhouse gas emissions) and SSP5-8.5 (very high greenhouse gas emissions) were included from October 2010 to September 2100. The overall groundwater balance for each scenario is represented in Table 10.

Table 9. List of scenarios simulated in the Southern Bari Boab model

Scenario Title	Scenario Description
Scenario 1: Baseline scenario – No change in current practices	All the hydrological stress remains the same as 2010–2020
Scenario 2: Increase in groundwater pumping with no change in canal supply	Cropping intensity and industrialisation are increasing, which will raise groundwater demand in future while canal supply remains unchanged
Scenario 4: Climate change Scenario SSP2-4.5	Shared Socioeconomic Pathway SSP2-4.5
Scenario 5: Climate change Scenario SSP5-8.5	Shared Socioeconomic Pathway SSP5-8.5

Table 10. Groundwater balance of the model under different scenarios

Inflows	Scenario 1 (Baseline)	Scenario 2 (Pumping Increase)	SSP2-4.5	SSP5-8.5
Simulation Period	2010-2060	2010-2060	2010-2100	2010-2100
River	1,748.8	1,815.2	2,045.8	2,048.6
Recharge	1,469.9	1,475.7	1,437.1	1,420.9
Total Inflows	**3,218.7**	**3,290.9**	**3,482.9**	**3,469.5**
Outflows	**Scenario 1**	**Scenario 2**	**SSP2-4.5**	**SSP5-8.5**
River	178.1	160.6	100.6	99.7
Well	3,341.1	4,068.8	5,573.8	5,573.8
ET	1.4	1.1	0.7	0.7
Total Outflows	**3,520.6**	**4,230.5**	**5,675.1**	**5,674.1**
Net	**-301.9**	**-939.6**	**-2,192.2**	**-2,204.6**

Two sets of four scenarios were simulated: managerial scenarios and climate change scenarios. The initial head conditions in October 2010 were considered as the starting point for these scenarios. These scenarios were developed to inform the irrigation department about the impact of declining trends in water levels in response to increased pumping and climate change impacts on groundwater conditions in the Sujawal district. These were simulated to guide the development of a policy brief for Southern Punjab. Table 10 summarises the water balance for the management and climate change scenarios undertaken. A key message from these scenarios is the loss in groundwater storage in response to increased pumping based on trends observed over the decade from 2010 to 2020. Under the climate change scenarios, the loss in groundwater storage would significantly increase to -2192.2 MCM/yr for the SSP2-4.5 scenario and similarly for the SSP5-8.5 scenario. This loss in storage would lead to unacceptable outcomes for irrigators and smallholder farmers in Southern Punjab.

7.1. Scenario 1: Baseline Scenario: Policy Remains Unchanged

The layered water balance of the baseline (BL) scenario for October 2010 to September 2020 is presented in Figure 32. The water balance under the BL scenario indicates if the conditions from October 2016 to September 2020 remain unchanged, the net loss in the storage will be -301.9 MCM/yr compared to a net loss in storage of -533.4 MCM/yr during the calibration period (October 2010 to September 2020). The estimated groundwater pumping will be 3,341.1 MCM/yr if conditions remain unchanged. Hydrographs of selected piezometers indicate that water levels are expected to stay same up to 2060 under the BL scenario (Figure 33).

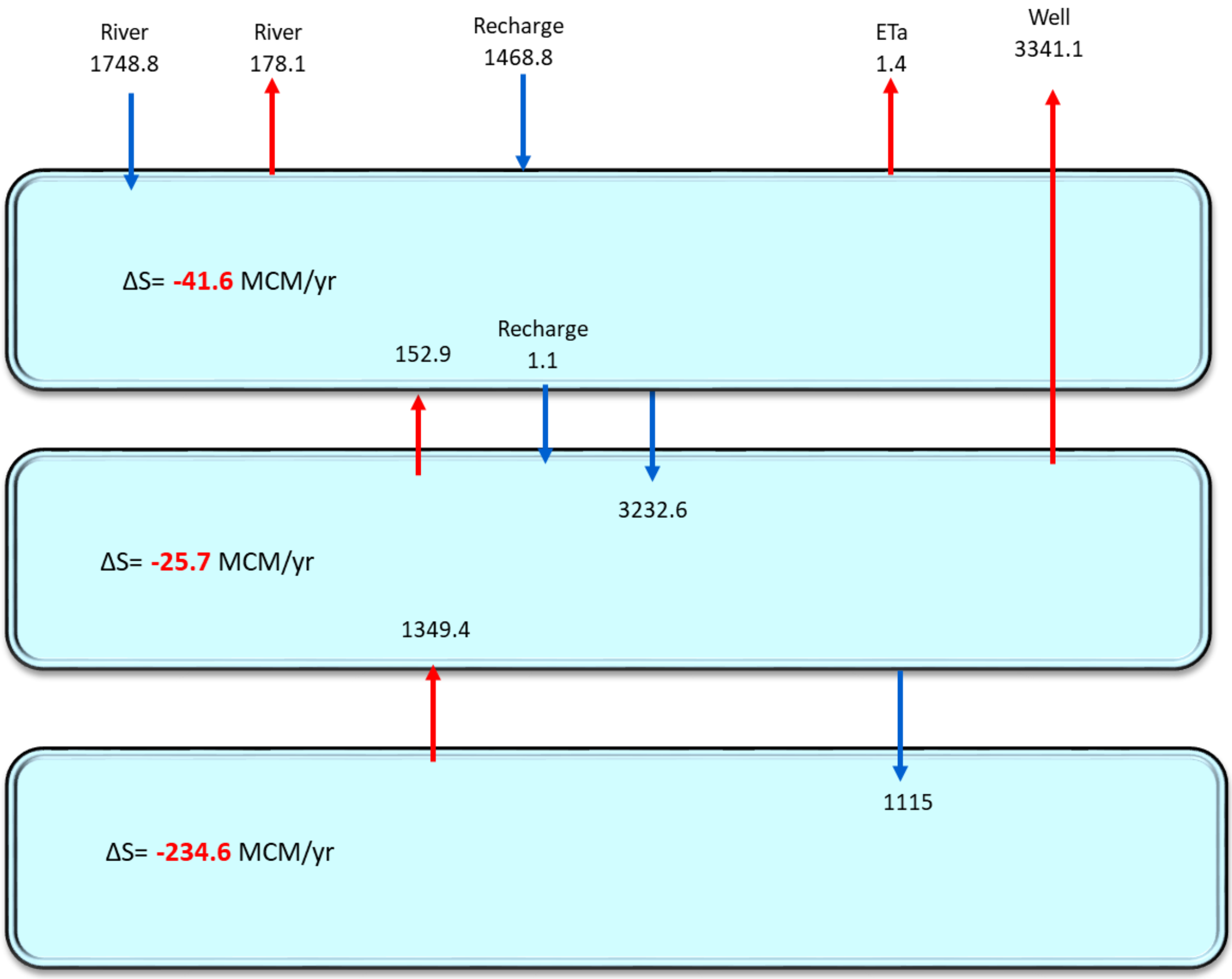
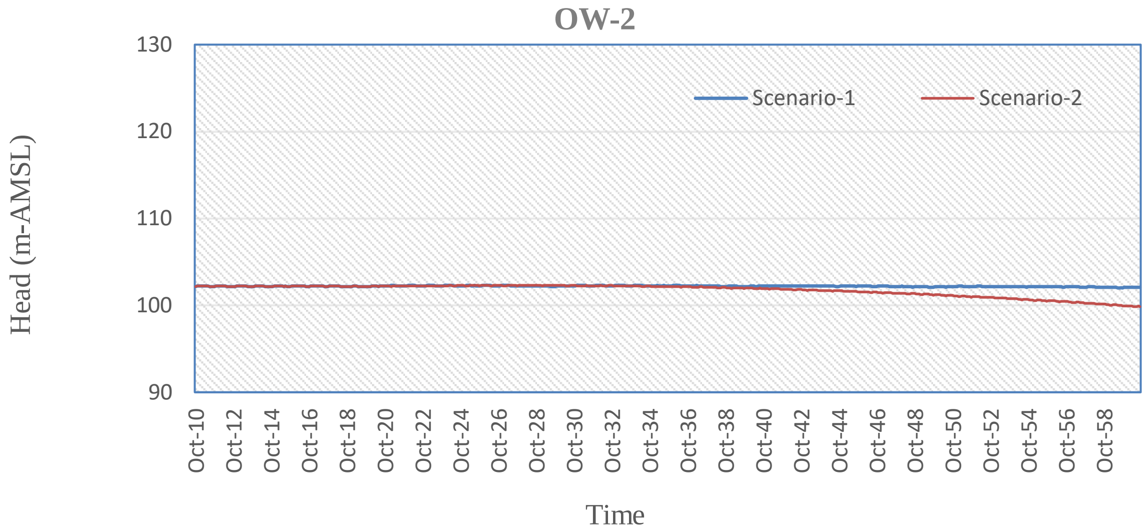
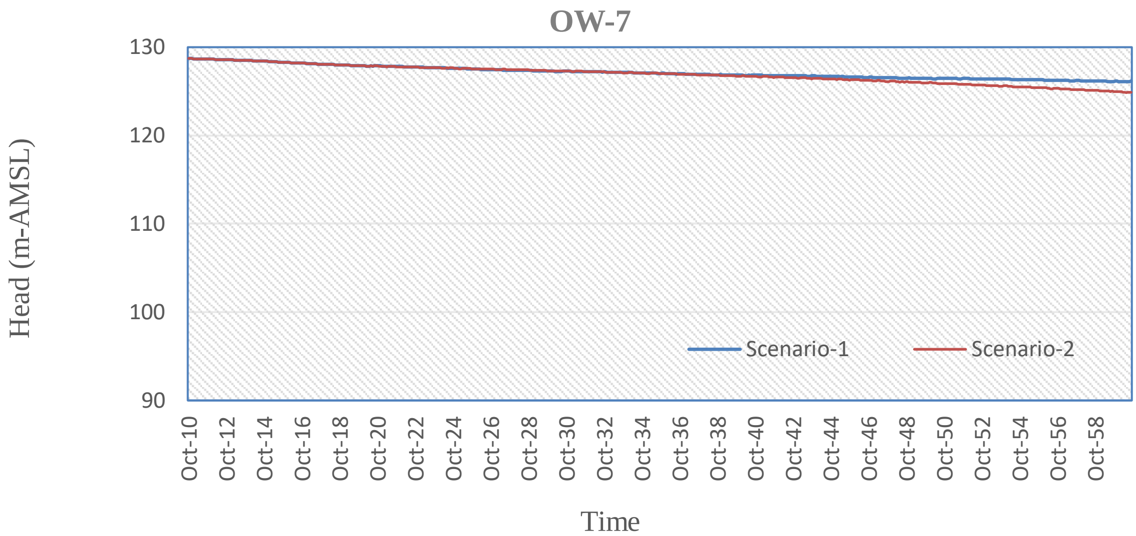
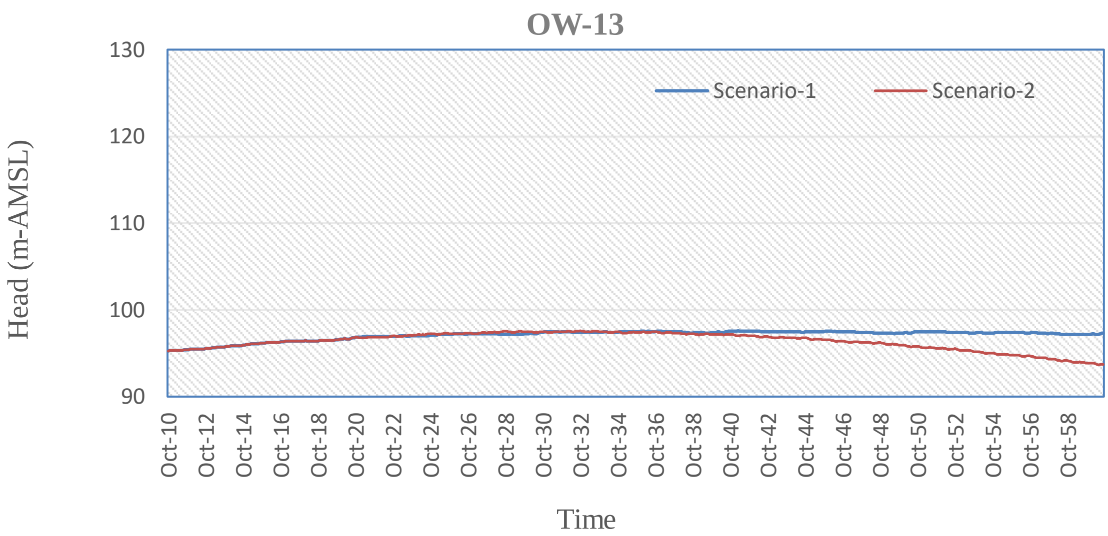


