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Modelling Climate Change Impacts and Adaptation Strategies for Managing Groundwater Resources in Pinyari Canal Command Area and Coastal Sujawal, Sindh

Shahryar Jamali, Jehangir F Punthakey, Waqas Ahmed, Abdul Latif Qureshi, Abdul Raheem, Mansoor Ahmed

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We also gratefully acknowledge funding support from 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 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, 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 Centre for Biosaline Agriculture (ICBA, UAE). This report covers the extensive modelling of the groundwater systems of the coastal district of Sujawal in Sindh, 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

Agriculture plays a pivotal role in ensuring sustainable economic development in Pakistan. Agriculture's contribution to Pakistan's Gross Domestic Product is about 19%; however, it provides decent employment opportunities to about 40% of the rural population (Young et al., 2019). Historically, Pakistan has relied on its extensive network of canals, which was designed for a cropping intensity of 67%. The increase in cropping intensities in recent decades has resulted in rapid growth in groundwater usage (Qureshi et al., 2010).

Surface water irrigation continues to play a crucial part in agricultural production. However, in Balochistan, Punjab and the freshwater regions of Sindh, the proportion of groundwater irrigation has grown dramatically in recent years. To meet the steadily increasing demand for food and fibre globally, the water requirements for agricultural practices are significantly increasing, particularly in South Asia, which depends on agricultural resources for food security and industry. More than 60% of the irrigation water needed for Pakistan's agriculture-based economy comes from the country's groundwater. Groundwater provides over 100% of the water used in industry and more than 90% for drinking. Pakistan's total agricultural intensity increased from over 63% in 1947 to over 120% in 2000, largely due to access to groundwater (Lytton et al., 2021). The key drivers for increased groundwater exploitation are increased cropping intensity for greater food security and increased incomes, which benefit farmers, particularly smallholder farmers.

Over the past two decades, increased groundwater pumping has resulted in significant declines in groundwater levels and, in some cases, has impacted groundwater quality in areas of Sindh with underlying shallow freshwater lenses. The growth in groundwater extraction in Sindh is constrained, as much of the province is underlain by shallow watertables of marginal to saline groundwater. However, large parts of the irrigated areas of central and lower Sindh within the Indus Basin Irrigation System are underlain by a thin freshwater lens that has accumulated from seepage from the canal supply network, as well as from rainfall and irrigation recharge. These freshwater lenses are now actively exploited by farmers to supplement shortfalls in the surface water supply system. With the impacts of climate change already affecting Pakistan, we can expect increased stresses on the fresh groundwater lenses underlying the districts of central and lower Sindh. High pumping rates will result in the overexploitation of these lenses with consequent effects of lateral saline intrusion and upconing from deeper saline layers.

Farmers in Sindh's lower regions are meeting their water needs by mixing surface and marginal quality groundwater or using groundwater when surface water is unavailable. Some places are severely exploited resulting in depletion of the freshwater lens, while some are experiencing salinisation and waterlogging. To maintain the local economy and agricultural land, farmers will need to adopt improved conjunctive use practices, improved monitoring systems along with an improved understanding of the fresh and saline groundwater response to pumping stresses, and determine sustainable yields and thresholds to facilitate the implementation of policies outlined in the Sindh Water Policy.

Salinity and waterlogging are widespread in Sindh due to shallow watertables and high evapotranspiration rates, which enhance salt transport into the crop root zone. The increased use of marginal quality groundwater in the Lower Indus Basin also contributes to salinity accumulation in the crop root zone. Salinity has become increasingly prevalent in coastal Sindh due to shallow brackish groundwater and the curtailment of flows downstream of the Kotri Barrage, which has enhanced sea water intrusion into the coastal zone with adverse impacts on coastal ecosystems. A changing climate has also enhanced sea level rise, which has affected coastal villages, resulting in some settlements being abandoned (Kalhoro et al., 2016; Siyal, 2018).

In this study, we developed a groundwater model covering the districts of Sujawal and parts of Hyderabad and Tando Muhammad Khan. The Indus River forms the western model boundary, and the southern model boundary lies along the Arabian Sea. The eastern model boundary lies along the drainage network, which forms part of the Left Bank Outfall Drain (LBOD), for draining saline water into the Arabian Sea. The model area encompassed the Pinyari Canal Command Area (CCA) and the coastal belt to the south of the Pinyari CCA. The Sindh Irrigation Department provided data related to the Pinyari CAA, which included canal flow and river stage for the Indus River at the Kotri Barrage. The study area was divided into four zones, of which the Pinyari CCA was divided into the Pinyari Lower Feeder, Daro Branch, and Pinyari Branch, while the area south of the CCA comprised the coastal zone.

Hydrogeological datasets, seepage from the Indus River and canal network, recharge from rainfall and field application losses, evapotranspiration, and aquifer characteristics were used to develop a groundwater model to understand the flow dynamics of the aquifer. The transient model for Sujawal covered the period from

October 2010 to September 2020. The water balance indicates 2,246.6 MCM/yr is recharged into the aquifer from rainfall and irrigation return flows (68% of inflows), and seepage from the Indus River and the canal network contributes about 720.4 MCM/yr, amounting to 22% of inflows. Outflows to the Indus River along the western model boundary are 610.7 MCM/yr, and net flows are 109.7 MCM/yr, indicating this section of the river is highly connected to the aquifer. By far the largest outflow of -2,199.8 MCM/yr is via evapotranspiration, driven by shallow watertables and high summer temperatures in the district of Sujawal. The high rate of evapotranspiration and marginal to brackish watertables in Sujawal increase the risk of salinity transport into the crop root zone, which is often manifested by surface salinity. The net gain in storage was 87.6 MCM/yr primarily due to inflows from the constant head boundaries along the coast, which add 316.7 MCM/yr, indicative of seawater intrusion into the coastal lands along the sea interface.

Scenario modelling assessed the impact of reduced surface water flows compared with the Baseline scenario from 2010 to 2060. The Baseline scenario indicates that net storage decreased from 83.6 MCM/yr for the calibrated model (2010–2020) to 18.3 MCM/yr, indicating that should conditions remain the same as in 2010–2020, the aquifer will eventually reach an equilibrium. The layer water balance indicates significant flows between Layers 1 and 2 and, to a lesser extent, between Layers 2 and 3. Interlayer leakage shows net flows are occurring from Layer 1 to Layer 2 and similarly from Layer 2 to Layer 3, which is important to maintain as a reversal of gradients will result in increased waterlogging and the spread of salinity.

The water balance for the Reduced Flow scenario shows a decrease in inflows from the river and canal network to the aquifer of 13.6% compared with the Baseline scenario. Additionally, the reduction in surface water flows available for irrigation results in a 17.9% decrease in irrigation recharge, resulting in a decline in water levels, which also decreases evapotranspiration by 15.8% compared with the Baseline scenario, and a decrease in the drain outflow of 15%. These results indicate that areas affected by shallow watertables and salinity can be reduced if water efficient crops are introduced, along with improved water and land management practices. Future water security in Pakistan is a significant concern for policymakers. In particular, competition for water from a growing population and industrial base will likely result in marked reductions in surface water flows, which will be the key driver in transforming cropping patterns to less water intensive crops. Due to the high summer temperatures in Sujawal and the shallow groundwater table, a decrease in evapotranspiration rates will decrease capillary rise and reduce areas where salinity manifests itself on the soil surface, which can improve agricultural production in areas prone to salinity and waterlogging. This scenario also shows outflows to the sea decrease by 13.4%, resulting in an increase in net inflows from the sea boundary from 42.6 MCM for the Baseline scenario to 76.5 MCM, which could increase the risk of seawater intrusion. To minimise this risk, green barriers and engineering solutions may also be required to manage an encroaching sea boundary, particularly as sea levels rise in response to climate change.

Two climate change scenarios were modelled using precipitation and temperature data for SSP2-4.5 and SSP5-8.5, corresponding to medium and high emission scenarios, to simulate the likely impact of climate change in Sujawal. The SSP2-4.5 and SSP5-8.5 water balance indicates recharge is 1,902.9 MCM and 1,927.3 MCM compared to 1,844.7 MCM for the Reduced flow scenario. The resulting increase in water levels decreases flows from the river to the aquifer by18% and 20% for the SSP2-4.5 and SSP5-8.5 scenarios and correspondingly results in higher outflows from the aquifer to the river. The river now acts as a gaining stream with net flows from the aquifer of 87.2 MCM, compared to a losing stream for the Reduced Flow scenario of 94.8 MCM. Additionally, the projected sea level rise for SSP2-4.5 scenarios with a medium confidence level indicates net inflows increased by 18% along the sea boundary compared to the Reduced flow scenario as outflows have decreased by over 50%. However, inflows can be expected to increase as sea levels continue to rise beyond 2100.

The projected rainfall and evapotranspiration for the SSP5-8.5 scenario indicates a marginal increase in rainfall recharge, and a marginal increase in evapotranspiration compared to the SSP2-4.5 scenario. A significant increase occurs in boundary inflows from the sea due to the rising sea levels, resulting in an increase in net inflows of 188.4 MCM for the SSP5-8.5 scenario compared to 76.5 MCM for the Reduced Flow scenario. The simulated increase in net inflows from the sea boundary is expected to continue to increase post-2100 as sea levels continue rising to 1.86m to 2150, or under the potential effect of low-likelihood, high-impact ice sheet processes, the net inflows and coastal inundation are expected to be even greater.