Figure 32. Groundwater balance for the baseline scenario (2010-2060)


OW-2
130
120
110
100
90
Head (m-AMSL)
Scenario-1
Scenario-2
Oct-10
Oct-12
Oct-14
Oct-16
Oct-18
Oct-20
Oct-22
Oct-24
Oct-26
Oct-28
Oct-30
Oct-32
Oct-34
Oct-36
Oct-38
Oct-40
Oct-42
Oct-44
Oct-46
Oct-48
Oct-50
Oct-52
Oct-54
Oct-56
Oct-58
Time


OW-7
130
120
110
100
90
Head (m-AMSL)
Scenario-1
Scenario-2
Oct-10
Oct-12
Oct-14
Oct-16
Oct-18
Oct-20
Oct-22
Oct-24
Oct-26
Oct-28
Oct-30
Oct-32
Oct-34
Oct-36
Oct-38
Oct-40
Oct-42
Oct-44
Oct-46
Oct-48
Oct-50
Oct-52
Oct-54
Oct-56
Oct-58
Time


OW-13
130
120
110
100
90
Head (m-AMSL)
Scenario-1
Scenario-2
Oct-10
Oct-12
Oct-14
Oct-16
Oct-18
Oct-20
Oct-22
Oct-24
Oct-26
Oct-28
Oct-30
Oct-32
Oct-34
Oct-36
Oct-38
Oct-40
Oct-42
Oct-44
Oct-46
Oct-48
Oct-50
Oct-52
Oct-54
Oct-56
Oct-58
Time

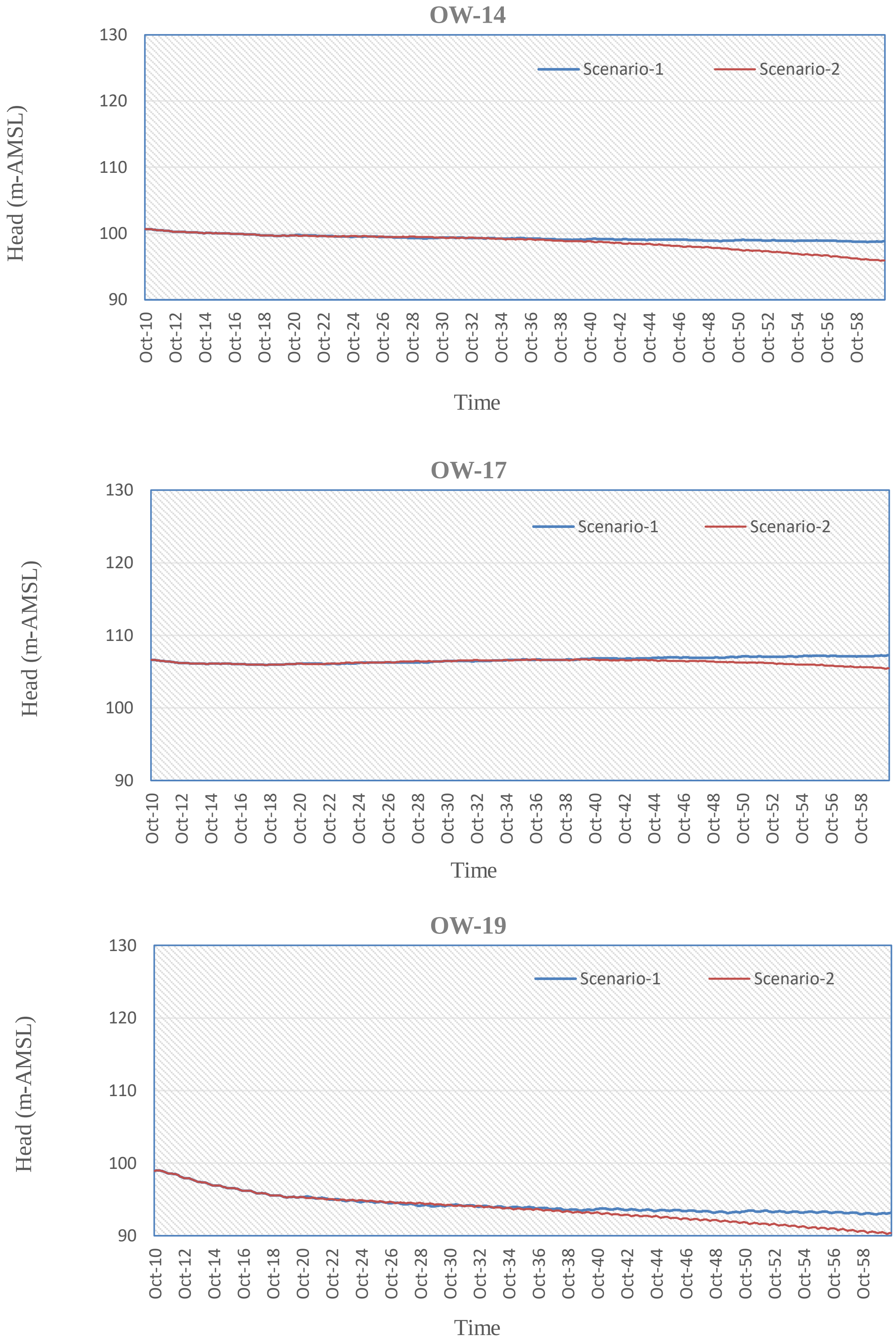


Figure 33. Simulated versus observed head under Scenario 1 and Scenario 2 (m-AMSL=metres above mean sea level)

7.2. Scenario 2: Increase in Groundwater Pumping with No Change in Canal Supply

The increased pumping scenario (PS) which simulates pumping increasing based on the historical trend from 2010 to 2020, indicates the net loss in groundwater storage has declined to -939.6 MCM/yr. Under the PS scenario, canal supply remains unchanged, and recharge and evapotranspiration are replicated using historical data from 2016 to 2020. The layered water balance under an increasing PS scenario is represented in Figure 34. The hydrographs of the selected piezometers show a drop in the water levels particularly after 2040 under this scenario (Figure 33). This tells us that continued increasing in pumping beyond 2040 will induce a noticeable decline in groundwater levels.

The water balance shows enhanced depletion in all layers. The dewatering of Layer 1 in response to pumping in Layer 2 is particularly concerning for smallholder farmers who may have restricted access to groundwater. The increased inflows into Layer 2 from the deeper Layer 3 are equally concerning. This amplifies the risk of salt mobilisation and will result in extracting groundwater of higher salinity, adding to the build-up of salts in the crop rooting zone.

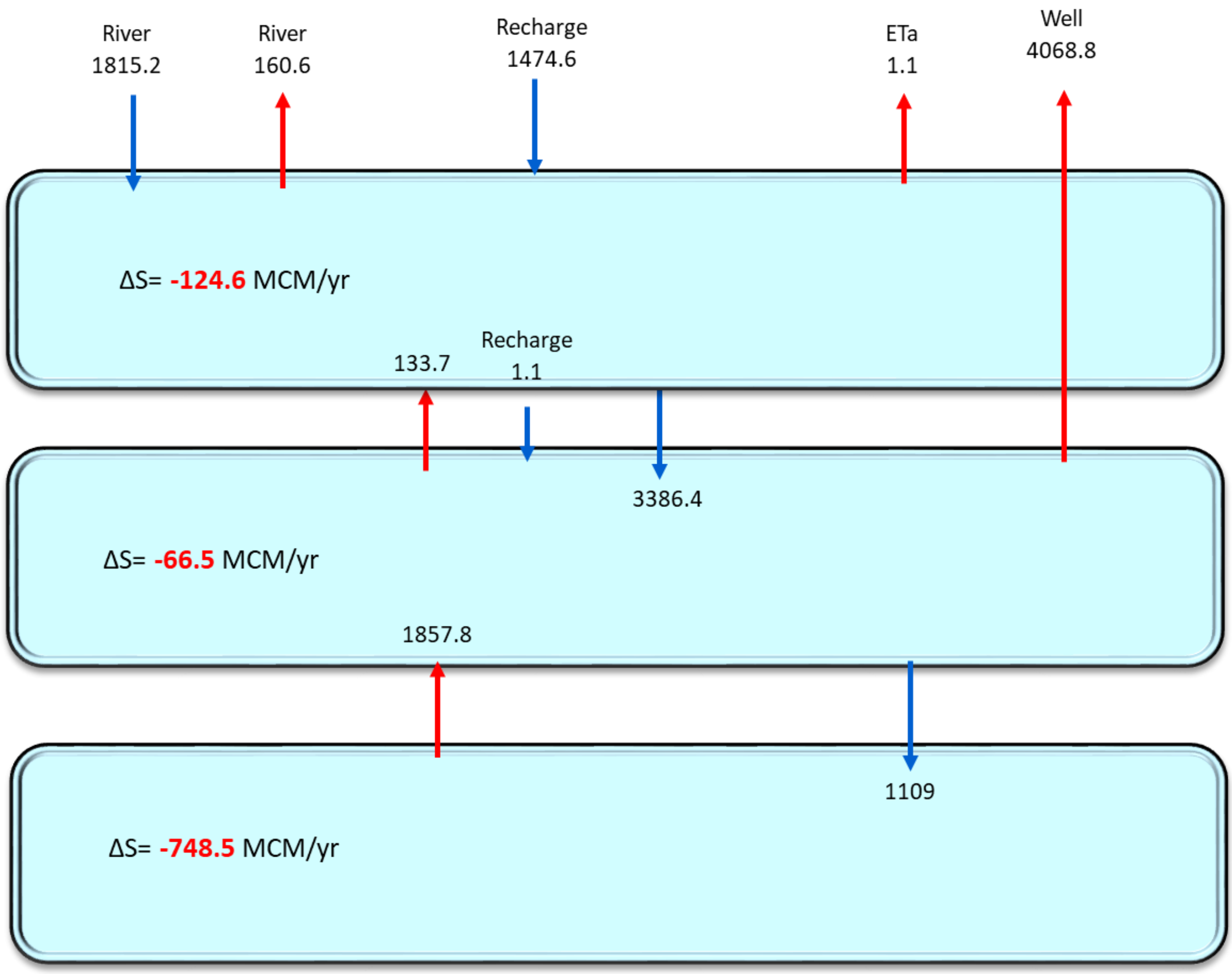


Figure 34. Groundwater balance under pumping increase scenario (2010-2060)

7.3. Scenario 3: Climate Change Scenario SSP2-4.5

The SSP2-4.5 scenario was simulated from 2010 to 2100 using projected rainfall and temperature data used to estimate evapotranspiration. In this scenario pumping was increased based on historical trends observed during the calibration period, and canal supply is replicated using data from 2016–2020 indicating an average deficit in groundwater storage of 2,192.2 MCM/yr. The net loss in groundwater storage was highest for Layer 3 which highlights earlier concerns about salinity mobilisation from the deepest layer. The water balance also indicates that the average annual recharge is slightly lower than the BL scenario, and evapotranspiration reduces due to declining water levels. The layered water balance under the SSP2-4.5 scenario is represented in Figure 35. The hydrographs of the selected piezometers show a significant drop in the water levels under this scenario.

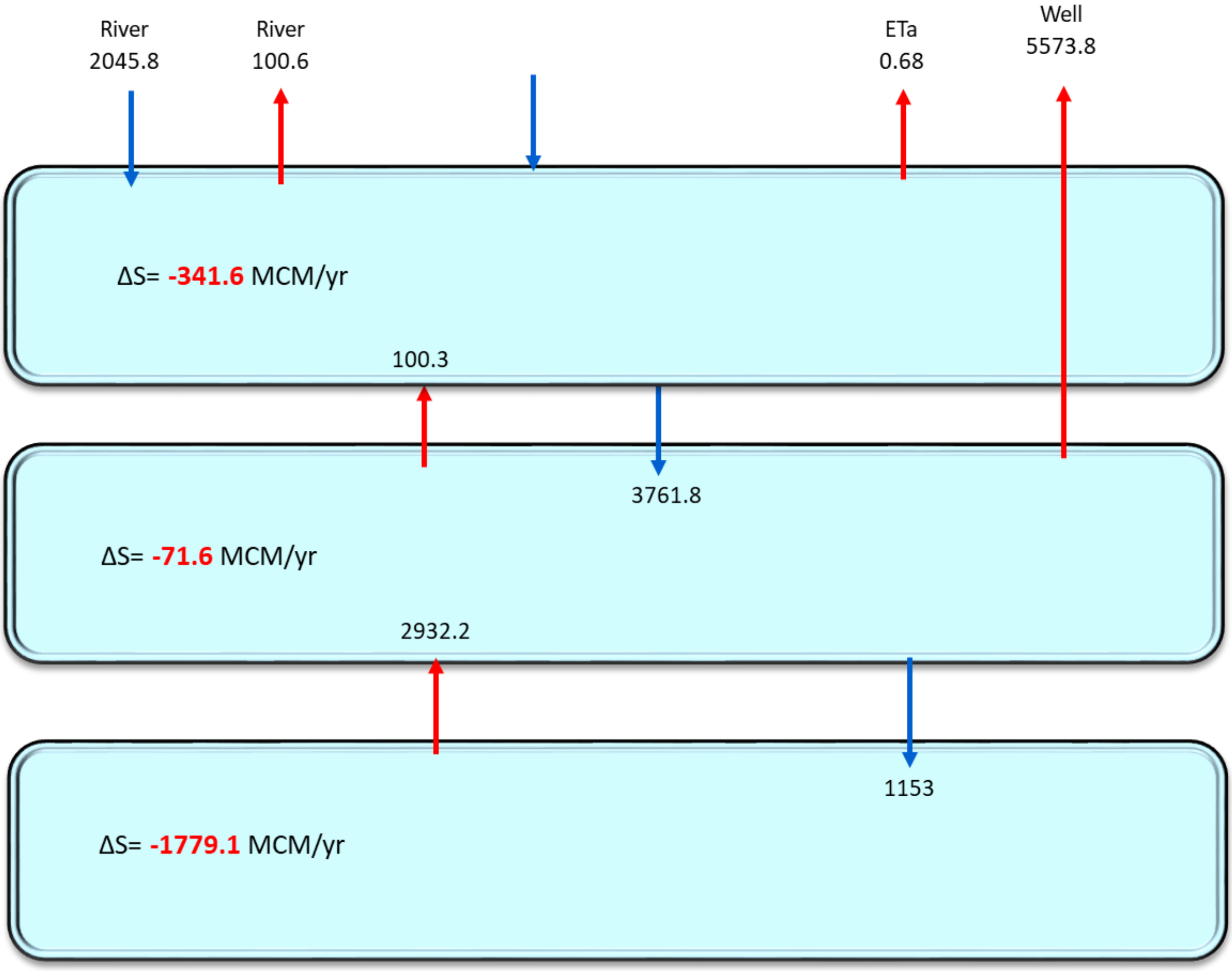


Figure 35. Groundwater balance under climate change SSP2-4.5 scenario (2010-2100)

7.4. Scenario 4: Climate Change Scenario SSP5-8.5

The SSP5-8.5 scenario was simulated from 2010 to 2100 using projected rainfall and temperature data to estimate evapotranspiration. In this scenario, pumping was increased based on historical trends observed during the period of calibration, and canal supply was based on data from 2010–2020, which is similar to the SSP2-4.5 scenario. The net loss in groundwater storage was highest for Layer 3 and similar in magnitude for the SSP2-4.5 scenario, highlighting earlier concerns about salinity mobilisation from the deepest layer. The layered water balance under SSP5-8.5 scenario is represented in Figure 36 indicating an average deficit in groundwater storage of 2,204.6 MCM/yr. The projected increase in groundwater pumping will dry out the top layer in the lower reaches of the Southern Bari Doab Canal Command in future years for both climate scenarios. Figure 37 shows a significant part of the study area has contributed to dewatering Layer 1 indicating many farmers will be unable to access groundwater unless they invest in deepening wells. The hydrographs of the selected piezometers show a significant drop in the water levels under this scenario particularly in the 40 years from 2060 to 2100 (Figure 38).

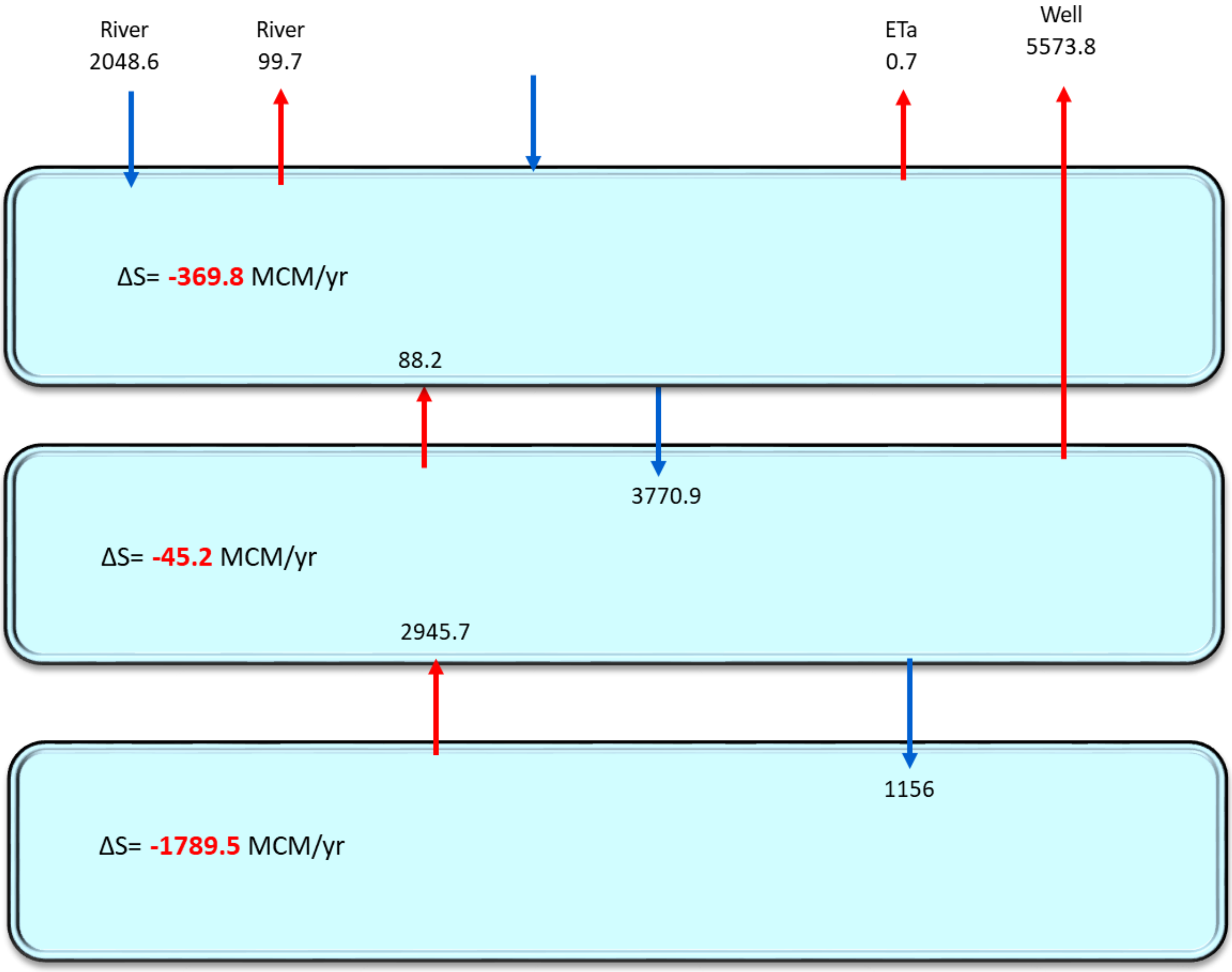


Figure 36. Simulated versus observed head (m AMSL) under climate change SSP5-8.5 scenario