We simulated selected adaptation options that must be implemented to allow agricultural activities to continue to support the communities in Sujawal. Also, specific adaptation options, such as green barriers, are required to improve the health and productivity of coastal ecosystems. To manage the widespread shallow watertables and reduce salinity impacts on agricultural land, we have designed a mix of adaptation options, which include changes to cropping systems and nature-based solutions to guide farming communities and institutional actors on possible strategies to reduce the risk of land salinisation and seawater intrusion in the coastal district of Sujawal. The first adaptation option included substituting 25% of the rice crop with sunflower and 25% of the sugarcane crop with mustard to replace these high delta crops with water efficient crops in areas with shallow watertables and relatively high salinities. To mitigate the impacts of seawater intrusion in the medium to long term, we proposed nature-based solutions that would be beneficial for reducing some of these risks for coastal areas and communities. We identified three zones in the coastal zone for environmental amelioration, which included a primary barrier of mangroves along the coast, a secondary barrier of saltbush in areas with salinities in the 5,000–15,000 µS/cm range, and a tertiary barrier of native trees along the southern boundary of the Pinyari CCA where salinities reach a maximum of ,5000 µS/cm. Simulating outcomes for the high emission climate change scenario SSP5-8.5, we found the proposed adaptation options would reduce net outflows from the aquifer to the river from -117.1 to -8 MCM which indicates increased freshwater flows from the Indus recharging the aquifer, which will be beneficial for creating a freshwater lens along the banks of the Indus.

Establishing mangroves will provide a primary barrier to coastal erosion, while the secondary and tertiary barriers provide added protection to the southern areas of the Pinyari CCA. Our suggested options will play an important role in mitigating waterlogging and salinity intrusion risks in the medium term, but these alone will not mitigate the overarching risk posed by rising sea levels and climate change. Mitigating the adverse impacts of sea level rise will need a rethink of additional adaptation strategies to address politically sensitive issues, such as an additional allocation of freshwater to the Indus River for release below the Kotri Barrage, and physical barriers such as dikes or polders, drainage of shallow saline groundwater, and extensive land reclamation.

An explicit goal of Pakistan’s 2018 National Water Strategy was to increase understanding of the country’s groundwater supplies and quality. To enhance water governance in Sindh, the Sindh Water Policy (2023) has emphasised groundwater monitoring and management of freshwater lenses. The policy also places significant importance on water quality and advocates the creation of a committee to regulate and actively monitor groundwater. However, groundwater usage was and is unregulated despite being emphasised as an important resource in the policy. The findings of this study aim to assist key institutional stakeholders (the Sindh Irrigation Department, Sindh Irrigation and Drainage Authority and Sindh Agriculture Department) and researchers to identify best management practices and strategies to implement strategic monitoring of groundwater resources in the Pinyari CCA and the coastal zone, which is at risk from seawater intrusion. An equitable share of surface water supplies for the Pinyari CCA will be required to improve productivity in this non-perennial canal system. The mapping of the freshwater lenses in the Pinyari CCA and along sections of the Indus will allow access to limited groundwater resources to supplement shortfalls in surface water supplies, allowing farmers to improve productivity. The adoption of skimming wells will be required to access these fragile freshwater lenses, along with financial assistance and significant knowledge transfer to participating farmers. With a good network of drains, a possible option is using solar-powered tubewells to pump deeper saline groundwater for disposal into the drainage network, which is transported via a tidal link to the sea. Agriculture in Sujawal comprises smallholder farmers, and impacts on agricultural productivity will affect livelihoods, likely resulting in out-migration to cities for employment opportunities. Policy experts in agriculture, irrigation and rural development are required to develop an integrated solution for coastal agricultural communities. Supporting the transition to a sustainable future in an era of climate change will be a priority for the Government of Sindh.

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Abbreviations

ACIAR	Australian Centre for International Agricultural Research
AMSL	above mean sea level
BCM	Billion cubic metres
CCA	Canal Command Area
CSIRO	The Commonwealth Scientific and Industrial Research Organisation
DTW	Depth to watertable
EC	Electrical conductivity (1 mS/cm= 1dS/m = 1000 µS/cm)
LBOD	Left Bank Outfall Drain
MCM	Million cubic metres
SCARP	Salinity Control and Reclamation Project
SID	Sindh Irrigation Department
SIDA	Sindh Irrigation and Drainage Authority
SMO	SCARP Monitoring Organisation
WAPDA	Water and Power Development Authority

1. Introduction

Agricultural enterprises contribute significantly to Pakistan’s economy and food security for the growing population. The agriculture industry contributes about 20% to the GDP and provides livelihood opportunities for about 40% of the rural population (Azam & Shafique, 2017). Agriculture uses more than 95% of surface water for irrigation. Pakistan has vast agricultural lands with inadequate freshwater availability throughout the year and an occasional water surplus during the monsoon season. Meeting the needs of a rapidly growing population with limited freshwater availability is a major challenge for government authorities. The Indus Basin Irrigation System predominantly supports Pakistan’s agriculture with its well-established irrigation infrastructure. The Indus River and its western tributaries, Jhelum and Chenab, provide significant water to this irrigation system. The three eastern tributaries, including the Ravi and Sutlej Rivers, have flow curtailed by upstream dams in India. Pakistan’s total renewable water resource is estimated to be 229 billion cubic metres (BCM) per year, of which about 95% is from the Indus Basin. This network’s annual surface water supply is about 205 BCM, with a canal command area of 16.2 million hectares and 125 BCM of annual canal diversions. Water resources are crucial for Pakistan’s economy and the prosperity of its communities. However, water resource use in Pakistan is poorly managed compared to countries with similar water supplies and allocations, exacerbating socio-economic and environmental issues (Lytton et al., 2021).

Surface water supply is inadequate to meet irrigation requirements as cropping intensities have increased substantially from 67% to over 120%. The shortfall is made up by accessing groundwater for irrigation. The conjunctive use of surface and groundwater plays a significant role in productive farming enterprises (Van Steenbergen et al., 2015). This is particularly so in Punjab, where the share of groundwater for irrigation exceeds surface water in many parts of the province. In Sindh, surface water and, to a lesser extent, groundwater are vital for increasing cropping intensity and improving agricultural productivity. The shallow, often marginal to brackish groundwater that underlies much of the Lower Indus Basin (LIB) does not allow for extensive use of groundwater; nevertheless, access to groundwater in the LIB has allowed many Sindh farmers to increase cropping intensity and livelihood opportunities. The downside is the extensive exploitation of the freshwater lens results in increased use of marginal quality groundwater, which impacts soil and crop health through the accumulation of salts in the crop root zone (Lytton et al., 2021).

The National Water Policy (2018) highlighted the importance of improving knowledge of groundwater resources and water quality in Pakistan. The recently promulgated Sindh Water Policy (2023) emphasises the importance of groundwater management, including water quality, to improve water governance in Sindh. It also advocates for a committee to regulate and actively monitor groundwater. However, a framework for monitoring and managing groundwater has yet to evolve.

Punjab has better access to good-quality groundwater where groundwater is relatively deep, and seepage from an extensive network of canals and link canals has contributed to a thick layer of relatively fresh groundwater. In contrast, aquifers in Sindh have shallow watertables, which are generally higher in salinity. Consequently, access to fresh groundwater is limited to a thin freshwater lens overlying deeper marginal and brackish groundwater. Nevertheless, there is extensive exploitation of the freshwater lens in the Rohri canal command area covering the districts of Khairpur, Naushero Feroze and Shaheed Benazirabad. Sindh, being a lower riparian of the Indus River, faces challenges of water scarcity in the dry seasons, which compels farmers to exploit groundwater to supplement shortfalls in surface water supplies. However, farmers generally prefer surface water, which is of better quality, than groundwater, which is also more expensive. Towards the end of the twentieth century, about 70% of the watertable had increased up to depths of 1.5m and 20% to 2m (Ahmed et al., 2021). The Salinity Control and Reclamation Project (SCARP) initiated by the Sindh government aimed to address waterlogging and salinity by installing cost-effective shallow tubewells. While initially successful in lowering the watertable and promoting sustainable groundwater use, the project faced setbacks due to non-functional tubewells caused by a lack of operation and maintenance and funding constraints. Improved groundwater management in Sindh will require a robust monitoring program and sufficient investment in capacity building for irrigation managers and local communities.

Coastal areas in Sindh are essential environmental assets. These areas are vulnerable to climate change impacts due to their proximity to the sea and river delta. Fresh groundwater resources in the coastal areas of Sindh are limited, as much of the area is underlain by shallow marginal to brackish groundwater. Pockets of relatively fresher groundwater are exploited mostly by hand pumps for potable and domestic uses (Siyal, 2018). Additionally, the curtailment of flows from the Kotri Barrage has adversely impacted coastal communities, agriculture, and biodiversity due to seawater intrusion into coastal lands (Solangi et al., 2019a).

Consequently, coastal communities require significant assistance in adopting agricultural practices for improved management of waterlogging and salinity and to be made aware of adaptation options to enhance the viability of agriculture in these marginal environments.