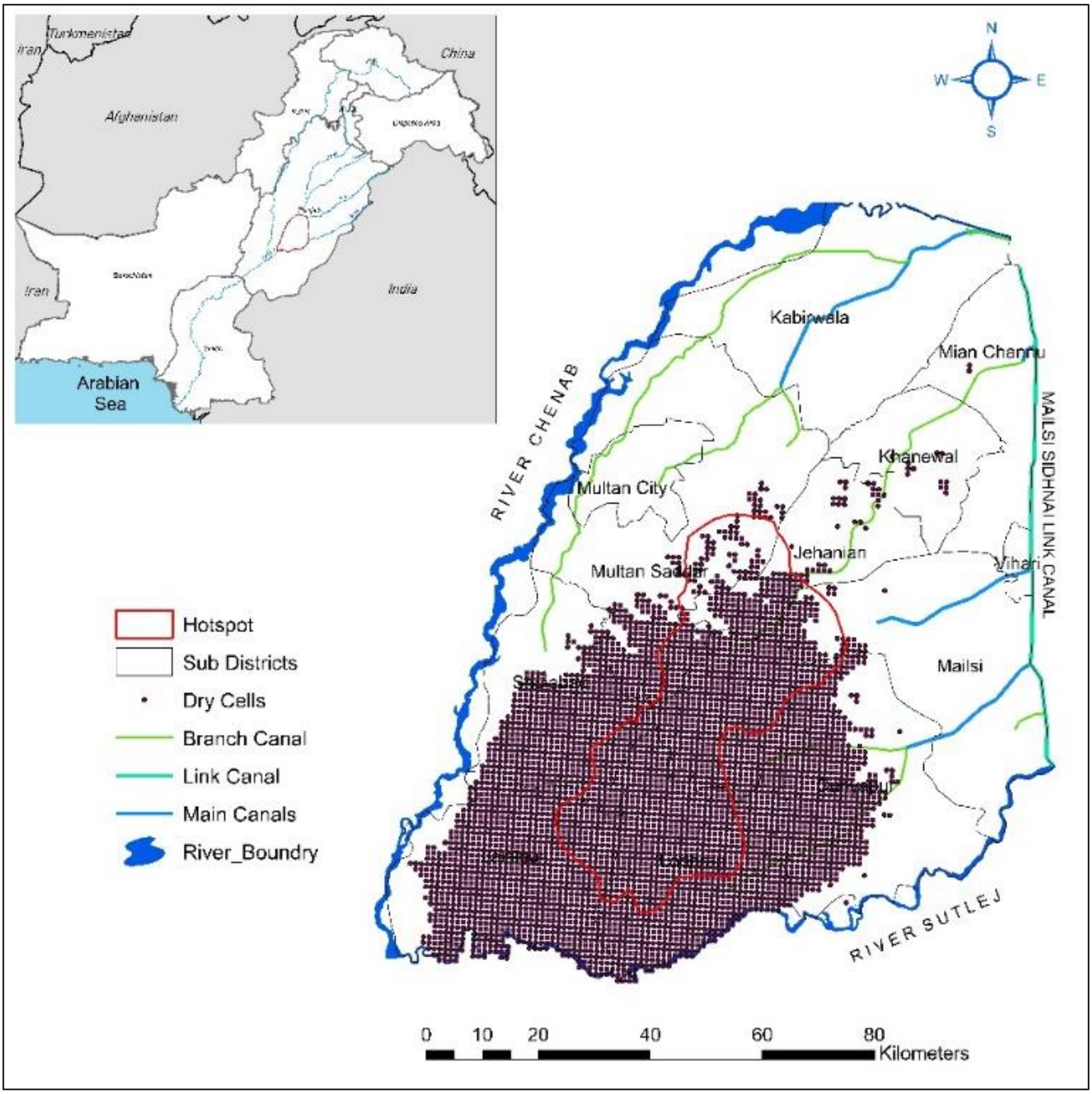
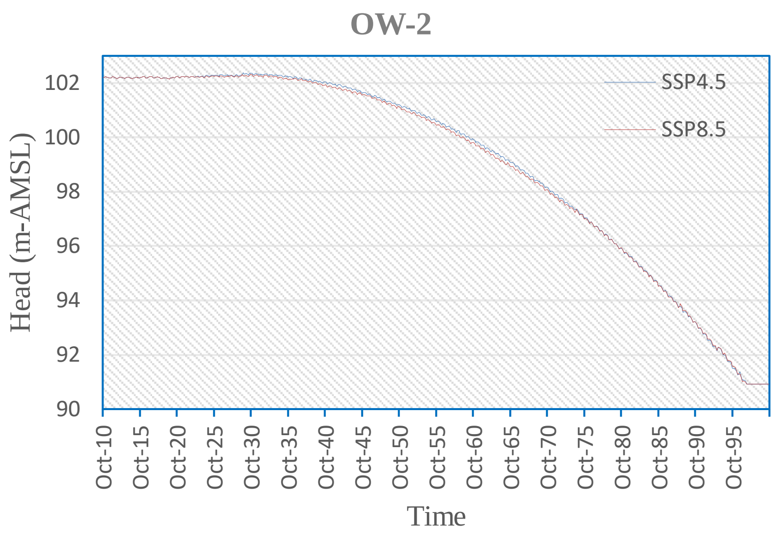
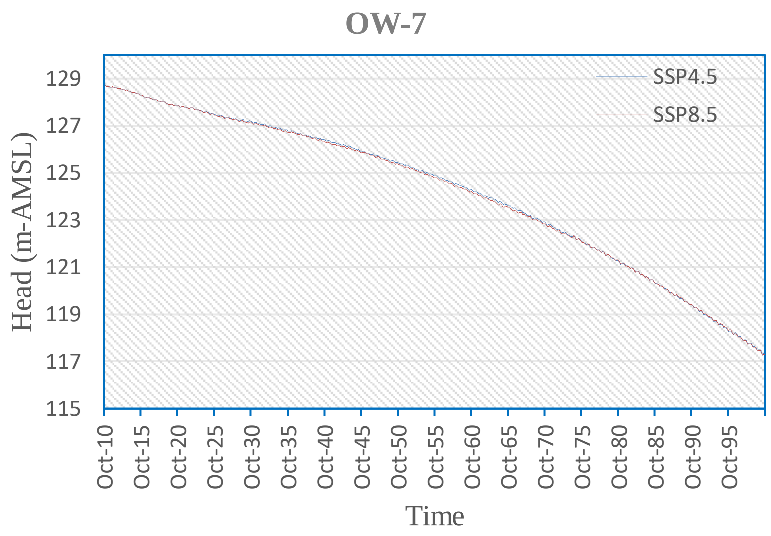
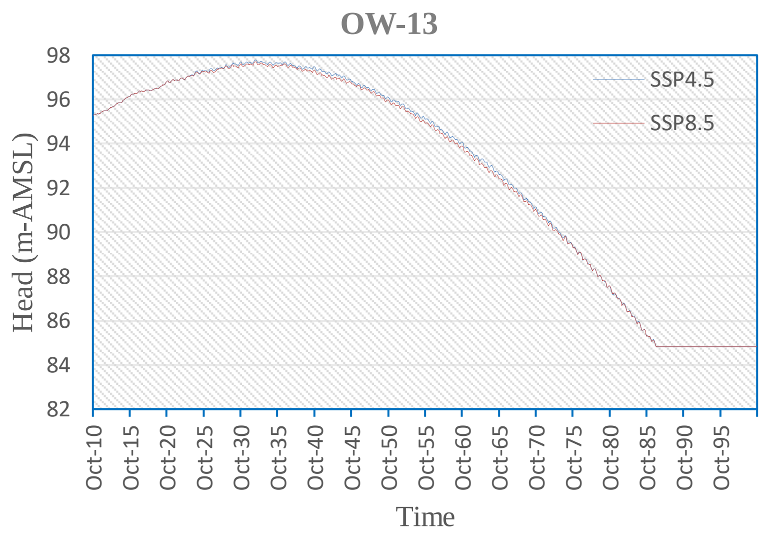
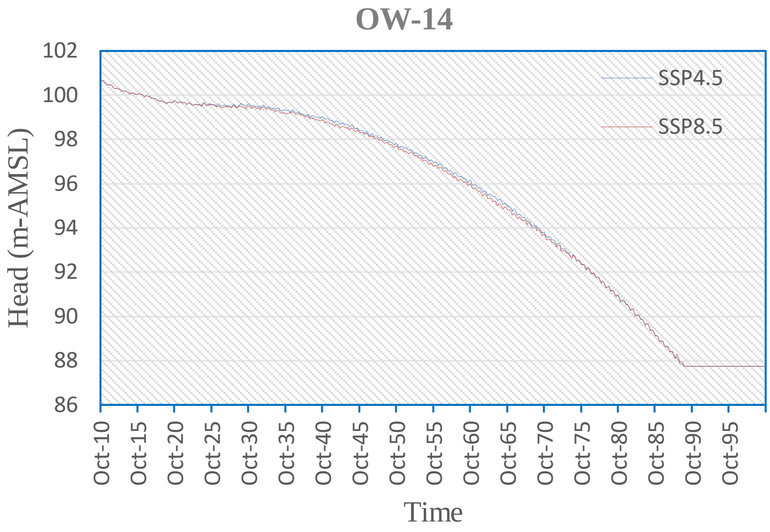


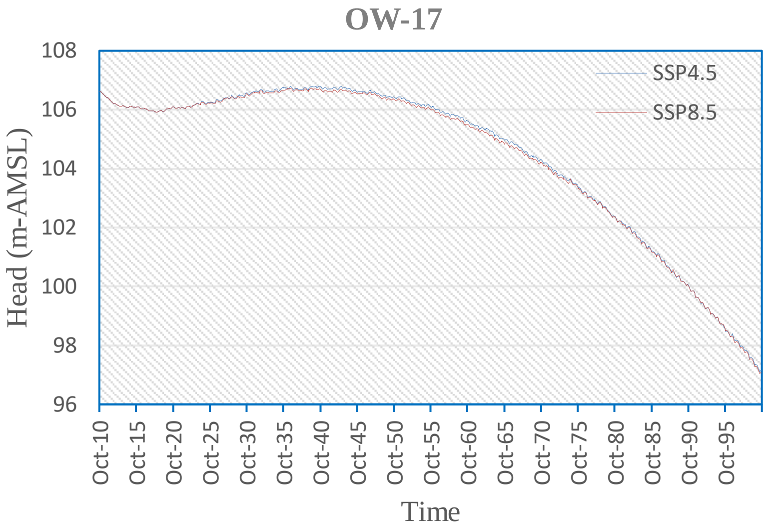
Figure 37. The model output showing drying out of the top model layer in the lower reaches of the model area under climate change scenarios


OW-2
Head (m-AMSL)
Time
SSP4.5
SSP8.5


OW-7
Head (m-AMSL)
Time
SSP4.5
SSP8.5


OW-13
Head (m-AMSL)
Time
SSP4.5
SSP8.5





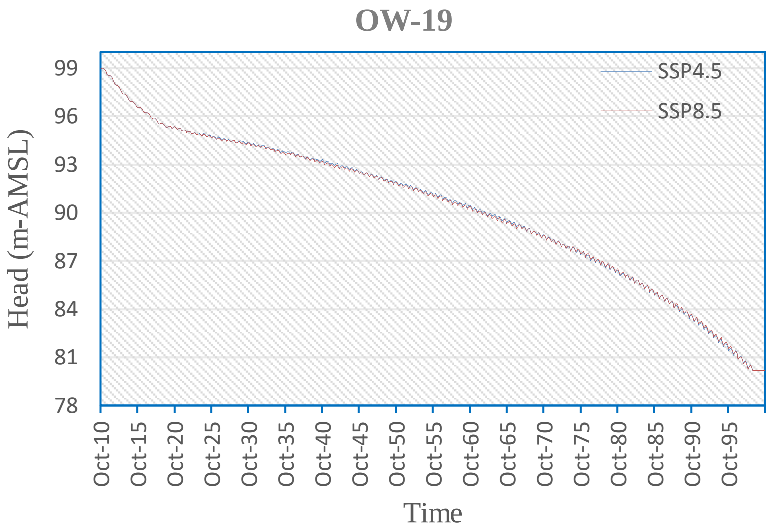


Figure 38. Simulated versus observed head under climate change for SSP2-4.5 and SSP5-8.5 scenarios (m AMSL=metres above mean sea level)

7.5. Comparison of the Water Balance for 2020-2030 and 2050-2060 under the BL and PS Scenarios

The water balance for the BL and PS scenarios was compared during the early stage of the simulation from 2020–2030 and the final ten years from 2050–2060 (Table 11). The net change in storage for the BL scenario indicates that net storage in 2020–2030 is -355.7 MCM/yr and that if pumping is kept near the 2010–2020 levels the aquifer will tend to reach a new equilibrium over time with net storage at -162.8 MCM/yr. This does not mean that parts of the aquifer will not experience stresses or increased salinity mobilisation, however, it indicates that with improved resource management, the system can withstand this level of pumping over the next 50 years. The PS scenario shows that the net storage is -212.4 MCM/yr during 2020-2030 which rapidly declines to -1,886.4 MCM/yr by 2050–2060. The hydrographs presented earlier demonstrate an inflection point around 2040 indicating that a sustained increase in pumping beyond 2040 will result in significant declines in water levels and increased salinity mobilisation from deeper layers, resulting from a significant increase in stresses on the aquifer.