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) led by Charles Sturt University with national and international partners. It aims to develop and investigate adaptation options and strategies for people living in salinity affected agricultural regions in the Southern Indus Basin. A shallow watertable and salinity are widespread in the coastal district of Sujawal, requiring an in-depth understanding of the impact of stresses on the groundwater system. As part of this research, we developed a groundwater model of the Lower Indus Basin covering parts of Hyderabad, Tando Muhammad Khan and the coastal district of Sujawal to improve understanding of the key drivers for waterlogging and salinity and assess the increasing risk of seawater intrusion from rising sea levels in the coastal belt in Sujawal. The groundwater model provides the basis for understanding the impacts of reduced surface flows on groundwater resources, and the impact of climate change scenarios on waterlogging and salinity in the Pinyari CCA and the coastal regions of Sujawal. The model simulated the impacts of sea level rise under two climate change scenarios, SSP2-4.5 and SSP5-8.5, to understand the inflows into the coastal zone that are likely to occur from the sea boundary. We have also simulated adaptation options that farmers will need to implement to extend the viability of agriculture under a changing climate regime.

This study will achieve the following outcomes that will guide the sustainable management of groundwater in the Pinyari CCA and coastal areas of Sujawal:

- An improved understanding of aquifer responses to stresses and quantifying the water balance for the region.
- Developing scenarios related to variations in surface water supply and climate change to assess impacts on the water balance in 2060 and 2100.
- Evaluating the impact of sea water intrusion in response to rising sea levels for the coastal areas of Sujawal.
- Building the capacity of institutions to carry out effective research in groundwater modelling and sustainable groundwater management and guiding institutional actors in improving the management of surface and groundwater resources in support of the Sindh Water Policy.

2. A Review of Groundwater Studies in the Sujawal District

A few studies focusing on groundwater in the Lower Indus Basin have been undertaken since the 1960s. The most comprehensive field investigations were undertaken during the Lower Indus Plains project. Since then, little or no attention has been given to groundwater in Sindh and the sparse monitoring of groundwater undertaken by the Sindh Monitoring Organization (SMO) under WAPDA. In the past, the Sindh Irrigation Department did not play a significant role in groundwater monitoring or management. However, the Sindh Water Policy (2023) sets out clear guidance on the need to monitor groundwater quantity and quality. The Sindh Irrigation Department is designated as responsible for monitoring and managing groundwater, with particular attention on managing Sindh's freshwater lenses, lakes and environmental assets. This section briefly reviews selected groundwater studies relevant to the Lower Indus Plains, particularly the coastal districts of Thatta, Badin and Sujawal.

2.1. Groundwater Studies in the Lower Indus Basin

An increase in population and the need for food security has compelled farmers to use groundwater to supplement shortfalls in surface water supplies for irrigation and domestic uses in Sindh. Van Steenbergen et al. (2015) attributed the low exploitation of groundwater in Sindh to relatively high surface water allocations in some of the canal command areas and the marginal to brackish groundwater in much of Sindh. They further cited the drought from 1999 to 2002, which reduced waterlogging significantly due to reduced surface water availability.

In lower Sindh, farming livelihoods increasingly depend on access to shallow fresh groundwater lenses that have accumulated from rainfall, canal seepage, and irrigation return flows. The freshwater lenses in the districts of Khairpur, Naushero Feroze, and Shaheed Benazirabad along the Rohri Canal in Lower Sindh are increasingly exploited to supplement surface water supplies, particularly at the tail end of canals. Shortfalls and inequity in canal water supplies are the main drivers for increased reliance on groundwater. In these areas where watertables are relatively deep, the risk of depletion increases the risk of saline groundwater upconing and lateral intrusion. A modelling study of the districts along the left bank of the Sukkur Barrage found declining trends in groundwater in the districts of Khairpur, Naushero Feroze and Shaheed Benazirabad (Ahmed et al., 2021). This study indicated that excessive pumping during the dry months depletes the freshwater lens and increases the risk of using marginal quality groundwater for irrigation. The loss of access to groundwater in these regions will compel farmers to lower cropping intensity, impacting food security in the region. For groundwater irrigation in Sindh to continue, improved conjunctive use practices and equitable access to surface water supplies will be required to reduce salinisation and maintain freshwater lenses along with investments in water productivity and modifying cropping regimes towards low delta crops.

This study also guided the Sindh Irrigation Department in managing groundwater extractions in the Rohri canal command area (CCA) within a limit of 3(±0.3) BCM to sustain groundwater resources in the CCA. The study also suggested that farmers should be allowed to increase extraction during drought years by 10% of the sustainable yield (0.3 BCM), which could then be replenished when surface water flows and rainfall were sufficient. The study also recommended instituting a groundwater monitoring program and the establishment of Groundwater Management Zones for the Northern Rohri CCA with a focus on areas where the freshwater lenses are being exploited for groundwater irrigation (Ahmed et al., 2021).

2.2. Groundwater Studies in Sindh's Coastal Region

A mapping and modelling study of the Lower Indus Basin revealed that between 1984 and 2015, pumping rose from 1.6 BCM annually to 19 BCM (Iqbal et al., 2020). In Sindh, there are over 230,390 tubewells that pump marginal to brackish groundwater, increasing the risk of secondary salinisation (Government of Pakistan, 2018). The Indus Delta is a low-lying region with extensive areas impacted by waterlogging and salinity. The marginal to brackish groundwater in much of the coastal areas of Sindh constrains extensive groundwater use. Within the Indus Delta, shallow watertables ranging in depth from 0.25 to 1.5 metres impact over 61% of the region with salinity concentrations increasing with depth. Fresh groundwater availability in these regions is limited to areas near the Indus River or the headwaters of canals and distributaries. The Indus Delta is formed by the southern portions of the Lower Indus Plain aquifer, where groundwater flow follows the Indus River with little to no flow towards the sea. The reduction in flows downstream of the Kotri Barrage has considerably increased the risk of seawater intrusion in the delta regions.

A cross-section of the surficial aquifer through the coastal districts of Thatta, Sujawal and Badin shows sand sequences ranging from a few metres to about 50 metres, generally interlayered with clays (Figure 1). The cross-section also shows a greater presence of clays compared to other areas of Sindh. The true thickness of the alluvium in the coastal areas is not known as it is likely that drilling would have stopped once saline groundwater was encountered (at 10 to 30 metres); however, the alluvium is expected to be much deeper as the thickness increases towards the coast (Lytton et al., 2021).

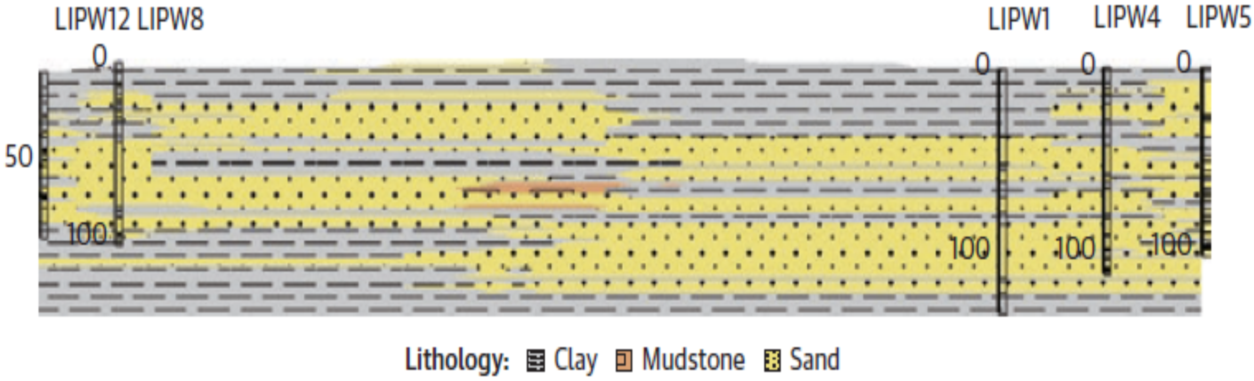


Figure 1: Cross-section through Sujawal, Badin and Thatta coastal districts
(Source: Lytton et al., 2021)

2.3. Seawater Intrusion Impacts in Coastal Sindh

Coastal flooding as a result of tidal infringement from spring tides affect over 0.49 million hectares in the Indus Delta (Kalhoro et al 2016). The areas which are most affected by seawater intrusion comprise the districts of Thatta, Sujawal and Badin, of which over 0.33 million hectares are affected in the Talukas of Shah Bandar in Thatta and Jati in Sujawal. Additionally, low flows and low silt loads in the Indus River below the Kotri Barrage are the main drivers which are degrading the lower reaches of the Indus Delta, affecting biodiversity, mangroves, and coastal subsistence communities in the delta.

There has been a major loss of ecosystem services in the estuarine plains due to habitat loss, biodiversity loss, and effects on lakes and dhands (salt lakes). Vegetation in the coastal belt increased between 1980 and 2010 but subsequently declined because of seawater intrusion in the coastal zone, adversely impacting livelihoods in coastal communities (Siyal, 2018). Additionally, contaminants such as arsenic and calcium in surface and groundwater samples were detected in the coastal belt (Siyal, 2018). Coastal erosion and the lack of silt recovery have also adversely impacted the Indus Delta ecosystem (Kalhoro et al., 2016), and coastal communities are also affected by extreme weather events and accelerated seawater intrusion during the dry season (Jain, 2010; Khaskheli et al., 2018). Salinity has significantly impacted groundwater, land resources and agricultural productivity in Sindh’s coastal zone, which has caused many farmers to abandon once productive agricultural lands.

2.4. Groundwater Quality in Sindh’s Coastal Region

Groundwater contamination is a serious concern in Sindh’s coastal region. In Sujawal, about 13.83% of water samples were found to be unsuitable for drinking purposes and only 6.38% of water samples were fit for potable use (Solangi et al., 2020). Using the SPI model, Solangi et al. (2019b) found 32%, 13.83%, 20.12%, 18.1%, and 15.95% of samples were slightly polluted, moderately polluted, highly polluted, suitable, and unsuitable, respectively. Most of the groundwater samples did not meet the WHO guidelines for drinking water and irrigation, which suggested avoiding the use of coastal groundwater.