Table 11. Comparison of the groundwater balance for 2020–2030 and the last decade for the baseline and increased pumping scenarios (units are MCM/yr)

Inflows	Scenario 1 (Baseline)	Scenario 1 (Baseline)	Scenario 2 (Pumping Increase)	Scenario 2 (Pumping Increase)
Simulation Period	2020–2030	2050–2060	2020–2030	2050–2060
River	1,730.1	1,806.6	1,719.4	2,033.9
Recharge	1,410.3	1,495.1	1,425	1,526
Total Inflows	**3,140.4**	**3,301.7**	**3,144.4**	**3,560.0**
Outflows	**Scenario 1**	**Scenario 1**	**Scenario 2**	**Scenario 2**
River	156.8	139.7	158.3	85.0
Well	3,338.0	3,323.8	3,197.2	5,361.1
ET	1.4	1.1	1.4	0.3
Total Outflows	**3,496.1**	**3,464.6**	**3,356.9**	**5,446.4**
Net	**-355.7**	**-162.8**	**-212.4**	**-1,886.4**

7.6. Adaptation Scenario for Southern Punjab to Manage Overexploitation

We designed a possible adaptation scenario by selecting the increased pumping scenario described in Section 7.2. This scenario simulates increased pumping along past trends between 2010 and 2020 which encapsulates present pumping trends. The continued increase in tubewells in Southern Punjab and the lack of mechanisms to reach a water sharing agreement with groundwater users formed the basis for selecting this scenario to model adaptation options.

Changes in the groundwater regime take time to take effect and there is no one solution that can manage the overexploitation of groundwater in Southern Punjab. Our approach did not include any direct regulatory mechanisms for reducing the rate of groundwater extraction due in part to the lack of regulation for groundwater use and the absence of controls on tubewell installation. Rather we took the approach that changing the cropping patterns partially towards less water intensive crops that are suitable for the agro-climatic zone of

Southern Punjab would be a more acceptable option for famers. However, to affect this change will require establishing trust and knowledge transfer to communities.

The first of the adaptation options included mapping the spatial distribution of the major water intensive summer crops namely cotton and rice, and sugarcane in the Southern Bari Doab as illustrated in Figure 39. Land Use Land Cover (LULC) distribution in the kharif season indicated a 6.5%, 2.8% and 1.6% reduction in cotton, sugarcane and rice cultivation respectively from 1990 to 2020 illustrated in Table 12. Our first option recommended substitution of 20% of the area under cotton with mung bean, and 30% of rice and 20% of sugarcane with onion. Mung bean and onions are less water intensive crops with a shorter growing season, which we estimated can potentially reduce groundwater pumping by 15 to 16%. The aim here was not to replace all of the cotton, rice and sugarcane crops as this would not be economically viable for farming communities who rely on cash crops. Further, we opted not to change the winter crop as during the winter season wheat is the major crop which is crucial for food security for farming families as well as for Pakistan.

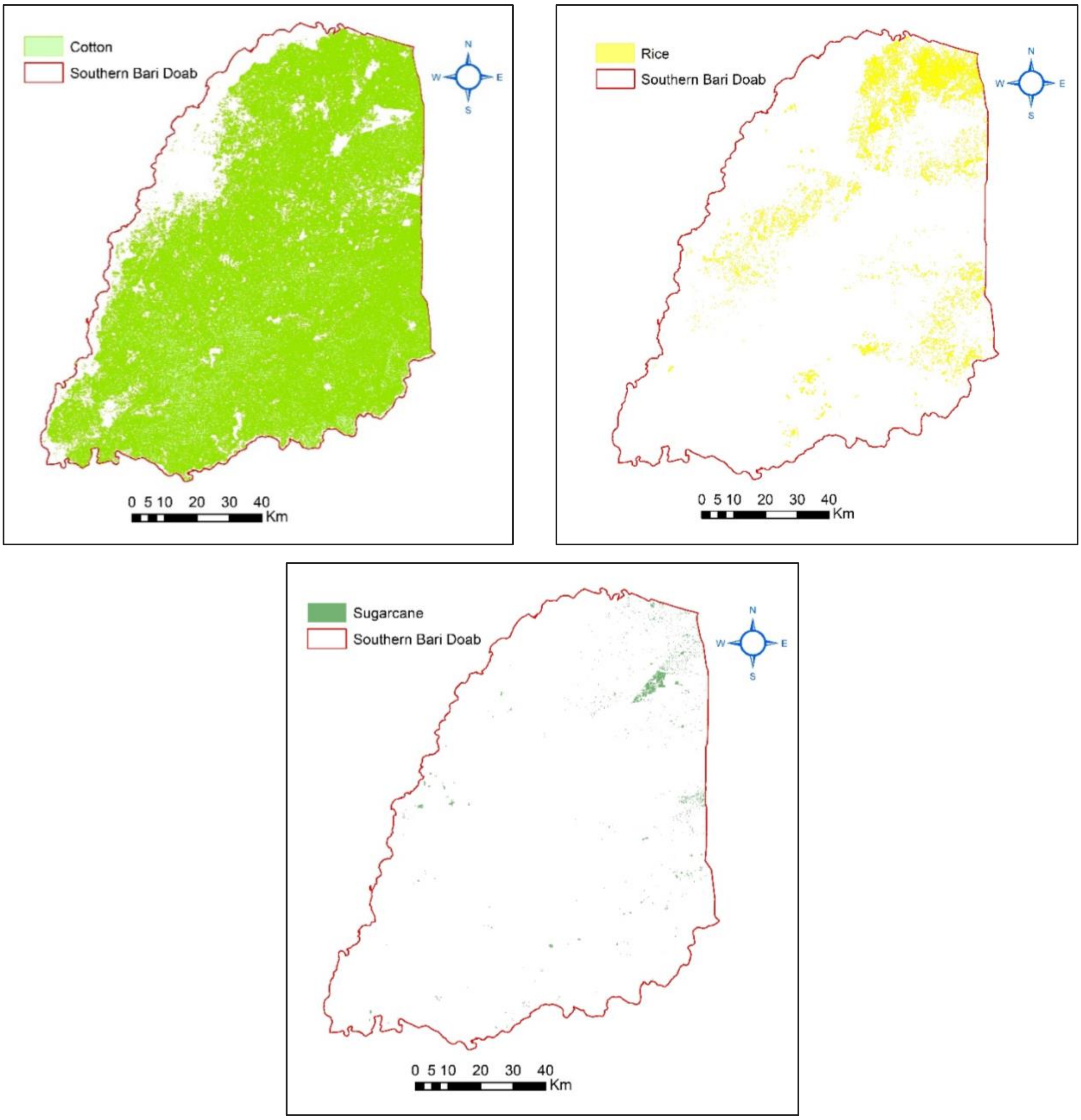


Figure 39. Spatial distribution of major crops being sown during Kharif season in the Southern Bari Doab Canal Command (2014-2015)

Table 12. Time series distribution of LULC for Kharif season based on remote sensing data (1990-2020) in the Southern Bari Doab Canal Command (Hussain et al., 2021)

LULC Classes	1990 area (%)	2000 area (%)	2010 area (%)	2020 area (%)	Change in area 1990 to 2020 (%)
Cotton	35.01	34.92	33.11	28.48	**-6.5**
Kharif Fodder	17.85	20.24	21.47	26.34	**8.5**
Rice	21.57	20.84	21.13	19.96	**-1.6**
Sugarcane	15.54	14.81	13.99	12.65	**-2.8**
Water bodies	2.66	2.21	2.09	1.63	**-1.0**
Built-up/barren	7.31	6.97	8.2	10.95	**3.6**

The annual monsoon rains often result in flood water in the Chenab and at times in the Sutlej. The flows in the Sutlej have been curtailed by upstream diversions in India (see Indus Water Treaty, 1960), however, occasional floods do occur in the Sutlej which offers an opportunity to capture some of the floods for recharge. Capturing a portion of these flood flows for managed aquifer recharge can potentially offer some relief for declining groundwater levels and potentially improve groundwater quality. In our case, the second adaptation option simulated monsoon floods with a return period of 10 years which was based on the flood event that occurred on August 25, 2013, in the Chenab and Sutlej Rivers. We simulated this flood for a 10-year return period from 2020 to 2060. The flood flows were simulated by increasing the river stage in the Chenab and Sutlej to provide an indication of how increased flows in the Chenab and Sutlej during monsoon could provide additional water for recharge. We recommend PID undertake detailed investigations to establish recharge structures such as large diameter vertical recharge wells which could be used to enhance recharge to the aquifer. Large floods such as the floods during 2022 inundate agriculture lands resulting in flood damage to crops, orchards and infrastructure. Recharging some of the captured flood flows is desirable for aquifer management and to mitigate the potential impact of flash floods in Chenab River during monsoon period.

The third adaptation option included simulating an environmental option by establishing a green barrier along the riverine corridor of the Chenab River as part of the adaptation scenario. This proposed plantation of native trees in the barren lands along the river would act to reduce flood impacts, provide a carbon sink and an opportunity for improving the environment and biodiversity in Southern Punjab. Once the establishment of a corridor of native trees could be successfully achieved, we recommend investigating suitable sites along both banks of the Sutlej River.

The combined impact of these adaptation options in Table 13 indicates the net storage has increased to -586.6MCM as compared to the increased pumping scenario which indicated a net loss in storage of - 939.6 MCM annually. This represents an increase in groundwater storage of about 353MCM/yr for the simulated period up to 2060 with adaptation options.

Table 13. Annual average groundwater balance of model under adaptation option scenario (2010-2060)

Source	Inflow (MCM)	Outflow (MCM)	Net (MCM)
Recharge	1509.0	0	1509.0
River	1874.3	-175.1	1699.3
Well	0	-3794.5	-3794.5
ETa	0	-0.4	-0.4
Net	**3383.4**	**-3970.0**	**-586.6**

Additionally, a separate simulation without the recharge option indicated a loss in groundwater storage of -678.9 MCM which indicates the inclusion of the recharge options by simulating flood flows adds an additional 92.3 MCM/yr to groundwater storage.

7.7. Water Balance for 2020–2030 and 2090–2100 under Climate Change Scenarios

The water balance for the SSP2-4.5 and SSP5-8.5 climate change scenarios was compared during the early stage of the simulation from 2020-2030 and the final ten years of simulation from 2090–2100 (Table 14). The net change in storage for the SSP2-4.5 scenario indicates net storage in 2020-2030 is -116.9 MCM/yr however, if the increased pumping trends continues the net storage will decline to -4819.1 MCM/yr. The SSP5-8.5 scenario shows similar results; however, rainfall recharge is noticeably lower for this scenario. Both these climate scenarios tell us that the current increasing pumping trend will not be sustainable under the climate change scenarios. Significant decreases in net storage, water levels, and water quality will occur. As shown in Figure 36, water levels for both climate scenarios indicate rapid declines in water levels, particularly beyond 2040, after which the declines accelerate. The impact on the drying out of a large part of Layer 1 in Figure 37 shows that there will be significant impacts on farmers who will be forced to deepen wells to access groundwater and increasingly use groundwater with higher salinity or, in the worst case scenario abandon groundwater irrigation, which will impact food security.

Table 14. Comparison of the groundwater balance for 2020–2030 and 2090–2100 for the climate change scenarios (units are MCM/yr)

Inflows	SSP2-4.5	SSP2-4.5	SSP5-8.5	SSP5-8.5
Simulation Period	2020-2030	2090-2100	2020-2030	2090-2100
River	1,718.6	2,388.6	1,722.8	2,390.2
Recharge	1,521.2	1,520.4	1,436.0	1,344.5
Total Inflows	**3,239.7**	**3,909.0**	**3,158.8**	**3,734.7**

Outflows	SSP2-4.5	SSP2-4.5	SSP5-8.5	SSP5-8.5
River	157.7	4.8	155.9	4.8
Well	3,197.2	8,723.3	3,197.2	8,723.3
ET	1.7	0	1.7	0
Total Outflows	**3,356.6**	**8,728.1**	**3,354.8**	**8,728.1**
Net	**-116.9**	**-4,819.1**	**-196.0**	**-4,993.4**

7.8. Discussion

The baseline (BL) water balance shown in Figure 32 is evidence of the interplay of groundwater exchange among all three model layers. The inflow into Layer 2 from the overlying Layer 1 is attributed to pumping which is concentrated in Layer 2 resulting in downward flows of 3,232.6 MCM/yr (BL scenario). For the PS scenario, which simulates increasing pumping based on recent trends from 2010 to 2020, the annual average net decline in storage is -939.6 MCM/yr for 2010–2060; however, water balance from 2050–2060 also tells us that the net decline in storage accelerates to 1,886.4 MCM/yr between 2050-2060.

The BL and PS scenarios also indicate significant upward flows from Layer 3 into Layer 2 of 1349.4 and 1,857.8 MCM/yr respectively, indicating pumping in Layer 2 is also enhancing upward flows from Layer 3. Several researchers (Ahmad et al., 2023; Lytton et al., 2021; Punthakey et al., 2015) have indicated increasing salinity with depth in the Indus Basin aquifer, which means these upward flows will enhance salinity mobilisation and consequently deteriorate the water quality in Layer 2 over the long-term which will result in groundwater pumping for irrigation of higher salinity. Over the long-term, current system's sustainability will be at risk as declining water levels in Layer 1 will increase pumping costs for farmers and costs for deepening wells for small-holder farmers or the costs associated with drilling deeper wells will exclude these farmers from using groundwater for irrigation. Based on the BL scenario, the projection indicates a decrease in the net loss in groundwater storage from -533.4 MCM/yr to -301.9 MCM/yr if all the water balance components remain unchanged from October 2016 to September 2020. The increase in net storage suggests the aquifer is possibly reaching a new equilibrium. However, other factors, such as inflows from the Chenab River were comparatively less from October 2010 to September 2015 compared to October 2015 to September 2020. We replicated the river data from October 2015 to September 2020 and found that the leakage from the Chenab River is higher, which affects the water balance of the scenarios. The net inflows from the Chenab River to the aquifer during the 2010-15 period was 1168.4 MCM/yr whereas during the 2015-2020 period the net inflows from the Chenab River to the aquifer were substantially higher at 1,509 MCM/yr. This finding indicates the average net inflows during the latter period were significantly higher than during 2010-2015.

Under the increased pumping scenario, the projected increase in the average net loss in groundwater storage was -939.6 MCM/yr upto September 2060, compared to the BL scenario, which was -301.9 MCM/yr indicating that current pumping practices, especially in the irrigated agricultural sector, are not sustainable and may lead to severe consequences for groundwater availability in the future.

The increasing trend in pumping experienced in Punjab over the past three decades was further explored using the climate change scenarios. Under climate change scenarios, SSP2-4.5 and SSP5-8.5, the projected average net loss in groundwater storage was -2,192.2 MCM/yr and -2,204.6 MCM/yr respectively, if pumping continues to increase following the historical trend of of 2010–2020, with the surface water supply remaining the same as during 2016–2020. Any shortage in surface water supply will have an immediate impact on further stressing the groundwater system. The analysis of the water balance from 2090-2100 also tells us that the net decline in storage accelerates to -4,819.1 MCM/yr and -4,993.4 MCM/yr for the SPP2-4.5 and SSP5-8.5 scenarios respectively. This accelerated depletion over time will be of significant concern for resource managers and policy specialists. Groundwater management in this context cannot rely solely on regulation; it will require consultation and building consensus among groundwater irrigators by allowing their voices to be heard to ensure a sustainable future. The findings especially under the increased pumping and climate change scenarios, highlight the need to adopt sustainable pumping practices to slow the rapid decline of groundwater storage. Implementing measures such as tubewell monitoring, regulating pumping in hotspots, managed aquifer recharge (MAR), revision of cropping patterns and adaptation of irrigation practices to enhance water use efficiency will be essential to bring about a hopeful future for Southern Punjab's farmers.

The simulated adaptation options for the Southern Bari Doab also indicates that despite inclusion of adaptation options, there will still be a significant loss in net storage in the underlying aquifer. Thus, additional options for managing groundwater sustainably will be required, which would require a groundwater management plan for the area and the co-development of a water sharing plan with strong community buy-in. Additionally, some regulation of pumping may also be required in hotspots to allow equitable access to groundwater for smallholder farmers. To moderate the impacts of overexploitation of groundwater and insufficient surface water supply under projected climate change conditions we have proposed a series of adaptation options suitable for simulation which will give provide insight for policy setters, institutional actors, and the farming community to assist in developing strategies for a sustainable future.

8. Groundwater Policy and Governance

The Punjab government has promulgated the Punjab Water Policy 2018 and Punjab Water Act 2019. It is the first time groundwater has been given due importance in these regulatory and policy frameworks. These Acts deal with groundwater management and related challenges, including augmentation, protection, and restricted extraction. At present, groundwater management in IRB is fraught with many challenges, including the reliability and adequacy of resource information, resource degradation, resource depletion and equity, resource efficiency, participation, and institutional and policy factors. Overlaying these challenges is the complex nature of groundwater resources, socio-cultural attitude towards a common pool resource, a lack of stakeholder and community awareness, and a lack of capacity within existing institutional setups (Hassan, 2023). A proper groundwater data management information system and technological, institutional, policy and regulatory interventions are vital for managing groundwater resources, including artificial recharge. Along with hydrological and geological considerations, economic and policy analyses are essential for the complete analysis of MAR and other groundwater replenishment options. The Punjab government has established new organisations – the Punjab Water Resources Commission and the Punjab Water Services Regulatory Authority. The Punjab Irrigation Department (PID) has established a dedicated zone for groundwater monitoring and regulation in the province.

Groundwater governance is more complex than surface water because it has fuzzy boundaries, and laws and rules governing water flow in channels cannot be applied. Similarly, groundwater is distinguished from natural mineral resources like oil and gas due to its renewability and ubiquity, and being essential for life. Unlike surface water, groundwater is a hidden resource with strong complexity in defining its boundaries and entitlements. Unfortunately, not much attention has been paid by the relevant authorities towards managing pumping and protecting groundwater reserves in the aquifer underlying the Indus Basin in Pakistan.

The level of extraction of groundwater is important information required for groundwater modelling, but in the Indus Basin, these levels are based on assumptions and estimates. To get more realistic estimates of groundwater levels in the province, the PID has started georeferencing all the tube wells. This exercise is almost complete and will yield the most accurate and reliable database for groundwater use and its potential in the province.

Rules and regulations supported by standard policy and implementation mechanisms are imperative for groundwater management in the Indus Basin. There are some existing regulatory frameworks that deal mainly with the operation of the canal irrigation network in the province. Existing laws and regulatory instruments that deal with water sector operational and management strategies are listed in Box 1 (Hassan, 2023).

The management of groundwater must consider both the demand and supply sides. Given the importance of groundwater management and groundwater recharge under the National Climate Change Policy and National Water Policy, the Punjab government's Punjab Water Policy (2018) has provided guidance for future lines of action for the beneficial use of flood water. The policy outlines guiding principles for groundwater augmentation through MAR, as shown in Box 2. The sustainable use of groundwater is imperative for its development, protection, and beneficial use.

Although much work exists regarding policy formulation and regulatory frameworks, a clear, holistic, and time-bound approach to implementing these instruments is lagging. The newly established organisations are not fully functional yet. There is an overlap between the organisational roles and policies regarding groundwater. Human resources and organisational setup for groundwater management and regulation are inadequate. On the one hand, groundwater plays a vital role in meeting the water demands of all sectors of society, but on the other hand, a dedicated institutional setup for groundwater management is almost non-existent. In neighbouring India, a Central Groundwater Board is supported by several state-based organisations and departments to manage groundwater use and development. A lack of awareness and capacity are also challenges for groundwater management in Pakistan. Specific recommendations for groundwater management to ensure its sustainable use are as follows:

- Demarcation of basins and sub-basins for groundwater budgeting and modelling studies.
- Development and calibration of groundwater models for flow and solute transport for different sub-basins in the Indus Basin.
- A time-bound implementation framework for the Water Act and Water Policy.

- Both demand and supply side management interventions for efficient water use.
- Strengthen groundwater monitoring network in Punjab.
- Design and implement a systematic, comprehensive, periodic, modernised monitoring framework.
- Develop a database or management information system for data storage and sharing, potentially hosted by the PID.
- Install additional piezometers at optimised grid sites throughout the province to augment the existing network by filling gaps and uncovered pockets.
- Expand the current groundwater quality monitoring scope.
- Include a vertical profile of groundwater quality parameters in the monitoring program.
- Reduce the number of water laboratories in the province and improve the standard of water laboratories.
- Enhance coordination, awareness raising, and capacity development.
- Enhance focus and investment in groundwater research.
- Remove any overlapping and duplicated groundwater policies and institutions.
- Enhance the use of modern tools and ICTs.
- More systematic research on qualitative aspects of groundwater.

Box 2

Punjab Water Policy and MAR

i. *Construction of flood channels to divert flood waters to desert areas like Cholistan, Thal and other similar areas.*

ii. *Allow flood waters to spread overland through pre-planned breaches.*

iii. *Harness flood waters in Hill Torrent areas like DG Khan through construction of storage and delay action dams, dispersion and diversion structures.*

iv. *Augment artificial recharge of aquifer from flood water.*

Box 1

Major water laws and policies in Pakistan

a) Federal/National Level

- *The Easements Act of 1882*
- *Land Improvement Loans Act (1883)*
- *The Constitution of Pakistan 1973*
- *The Pakistan Water and Power Development Authority Act (1958)*
- *Indus Water Treaty (1960)*
- *Water Apportionment Accord (1991)*
- *Indus River System Authority (IRSA) Act (1992)*
- *Pakistan Environmental Protection Act (1997)*
- *Pakistan Water Vision 2025 (2001)*
- *Pakistan Water Resource Sector Strategy (2002)*
- *National Environment Policy (2005)*
- *National Sanitation Policy (2006)*
- *National Drinking Water Policy (2009)*
- *18th Amendment in the Constitution of Islamic Republic of Pakistan*
- *Pakistan Water Vision/Framework for action 2025 (2010)*
- *National Climate Change Policy (2012)*
- *Pakistan Climate Change Act (2017)*
- *National Water Policy (2018)*

b) Provincial Level

- *The Canal & Drainage Act (1873)*
- *Punjab Minor Canals Act (1905)*
- *Soil Reclamation Act (1952)*
- *On Form Water Management Ordinance (1981)*
- *Punjab Water-User Association Ordinances (1981)*
- *Water Apportionment Accord (1991)*
- *The Punjab Irrigation and Drainage Authority Act (1997)*
- *Punjab Government Rules of Business (2011)*
- *Punjab Water Policy (2018)*
- *Punjab Water Act (2019)*

c) Local Level

- *Punjab Development of Cities Act (1976)*
- *Punjab Local Government Act (2019)*
- *The Punjab Village Panchayats and Neighbourhood Councils Act (2019)*
- *The Punjab Local Govt Ordinance 2021*
- *Punjab Khal Panchayat Act (2019)*

8.1. Groundwater Monitoring and Management

A portion of investment by the Punjab government, the World Bank, ADB, and ACIAR should be allocated for the collection, storage and timely access and sharing of updated groundwater monitoring data to allow the Water Resources Zone and Irrigation Research Institute to monitor the changing dynamics of water levels and water quality. The PID has recently installed CTD data loggers in some areas of Punjab; however, we recommend upgrading the monitoring program with water level and salinity loggers at strategic sites to better understand the status of the aquifer. This data can provide the basis for developing annual reports on the status of groundwater in Punjab.