Remote sensing was used to determine soil salinity conditions in Sujawal from 1990 to 2017 (Solangi et al., 2019b). The study found that vegetation has been reduced by 8.6%, and water bodies increased significantly in Sujawal's coastal zone. High soil salinities were found in the Jati and Shah Bandar sub-districts, which were attributed to climate change and seawater intrusion. This study has also formulated plans to implement salinity control strategies in this area. Suggestions to control salinity included restoring mangrove plantations, ensuring enough freshwater flow below the Kotri Barrage, building protective bunds, and reducing seawater intrusion impacts. Building on this foundation, the current research has undertaken scenario modelling and an adaptation scenario, which includes using green barriers in affected areas and adopting low delta crops for managing the coastal areas of Sujawal.

A study on the suitability of groundwater for domestic and irrigation purposes in the Indus Delta found that 18%, 87%, and 94% of groundwater was concentrated with arsenic, total dissolved solids, and chloride, respectively. Higher chloride levels in groundwater suggested enhancement of seawater intrusion in the Indus Delta, indicating limited opportunities for exploiting groundwater for irrigation and domestic purposes in coastal Sindh (Solangi et al., 2019b). Groundwater quality assessment in the Thatta region of coastal Sindh found groundwater samples were dominated by turbidity, faecal coliform, salinity, and heavy metals – demonstrating groundwater in this region is not satisfactory for drinking purposes (Alamgir et al., 2016).

3. Physical Setting

3.1. Overview of Sujawal District in Sindh

Sujawal became a new district of southern Sindh in 2013 with a geographical area of 8,600 km^2. Sujawal comprises four sub-districts: Sujawal, Shah Bandar, Mirpur Bathoro, and Jati. It has a dry tropical climate with an annual average precipitation of 220mm and its temperature varies between 23.8℃ and 28.7℃. The Pinyari Canal, also known as the old Phuleli Canal, is a non-perennial canal that offtakes from the left bank of the Kotri Barrage. It is the main supply source for agricultural, industrial, and domestic needs of the Sujawal and Hyderabad districts. Groundwater, despite its marginal quality, provides water for potable and domestic uses for many coastal villages. Groundwater in the delta region is also vulnerable to the threat of sea water intrusion and increased salinisation of land (Solangi et al., 2020). Coastal floods and waterlogging affect around 1.2 million hectares of fertile land in the districts of Sujawal and Badin (Khaskheli et al., 2018). Sujawal district is shown in Figure 2.

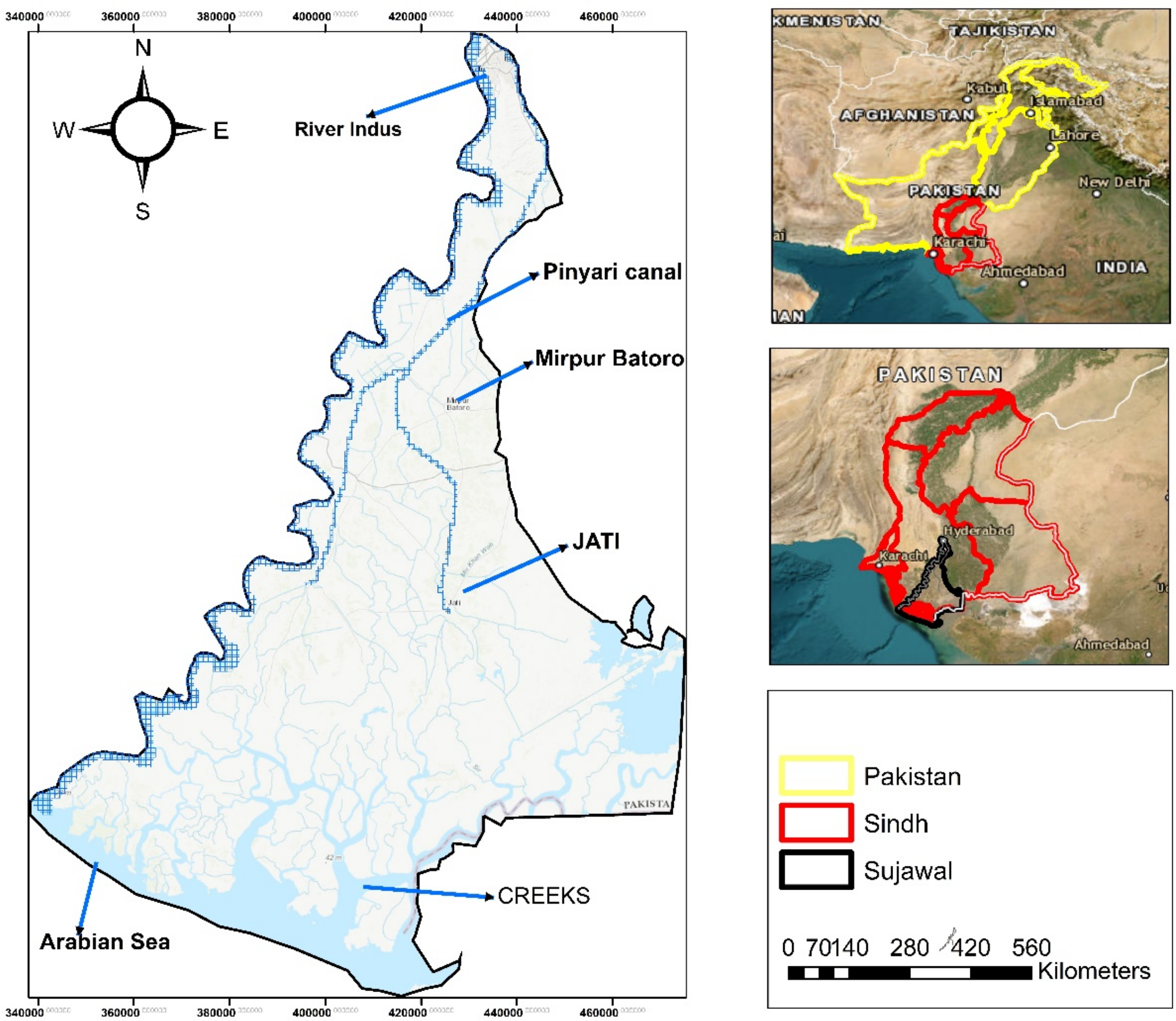


Figure 2: Sujawal district

3.2. Topography and Drainage of the Study Area

This study area is part of the coastal region in the lower Indus Plain bounded by the Kirthar Range plateau to the west. This vast flood plain was created due to silt deposition from the Indus River. In the northern part of the study area, the basement outcrops range in elevation from 30 to 75m above mean sea level (AMSL) and are situated in the district of Hyderabad. Small hills such as Ganjo Takar and others are also situated in the districts of Hyderabad and Tando Muhammad Khan. These small hills and peaks are outcrops of the Kirthar Range, which extends towards the Rann of Kutch. Other than the outcrop in the north of the modelled area, the rest of the study area is flat with a low slope, and the topography generally reduces in elevation from north to south towards the Arabian Sea (Basharat, 2005). The plains below the Kotri Barrage spread out in an alluvial fan, forming the Indus Delta. The Merit digital elevation model data were used for model elevation – they were superior to STRM data, particularly in the coastal zone (see Figure 3).

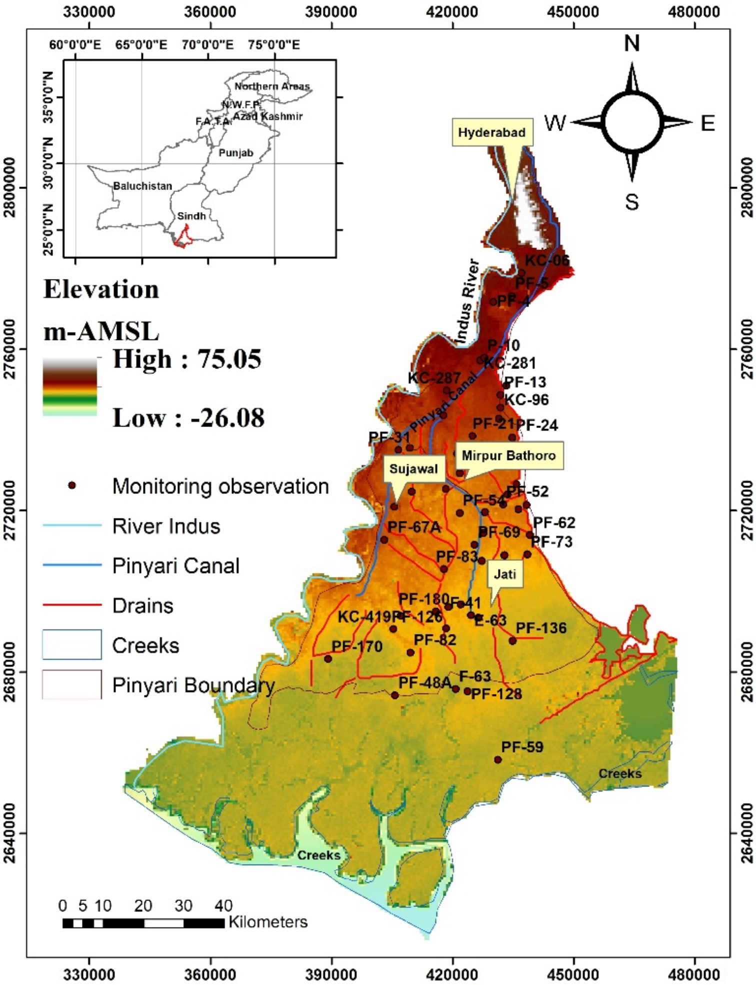


Figure 3: Topography for the study area

3.3. Lithology and Geological Overview of Sujawal

The lithology of the study area is diverse, and its lithological characteristics vary considerably. The upper reaches of the study area in the districts of Hyderabad and Tando Muhammad Khan are concentrated with flood plain deposits (lower terrace), stream beds and meander belt deposits. Stream bed and meander belt deposits are also found in the Sujawal district with multiple water bodies scattered around the area. Deltaic flood plain deposits are found in the southern regions of the Pinyari CCA. The coastal area is rich in tidal mudflat deposits and tidal delta marsh deposits, indicating periodic tidal incursions. Moreover, the distribution of different soil conditions at different depths shows considerable variation in the geological condition of this area. The upper regions of the study areas are covered with loamy soil that favours the cultivation of a range of crops. Lithological and soil distribution in the study area is shown in Figure 4 (Iqbal et al., 2020). An investigation of boreholes available in the study area found the major lithology in this region comprised clays, silts, sand, and limestone, as illustrated in Table 1.