The Punjab Bureau of Statistics annually reports the number of tubewells in each district of Punjab. Recently, the Water Resources Zone has completed a remarkable achievement of digitising the locations of the tubewells across the Punjab. However, there is no monitoring of groundwater pumping. We recommend metering tubewells at strategic locations to understand trends in groundwater extractions in stressed canal commands in Punjab.

The monitoring program should be carried out alongside hydrogeological investigations and a groundwater mapping program to develop an in-depth understanding of groundwater conditions and provide accurate information for improving resource management. The establishment of Groundwater Management Zones needs to be designated in the Bari Doab to inform groundwater users of long-term trends, the impacts of overextraction, and the salinity impacts that are likely to occur in response to pumping. The shortage in water availability for tail-end farmers will result in shifting agricultural water demand to groundwater, which will consequently cause the depletion of groundwater levels and quality deterioration. Knowledge transfer to farmers on groundwater quality risks and the potential impact on crop productivity and soils is essential for changing practices. However, avoiding salinity build-up as the share of groundwater use in irrigation increases will require the PID to offer farmers viable alternatives, such as increased surface water supply, expanded agricultural extension services to promote water-efficient crops, and advisory services for improved irrigation and land management practices. Additional guidance on developing a robust groundwater monitoring strategy to improve mapping, modelling and management of groundwater resources is provided in Raheem et al. 2024.

8.2. Institutional Policy, Licensing, Pricing

Based on existing studies, a policy framework should be developed for the integrated management of water resources. It should include conjunctive management and allocation of water for environmental benefits. Out of the total 1.4 million tubewells, more than 85% are installed in Punjab. To manage the increasing demand, we recommend licensing high-volume groundwater users to help control excessive groundwater depletion. A mechanism needs to be developed to provide information on new bores drilled in Punjab to the PID for archiving the bore depths, screen lengths, and depth of production bores. Where possible, a PID hydrogeologist could be on-site to log the bore. This will require investment in capacity building and the training of local drillers and eventually a system for licensing drillers.

8.3. Water Saving Technologies

No serious efforts have been made in the past to replenish the aquifer. To compensate for groundwater exploitation and enhance replenishment of the aquifer on a regional scale, managed aquifer recharge (MAR) needs to be prioritised along with suitable adaptation options. Introducing water saving technologies among progressive farmers needs to be encouraged. The PID needs dedicated staff with up-to-date knowledge of modern water savings technologies. Where feasible, accurate mapping of the underlying deposits and their hydraulic properties would need to be undertaken to ensure effective location and operation of MAR schemes, particularly in areas with deep watertables. The mapping of groundwater resources is essential to managing the freshwater zones and devising strategies for the conjunctive use of canal and marginal groundwater to benefit farmers in Punjab.

8.4. Institutional Capacity Building

A major commitment has been made to this project as well as other projects in the recent past, such as the ACIAR-funded project on improving groundwater management to enhance agriculture and farming livelihoods in Pakistan (LWR/2015/036) for developing groundwater models for improved understanding of impacts in these areas. A team from the Punjab Irrigation Department was also part of these projects. Expanding this structure to create a dedicated team with expertise in hydrology, hydrogeology, modelling, remote sensing, and environmental management is required to develop expertise in surface and groundwater modelling and improve the management of water resources. Establishing a groundwater modelling and hydrogeology unit would allow greater use of these models to benefit the community of groundwater users, industry, and the environment. The scenarios generated from these models will provide crucial information for policymakers and resource managers. Following are the key recommendations on capacity building and development:

- Groundwater monitoring and mapping.
- Groundwater modelling through training programs and secondments.
- Remote sensing with a focus on water resources.
- Groundwater protection legislation and policy development.
- Strengthen modelling of surface water resources.
- Water use and water savings technologies.
- Collaborate with national agencies, universities and international centres to enhance knowledge and skills within the Water Resources Directorate.

9. Conclusions and Recommendations

9.1. Conclusions

- The water balance of the model for the study period 2010–2020 indicated river/canal leakage was the major inflow source, incorporating 53% of the total inflow followed by recharge from rainfall and field application losses at 47%. Additionally, groundwater pumping was found to be the most significant outflow, comprising 92% of total outflows, which resulted in a decline in net groundwater storage of -533.4 MCM/yr. The net loss in groundwater storage indicates groundwater pumping impacts groundwater reserves in the Southern Bari Doab Canal Command.
- The net change in storage for the BL scenario indicates that net storage in 2020–2030 is -355.7 MCM/yr and from 2050–2060, the aquifer will tend to reach a new equilibrium with net storage at -162.8 MCM/yr. This does not mean that parts of the aquifer will not experience stresses or increased salinity mobilisation; however, it indicates that with improved resource management, the system can withstand this pumping level over the next 50 years. The PS scenario shows that the net storage is -212.4 MCM/yr during 2020–2030 which rapidly declines to -1,886.4 MCM/yr by 2050-2060. The most significant impact will be felt from increased pumping which increases from 3197.2 MCM/yr for 2020–2030 period to 5361.1 by 2050-2060. The hydrographs presented earlier demonstrate an inflection point around 2040, indicating a sustained increase in pumping beyond 2040 will result in significant declines in water levels and increased salinity mobilisation from deeper layers, resulting from a significant increase in stresses on the aquifer.
- The projected increase in groundwater pumping under the climate change scenarios SSP2-4.5 and SSP5-8.5 indicated a large area of the top layer of the model would dry out in future in the lower reaches especially the area accompanied by significant declines in groundwater levels and quality for the Southern Bari Doab Canal Command. Clearly, this level of pumping will not be sustainable and will have long-term impacts on groundwater quantity and quality.
- The average recharge during 2020-2030 under climate change scenarios SSP2-4.5 and SSP5-8.5 was 1,521.2 and 1,436 MCM/yr respectively, however, from 2090–2100 the recharge will be 1520.4 for SSP2-4.5 while for SSP5-8.5 the recharge will reduce to 1344.5, which indicates relatively lower rainfall under the SSP5-8.5 scenario. With lower recharge and increasing pumping over time, the aquifer will be subjected to significant stresses.
- The annual average T_{mean} under climate change scenarios SSP2-4.5 and SSP5-8.5 was 28.7 and 30.6 0C, respectively, which indicates a relatively higher mean temperature and higher evapotranspiration under the SSP5-8.5 scenario. Although it does not impact evapotranspiration in the model due to deep watertables, the increased evapotranspiration will significantly impact crop water needs as higher temperatures will require more irrigation and amelioration of crop microclimates.
- The simulated adaptation options for the Southern Bari Doab indicates that despite the adaptation options which included changing a portion of the high water use crops such as cotton, rice and sugarcane with low delta crops such as mung bean and onions, flood flows and environmental amelioration of the riverine corridors, there will still be a significant loss in net storage in the underlying aquifer of 586.6 MCM/yr. A simulation without the recharge option indicated a loss in groundwater storage of -678.9 MCM which indicates the inclusion of the recharge options by simulating flood flows adds an additional 92.3 MCM/yr to groundwater storage.

9.2. Recommendations

9.2.1 Enhance Data Collection and Monitoring

Currently, the PID is monitoring around 3300 piezometers and 4000 farmer-owned tubewells to record groundwater levels and quality, respectively, covering the Punjab province. Areas that have continuously declining groundwater levels or emerging water quality issues will require additional monitoring piezometers. Alongside the current groundwater level and quality monitoring, we recommend instrumenting bores with water level, temperature, and EC loggers, which will provide reliable time-series data, especially at strategic sites where groundwater levels are declining and water quality issues are emerging. Strengthening groundwater monitoring networks to gather accurate and up-to-date data on groundwater levels and quality is essential for informed decisions. In addition to monitoring, the best effective storage, retrieval, access, and use of the data among different stakeholders will enhance understanding of aquifer responses under increased pumping and climate stress.

9.2.2 Enhance Professional Institutional Capacity of PID

As per the Punjab Irrigation, Drainage and Rivers Act 2023, the office in-charge under the secretary irrigation is responsible to report the amount of extraction in each irrigation zone for each calendar year. In this context, we recommend the PID, besides reporting past groundwater abstraction data, enhance its professional capacity to understand the spatio-temporal dynamics of groundwater systems to project future groundwater pumping and levels for the sustainable management of groundwater in each irrigation zone.

9.2.3 Managed Aquifer Recharge

The managed aquifer recharge (MAR) has not been widely adopted to date and large-scale MAR projects such as the diversion of monsoon flood waters from Islam Barrage into the Old Mailsi Canal have only recently been considered in Pakistan (Hassan, 2023). The new approach for large-scale rural MAR projects (Hassan, 2023) provides a framework for the PID to develop MAR projects in consultation with each farmer's community for selecting locations best suited for managed aquifer recharge projects. Similarly, strategic sites to replenish the groundwater recharge on a local scale should also be considered, as water stress and climate change exacerbate groundwater availability in Pakistan.

9.2.4 Water Education

Farmers are key stakeholders in improving water resource management. Capacity building of farming communities to improve knowledge of on-farm water management, climate smart agriculture, and options for managing declining groundwater levels and quality will be essential for adapting to water and climate stress. A suitable approach to managing groundwater would be first to improve monitoring of the resource to improve assessment of the condition of the resource. Improved monitoring can also help irrigators, groundwater users, and stakeholders better understand the impact on groundwater resource conditions and the temporal and spatial changes in response to intensive aquifer exploitation. Engaging with groundwater users and irrigators is necessary to co-design a sustainable future over a specified planning period. An example of this is the RAPs (Representative Agricultural Pathways), which provide pathways for adopting low delta crops and high efficiency irrigation for fruit trees such as mango orchards, which is a high value crop (Nasir, 2021). Adopting new crops and sustainable farming practices with improved irrigation management will be a slow process that requires dedicated human and financial resources. A multi-skilled team consisting of social researchers, groundwater managers, hydrogeologists, irrigation, and agricultural specialists is required to work with community groups to develop a sustainable future for Southern Punjab.