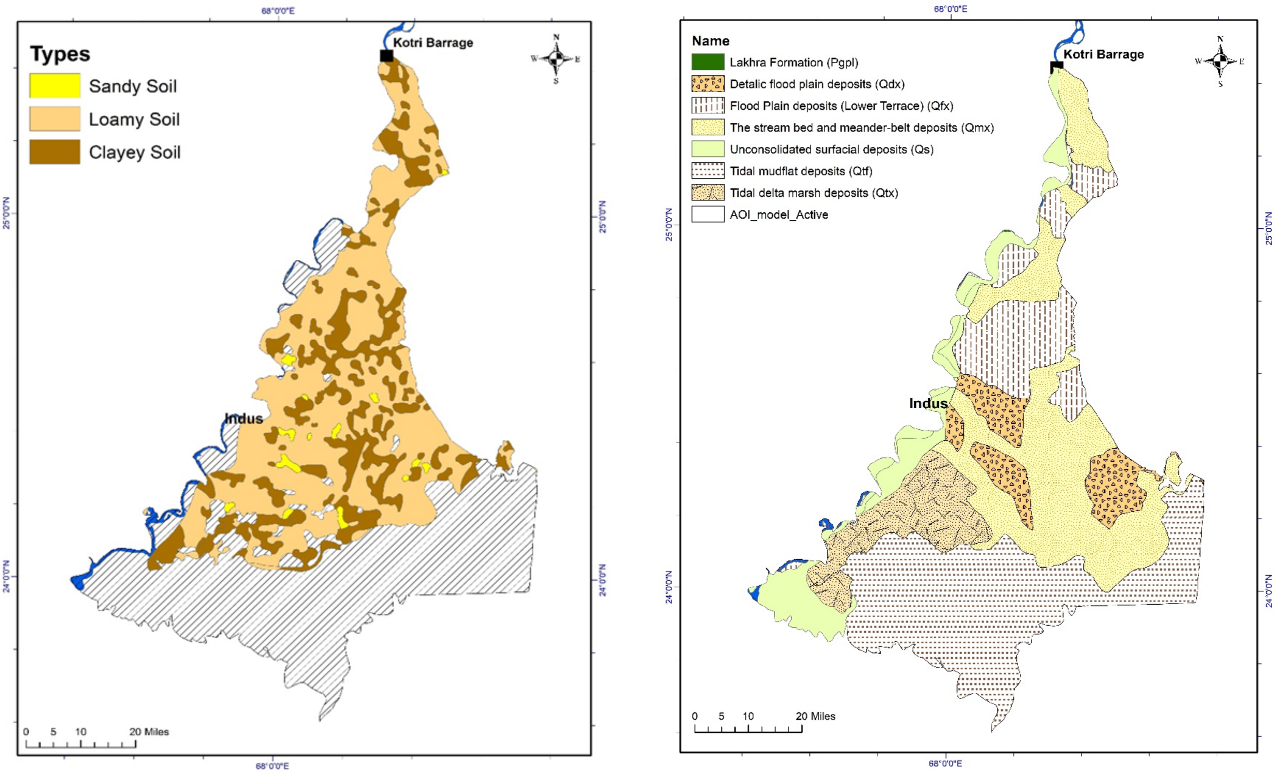


Figure 4: Soils and surficial lithology of Sujawal district

Table 1: Lithology of major bore logs available in the study area
(Source: Schmid et al., 2017)

Reference area	Well ID	Longitude	Latitude	Depth (m)	Major lithology
Kotri Command	G6	68.4229	25.12899	0–64	Clay, sand, gravel, limestone
Kotri Command	TW33	68.42314	25.11924	0–56	Clay, sand, limestone
Kotri Command	LIPW74	68.42933	25.09544	0–76	Clay, sand
Kotri Command	TW32	68.48834	25.12519	0–63	Clay, sand, limestone
Kotri Command	G9	68.3815	25.04881	0–137	Clay, sand, limestone
Kotri Command	LIPW86	68.34183	25.07034	0–69	Clay, sand
Kotri Command	LIPW72	68.34176	24.98851	0–61	Clay, sand
Kotri Command	G10	68.32986	24.95401	0–129	Clay, sand, gravel

3.4. Groundwater Monitoring in the Study Area

The depth to water in the study area ranges from 0 to 5.5m, which suggests the water levels are encountered at shallow depths. Depth to watertable data were acquired from WAPDA's SCARP Monitoring Organization (SMO) from 2010 to 2020 for both the pre- and post-monsoon seasons. There were significant gaps in monitoring between 2015 and 2018 as the monitoring program was suspended due to funding constraints. The presence of shallow watertables indicates much of the area is vulnerable to waterlogging, as shown in Figure 5. The available observation data were spatially interpolated using IDW to create the spatial maps of depth to watertable for the study area. There were no observation bores in the coastal zone south of the Pinyari CCA. While comparing post-monsoon water levels, we observed water levels were relatively high in the southern regions of the Pinyari CCA post-2011, and significantly decreased post-2020, possibly due to significantly high rainfall in 2011 in southern Sindh. During the pre-monsoon season, a depth to watertable >5 m was observed in some areas of the Pinyari CCA. During pre-2013, watertables adjacent to the Indus River were higher, increasing with distance away from the river (Figure 5). However, watertables were deep in some parts of the Daro and Pinyari Branch command areas, as canal flows had ceased in the dry season given the Pinyari Canal is non-perennial. In pre-2015, there was a considerable area with shallow watertables, shown in green in Figure 5. During the pre-monsoon season, large areas had watertables in the 0 to 1m range, whereas in the post-monsoon period, significant areas had watertables in the 0 to 0.47m range. These maps show that the watertables were higher during the post-monsoon season, suggesting a higher rate of recharge during the wet season as well as seepage from the supply system.

3.5. Groundwater Quality Status in the Study Area

Several monitoring bores show the electric conductivity (EC) exceeds the safe drinking water threshold, indicating the poor quality of groundwater in Sujawal. Total dissolved solids (TDS) concentrations higher than 500 mg/l were found in more than 80% of samples, suggesting poor water quality will likely impact human health in this region. Hardness, magnesium, calcium and other parameters were also found to be higher than their permissible limits, which suggests that groundwater quality in Sujawal is of concern (Solangi et al., 2020). Table 2 indicates that the freshwater zone decreased by 60% from 2011 to 2020. Figure 6 shows that the Pinyari Lower Feeder branch command area had freshwater in 2011, which transitioned to marginal quality in 2020. Near Mirpur Bathoro, the water quality was hazardous, indicating a deterioration of groundwater quality in the study area.

The salinity distribution pattern in the study area indicates the availability of freshwater pockets adjacent to the Indus River, specifically in the Main Pinyari Branch CCA. However, the temporal variation of electrical conductivity (EC) shown in Figure 7 indicates an increase in salinity concentrations along the left bank of the Indus River from 2011 to 2020. It is striking that there are significant changes in EC from year to year, which can be attributed to varying precipitation and availability of surface water flows in the kharif season.

The available data highlights the farming population's reluctance to use the marginal groundwater resource in the Pinyari CCA. No monitoring data are available in Sujawal's coastal region south of the Pinyari CCA. Monitoring in this area is essential to fully understand the effects of tidal intrusions and seawater intrusion on the coastal aquifer. Additionally, studies by Siyal (2018) and Kalhoro et al. (2016) demonstrate that seawater intrusion results in declining groundwater quality in the coastal belt, highlighting the need for monitoring and research in the coastal zone.

3.6. Precipitation Trends in Sujawal

The study area, which extends from Hyderabad to Sujawal to the coast, experiences moderate climatic conditions with dry cool winters, hot summers and occasional monsoon rains from July to October. During the summer, especially in May and June, maximum temperatures can reach 45℃ while it can fall below 10℃ in December and January. Sujawal receives low rainfall from November to March during the dry season and maximum rainfall occurs during the wet season from July to October. The average rainfall in the study area is 220 mm and about 80% of the rainfall occurs during the kharif season.

After the wet season, the temperature range is moderate from the coastal area to the Hyderabad district due to a sea breeze from the Arabian Sea. Wind velocities are generally higher in this area due to its proximity to the Arabian Sea, which also increases the intensity of dust and rain. Solangi et al. (2019b) suggest the weather has become extreme and unpredictable in this region due to climate change. The pluvial flood in August 2022 destroyed infrastructure, inundated crops, and caused significant loss of life and livelihoods. Precipitation is generally low in the coastal areas, which results in drought conditions in Sindh (Basharat, 2005; Solangi et al., 2019b). The box plot Figure 8 shows higher rainfall in July, August, and September, during the wet season. The yearly column chart (Figure 9) depicts the erratic behaviour of precipitation in the last ten years as a possible indicator of the changing climate in this region. Climate change and its adverse impact in the coastal areas of Sindh will require governments to direct additional resources for mitigation and adaptation.

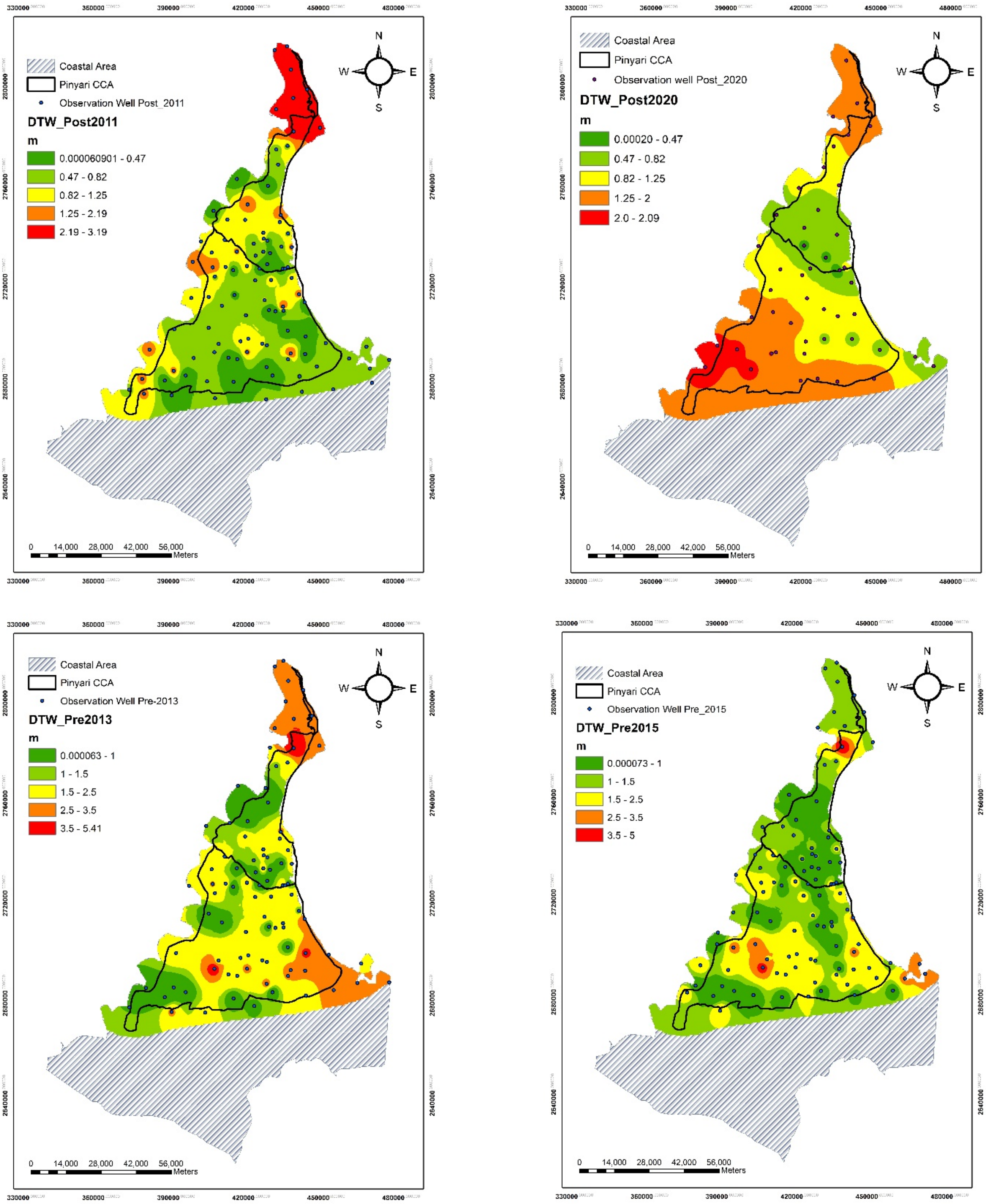


Figure 5: Spatial variation of depth to watertable (DTW) in Sujawal district for post-2011 and 2020, and pre-2013 and 2015

Table 2: Area change under different classes of EC in 2011 and 2020

Class	EC (µS/cm)	Area (km²) Post-2011	Area (km²) Post-2020	2011 to 2020 change (%)
Relatively fresh	<1,500	1,515.63	600	60.41
Marginal	1,600-4,000	2,430.01	3,255	33.95
Hazardous	>4,000	1.63	92.26	5,565.09
Total		**3,947.27**	**3,947.26**	

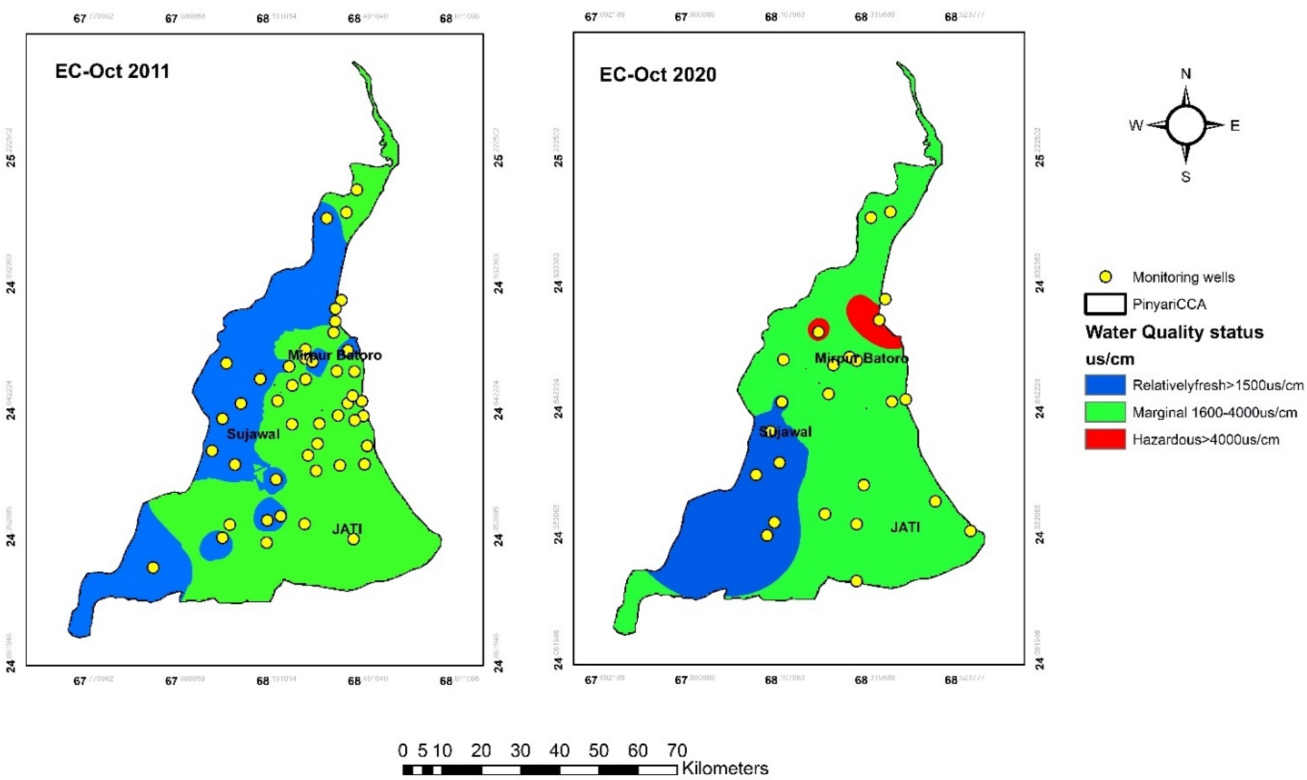


Figure 6: Spatio-temporal variation in EC for Pinyari CCA post-2011 and post-2020