References

Ahmad, M.-u.-D., Pena-Arancibia, J., & Yu, Y. (2023). High spatiotemporal resolution remotely sensed timeseries actual evapotranspiration estimates for irrigation management in salinity-affected areas of the southern Indus Basin. *MODSIM2023, 25th International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, July 2023* (pp. 7-13). https://doi.org/10.36334/modsim.2023.ahmad184

Akhter, G., & Hasan, M. (2016). Determination of aquifer parameters using geoelectrical sounding and pumping test data in Khanewal District, Pakistan. *Open Geosciences, 8*(1), 630-638. https://doi.org/10.1515/geo-2016-0071

Akinsanola, A. A., & Kooperman, G. J. (2022). Intensification of precipitation extremes in the United States under global warming. In V. Ongoma & H. Tabari (Eds.), *Climate Impacts on Extreme Weather* (pp. 117-129). Elsevier. https://doi.org/10.1016/B978-0-323-88456-3.00010-1

Ali, A. (2023). Improving salinity and agricultural water management in the Indus Basin, Pakistan: Issues, management and opportunities: A synthesis from a desk-top literature review (Republished) [Gulbali Report No. 1]. Albury, NSW: Gulbali Institute, Charles Sturt University. https://www.csu.edu.au/research/gulbali/about-us/publications/

Anjum, L., Awan, U. K., Ali Nawaz, R., Hassan, G. Z., Akhter, R. S., Haroon, C., . . . Punthakey, J. (2021). *Improving groundwater management to enhance agriculture and farming livelihoods: Groundwater model for the Lower Bari Doab Canal, Punjab Pakistan* [ILWS Report No. 158). Albury NSW: Institute for Land, Water and Society (ILWS), Charles Sturt University.

Ashraf, A., & Ahmad, Z. (2008). Regional groundwater flow modelling of Upper Chaj Doab of Indus Basin, Pakistan using finite element model (Feflow) and geoinformatics. *Geophysical Journal International, 173*(1), 17–24. https://doi.org/10.1111/j.1365-246X.2007.03708.x

Ashraf, M., Zeeshan, A. B., & Zakaullah. (2012). Diagnostic analysis and fine tuning of skimming well design and operational strategies for sustainable groundwater management - Indus Basin of Pakistan. *Irrigation and Drainage, 61*(2), 270–282. https://doi.org/10.1002/ird.636

Ashraf, M., Fatima, B., Hasan, F. u., & Salam, H. A. (2022). *Adapting to Salinity in the Southern Indus Basin: Policy Review.* Islamabad, Pakistan: Pakistan Council of Research in Water Resources. https://pcrwr.gov.pk/water-management-reports/

Basharat, M. (2012). Integration of canal and groundwater to improve cost and quality equity of irrigation water in a canal command. PhD Dissertation, University of Engineering and Technology, Lahore, Pakistan. http://142.54.178.187:9060/xmlui/handle/123456789/2945

Basharat, M., & Tariq, A. ur R. (2015). Groundwater modelling for need assessment of command scale conjunctive water use for addressing the exacerbating irrigation cost inequities in LBDC irrigation system, Punjab, Pakistan. *Sustainable Water Resources Management, 1*(1), 41–55. https://doi.org/10.1007/s40899-015-0002-y

Bennett, G. D., Ur-Rehman, A., Sheikh, I. A. & Alr, S. (1967). Analysis of aquifer tests in the Punjab region of West Pakistan. Water Supply Paper 1608-G. Washington DC: US Government. https://doi.org/10.3133/wsp1608G

FAO. (2024). Pakistan at a Glance. https://www.fao.org/pakistan/our-office/pakistan-at-a-glance/en/

Gidden, M. J., Riahi, K., Smith, S. J., Fujimori, S., Luderer, G., Kriegler, E., . . . Takahashi, K. (2019). Global emissions pathways under different socioeconomic scenarios for use in CMIP6: a dataset of harmonized emissions trajectories through the end of the century. *Geoscientific Model Development, 12*(4), 1443-1475. https://doi.org/10.5194/gmd-12-1443-2019

Greenman, D. W., Bennett, G. D., & Swarzenski, W. V. (1967). *Ground-water hydrology of the Punjab, West Pakistan, with emphasis on problems caused by canal irrigation* (Geological Survey Water-Supply Paper 1608-H). Washington DC: US Government Printing Office.

Hamza, A. (2023, March 11). From ‘water stressed’ to ‘water starved’ Pakistan. *The Nation.* https://www.nation.com.pk/11-Mar-2023/from-water-stressed-to-water-starved-pakistan

Hassan, G. Z. (2023). Improving sustainable groundwater management: A case study of managed aquifer recharge in Punjab, Pakistan. PhD Dissertation. School of Agricultural, Environmental and Veterinary Sciences, Charles Sturt University, Albury, Australia.

Hayat, K. (2003). Geotechnical zonation and their relation to geology of Pakistan. PhD Dissertation, Institute of Geology, University of the Punjab, Lahore, Pakistan. http://prr.hec.gov.pk/jspui/handle/123456789/3792

Hussain, S., Mubeen, M., Ahmad, A., Masood, N., Hammad, H. M., Amjad, M., ... & Waleed, M. (2021). Satellite-based evaluation of temporal change in cultivated land in Southern Punjab (Multan region) through dynamics of vegetation and land surface temperature. *Open Geosciences*, *13*(1), 1561-1577. https://doi.org/10.1515/geo-2020-0298

Iqbal, M. A., Rizwan, M., Abbas, A., Makhdum, M. S., Kousar, R., Nazam, M., . . . Nadeem, N. (2021). A quest for livelihood sustainability? Patterns, motives and determinants of non-farm income diversification among agricultural households in Punjab, Pakistan. *Sustainability, 13*(16), 9084. https://doi.org/10.3390/su13169084

Khaliq, T., Gaydon, D. S., Ahmad, M.-u.-D., Cheema, M. J. M., & Gull, U. (2019). Analyzing crop yield gaps and their causes using cropping systems modelling: A case study of the Punjab rice-wheat system, Pakistan. *Field Crops Research, 232*, 119-130. https://doi.org/https://doi.org/10.1016/j.fcr.2018.12.010

Kumar, P., Bansod, B. K. S., Debnath, S. K., Thakur, P. K., & Ghanshyam, C. (2015). Index-based groundwater vulnerability mapping models using hydrogeological settings: A critical evaluation. *Environmental Impact Assessment Review, 51*, 38-49. https://doi.org/https://doi.org/10.1016/j.eiar.2015.02.001

Lytton, L., Ali, A., Garthwaite, B., Punthakey, J. F., & Saeed, B. (2021). *Groundwater in Pakistan's Indus Basin: present and future prospects*. Washington DC: World Bank. https://openknowledge.worldbank.org/handle/10986/35065

Maraun, D. (2013). Bias correction, quantile mapping, and downscaling: Revisiting the inflation issue. *Journal of Climate, 26*(6), 2137–2143. https://doi.org/10.1175/JCLI-D-12-00821.1

Mujtaba, G., Ahmad, Z., & Ophori, D. (2011). Management of groundwater resources in Punjab, Pakistan, using a groundwater flow model. *Journal of Environmental Hydrology, 15*, 31. http://www.hydroweb.com/journal-hydrology-2007-paper-31.html

Nasir, J., Ashfaq, M., Baig, I. A., Punthakey, J. F., Culas, R., Ali, A., & Hassan, F. u. (2021). Socioeconomic impact assessment of water resources conservation and management to protect Groundwater in Punjab, Pakistan. *Water, 13*(19), 2672. https://doi.org/https://doi.org/10.3390/w13192672

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., . . . Sanderson, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development, 9*(9), 3461-3482. https://doi.org/10.5194/gmd-9-3461-2016

Osman, A. I. A., Ahmed, A. N., Huang, Y. F., Kumar, P., Birima, A. H., Sherif, M., . . . El-Shafie, A. (2022). Past, present and perspective methodology for groundwater modeling-based machine learning approaches. *Archives of Computational Methods in Engineering, 29*(6), 3843-3859. https://doi.org/10.1007/s11831-022-09715-w

Post, V. E. A. (2005). Fresh and saline groundwater interaction in coastal aquifers: Is our technology ready for the problems ahead? *Hydrogeology Journal, 13*(1), 120–123. https://doi.org/10.1007/s10040-004-0417-2

Punthakey, J. F., Khan, M. R., Riaz, M., Javed, M., Zakir, G., Usman, M., . . . Christen, E. (2015). *Optimising canal and groundwater management to assist water user associations in maximizing crop production and managing salinisation in Pakistan: Assessment of groundwater resources for Rechna Doab, Pakistan.* Final Report to ACIAR, Ecoseal.

Qian, W., & Chang, H. H. (2021). Projecting health impacts of future temperature: A comparison of quantile-mapping bias-correction methods. *International Journal of Environmental Research and Public Health, 18*(4), 1992. https://doi.org/10.3390/ijerph18041992

Qureshi, A. S., McCornick, P. G., Sarwar, A., & Sharma, B. R. (2020). Challenges and Prospects of Sustainable Groundwater Management in the Indus Basin, Pakistan. *Water Resources Management, 24*(8), 1551–1569. https://doi.org/10.1007/s11269-009-9513-3

Raheem, A., Saifullah, M., Punthakey, J. F., Baig, I. A. (2024). *Assessing groundwater monitoring in the Southern Bari Doab and guidance for strengthening groundwater monitoring across Punjab (Gulbali Report No. 6).* Gulbali Institute, Charles Sturt University, Albury, NSW. https://www.csu.edu.au/research/gulbali/about-us/publications/

Saeed, M. M., Ashraf, M., & Asghar, M. N. (2003). Hydraulic and hydro-salinity behavior of skimming wells under different pumping regimes. *Agricultural Water Management, 61*(3), 163–177. https://doi.org/10.1016/S0378-3774(03)00026-X

Schmid, W., Punthakey, J. F., Hodgson, G., Kirby, M., Ahmad, M., Podger, G., . . . Bodla, H. U. (2017). *Development of a regional groundwater model for the Indus Basin Irrigation System of Pakistan.* Status report for the South Asia Sustainable Development Investment Portfolio (SDIP) project. CSIRO, Australia.

Shakoor, A., Arshad, M., Ahmad, R., Khan, Z. M., Qamar, U., Farid, H. U., . . . Ahmad, F. (2018). Development of groundwater flow model (Modflow) to simulate the escalating groundwater pumping in the Punjab, Pakistan. *Pakistan Journal of Agricultural Sciences, 55*(3), 629–638. https://doi.org/10.21162/PAKJAS/18.4909

van Steenbergen, F. (2020). *Groundwater and surface water in the mega-irrigation systems of Pakistan: The case of conjunctive management* [Water Knowledge Note]. Washington DC: World Bank. http://hdl.handle.net/10986/33242

Van Steenbergen, F., Basharat, M., & Lashari, B. K. (2015). Key challenges and opportunities for conjunctive management of surface and groundwater in mega-irrigation systems: Lower Indus, Pakistan. *Resources, 4*(4), 831–856. https://doi.org/10.3390/resources4040831

Young, W. J., Anwar, A., Bhatti, T., Borgomeo, E., Davies, S., Garthwaite III, W. R., . . . Saeed, B. (2019). *Pakistan: Getting more from water*. Washington DC: World Bank. https://openknowledge.worldbank.org/handle/10986/31160

Zakir-Hassan, G., Punthakey, J. F., Shabir, G., Yasmeen, F., Sultan, M., Ashraf, H., . . . Majeed, F. (2022). Physicochemical investigation of rainfall for managed aquifer recharge in Punjab (Pakistan). *Water, 14*(14), 2155. https://doi.org/10.3390/w14142155

Gulbali Institute
Agriculture, Water and Environment

Charles Sturt University
Boorooma Street
Locked Bag 588
Wagga Wagga NSW 2678

1800 275 278 (free call within Australia)
+61 1800 275 278 (callers outside Australia)

gulbali@csu.edu.au

gulbaliinstitute

gulbali_inst

gulbaliinstitute

charlessturtuni

Charles Sturt University

Gulbali Institute
Agriculture Water Environment