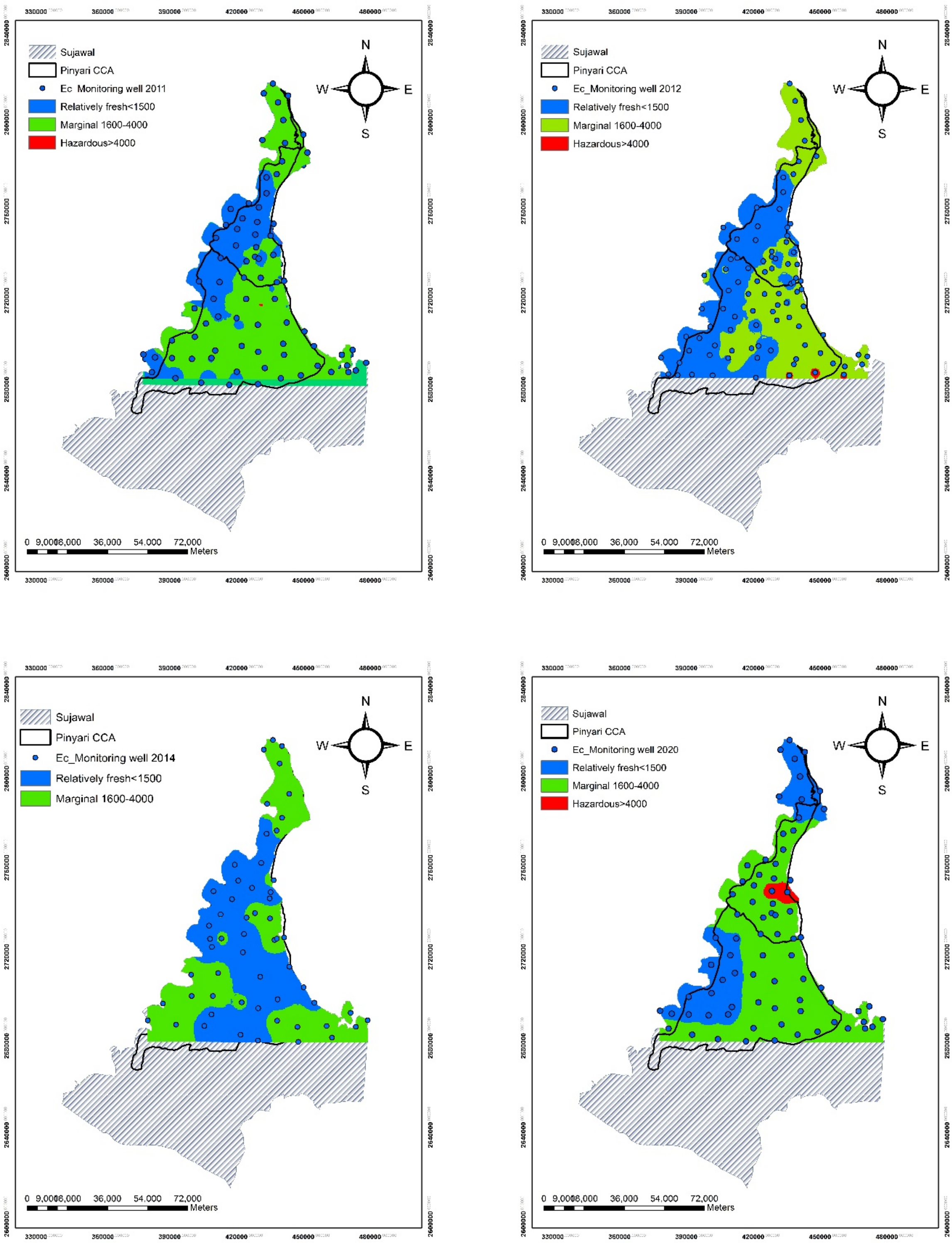


Figure 7: Spatial variation of EC in 2011, 2012, 2014 and 2020 in the study area

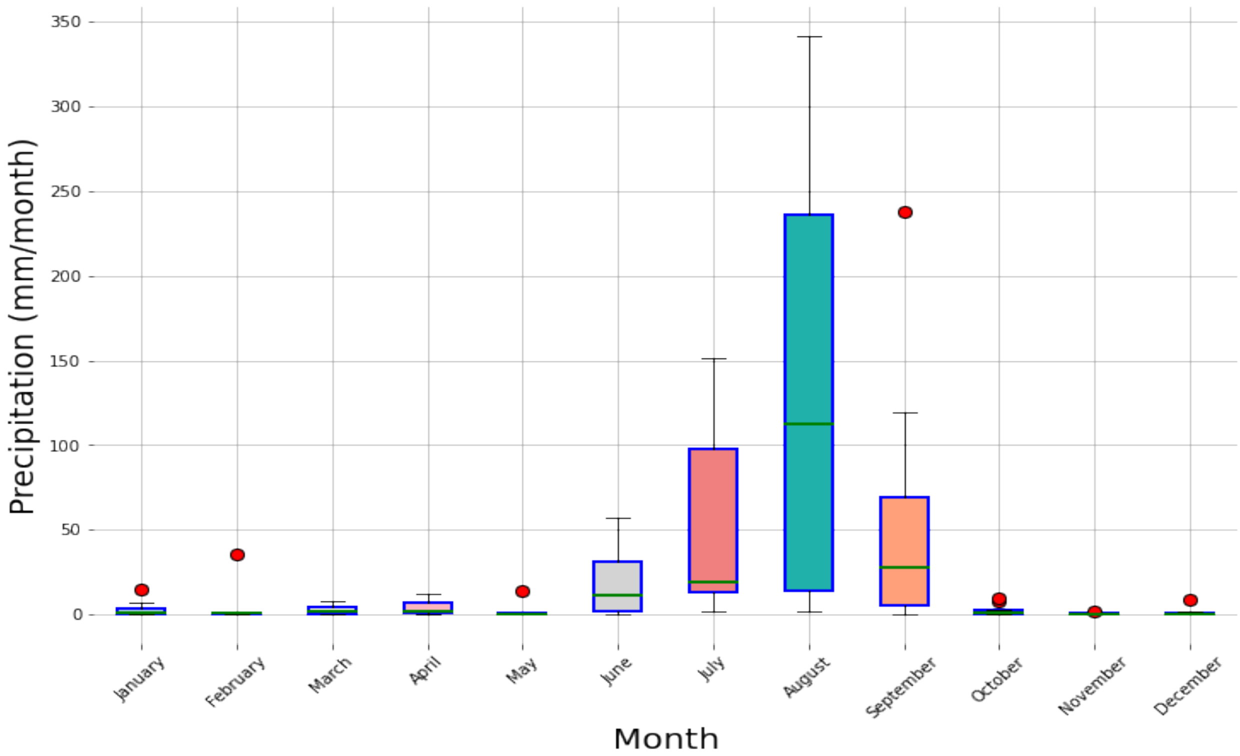


Figure 8: Monthly precipitation trend over 10 years

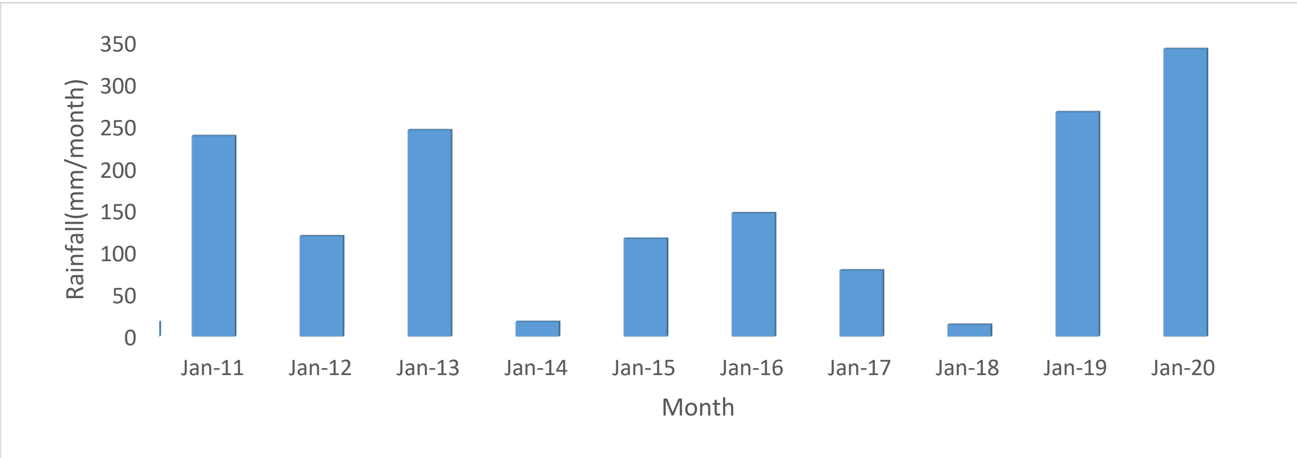


Figure 9: Yearly precipitation trend in Sujawal

3.7. Evapotranspiration Trend in Sujawal

The shallow watertables in Sujawal result in significant evaporative losses. Spatio-temporal values of actual evapotranspiration (Eta) were acquired from remote sensing. In groundwater models such as MODFLOW, the Eta is at maximum when the watertable is near the natural surface and decreases as the watertable declines. The rate of Eta decreases linearly with increasing depth to groundwater and ceases when it reaches the extinction depth. The extinction depth was specified at 1m for the Pinyari CCA and 0.5m for the coastal zone. Figure 10 shows the annual variation in evapotranspiration from 2010 to 2020. The boxplot in Figure 11 shows Eta is highest during the summer wet season.

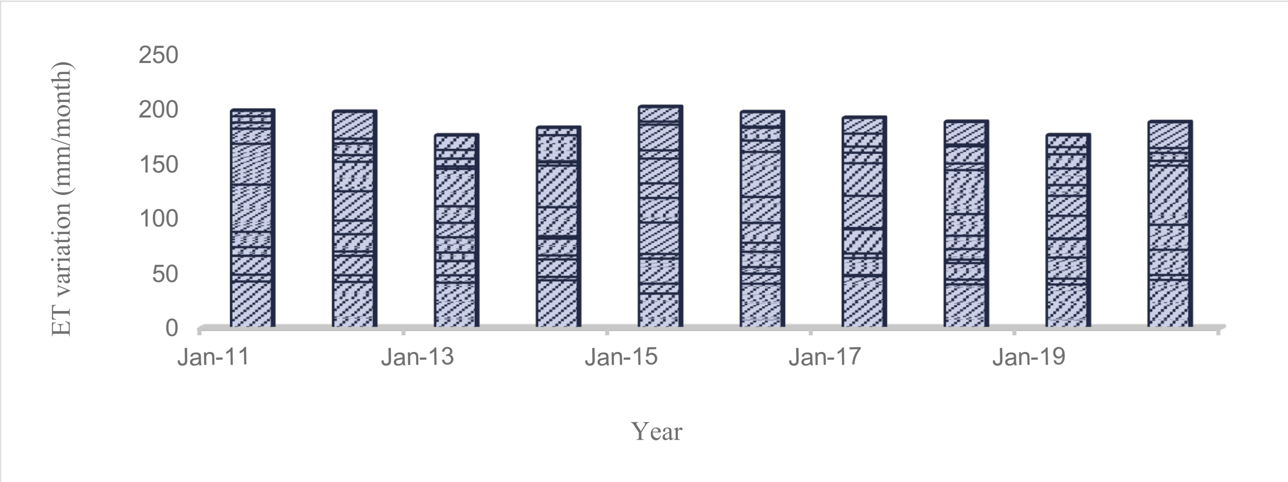


Figure 10: Annual evapotranspiration in Sujawal

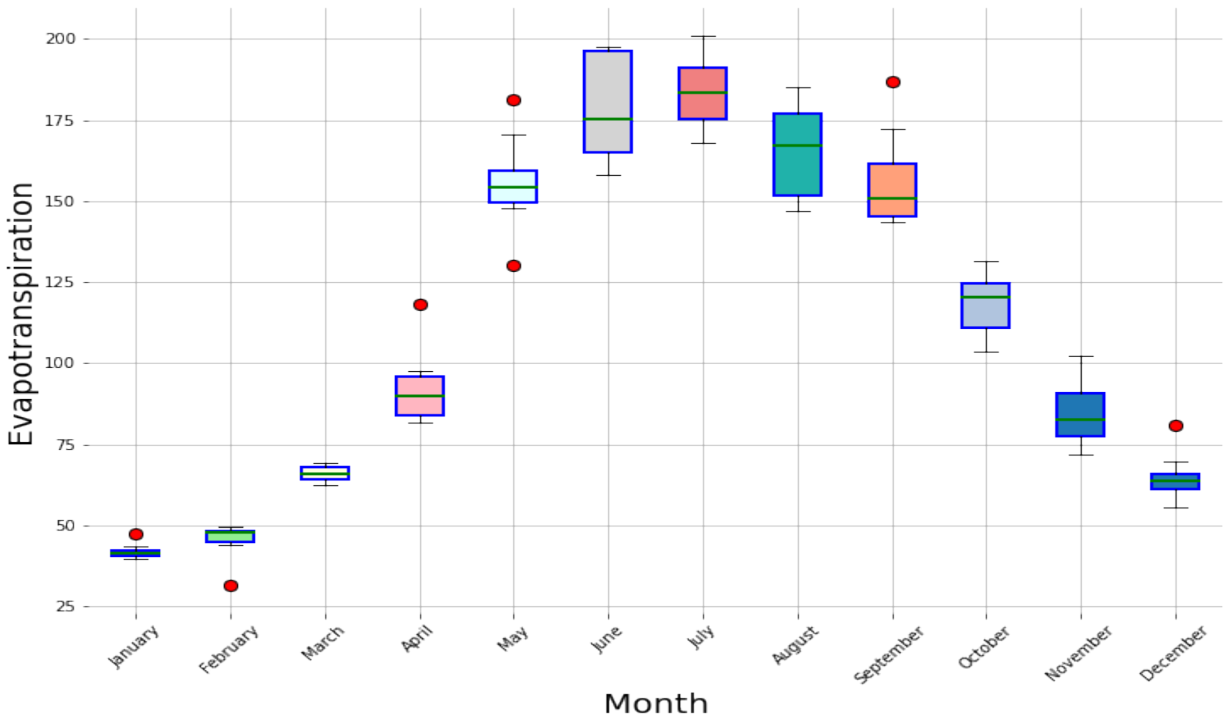


Figure 11: Monthly evapotranspiration in Sujawal

4. Model Development

4.1. Conceptual Model for Sindh

This model domain includes the Sujawal district of Sindh in the Lower Indus Basin. This deltaic region of the Indus River includes a complex network of estuaries, dhands (salt lakes), mudflats and marshes in the coastal zone. The Pinyari CCA is non-perennial and supports irrigated agriculture during kharif. In the rabi season, agriculture depends on infrequent rainfall, which averages about 30mm. The Indus River and the non-perennial Pinyari Canal are the main sources of surface water for irrigation, domestic and potable use. Along with precipitation, the Indus River, the canal network and creeks account for inflows to the groundwater system. Drains such as the LBOD and an extensive network of smaller drains and evapotranspiration are the main outflows from the aquifer. As Sujawal is a coastal district, the southern boundary of the model extends into the Arabian Sea. The Indus River, which forms the western model boundary, flows into the Arabian Sea.

The groundwater model for Sujawal is divided into three layers, each with different thicknesses. The top layer (Layer 1) extends from the surface to about 35m depth, which is an unconfined layer that encompasses the Indus River, Pinyari Canal and the drainage system. The thickness of Layer 2 is between 30 and 35m, and the thickness of Layer 3 varies depending on the base of the aquifer. A conceptual model showing stresses on the aquifer is given in Figure 12.

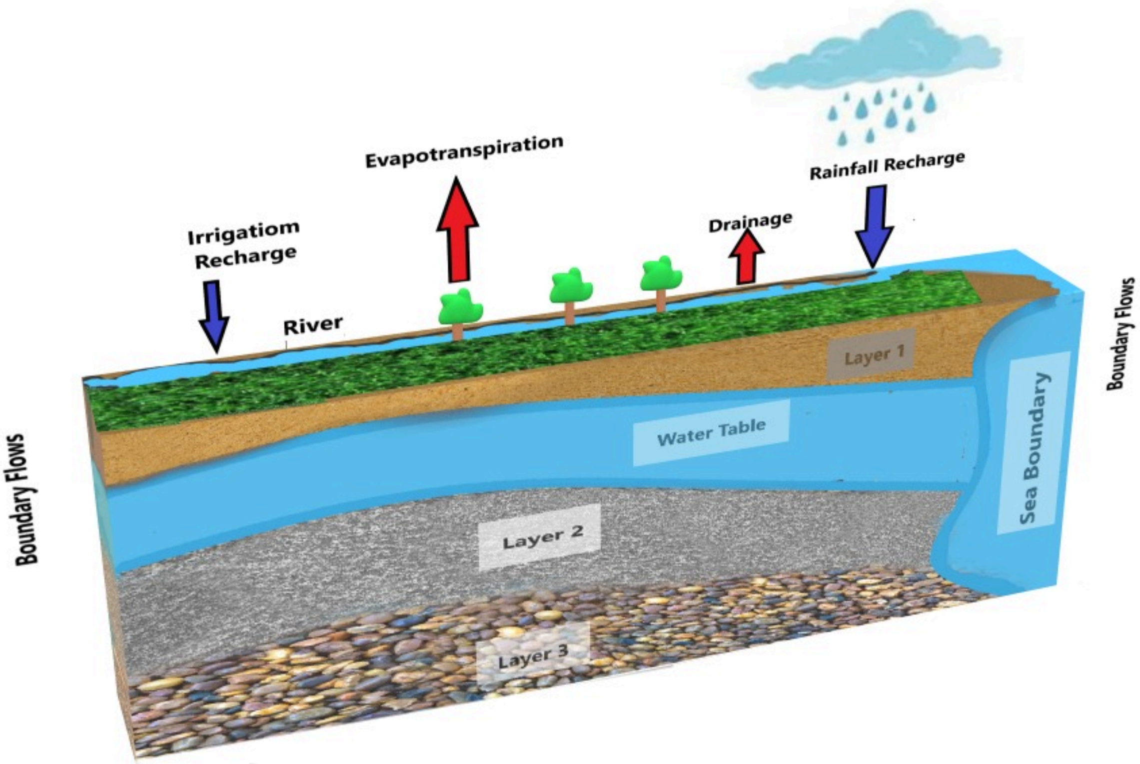


Figure 12: Conceptual model for Sujawal district

4.2. Model Grid and Boundaries

MODFLOW requires the model grid and boundary condition to be specified to perform a numerical solution of the flow equation. The Sujawal model in the coastal region of Sindh is bounded between 336,000m and 481,000m east and between 2,606,000m and 2,831,000m north. The size of each model grid is 500m x 500m with 450 rows and 290 columns. The focus area for this model is the Sujawal district, which comprises the Pinyari CCA and the coastal ecosystem south of the Pinyari CCA to the Arabian Sea. The rocky outcrops of the Kirthar formation in the model area are designated as non-active areas for all model layers. The Indus

River forms the western model boundary, and the southern and parts of the eastern boundaries are defined by constant head cells, as these are sea or estuary boundaries.

In MODFLOW, temporal discretisation is performed by defining stress periods in which the model stresses (i.e., recharge, evapotranspiration, river stage) remain constant for any given stress period. We have considered monthly stress periods and timesteps of 30.43 days. The model was simulated from October 2010 to September 2020 to cover the cropping seasons (rabi and kharif) in the modelling period. A description of the extent of the model is shown in Figure 13.

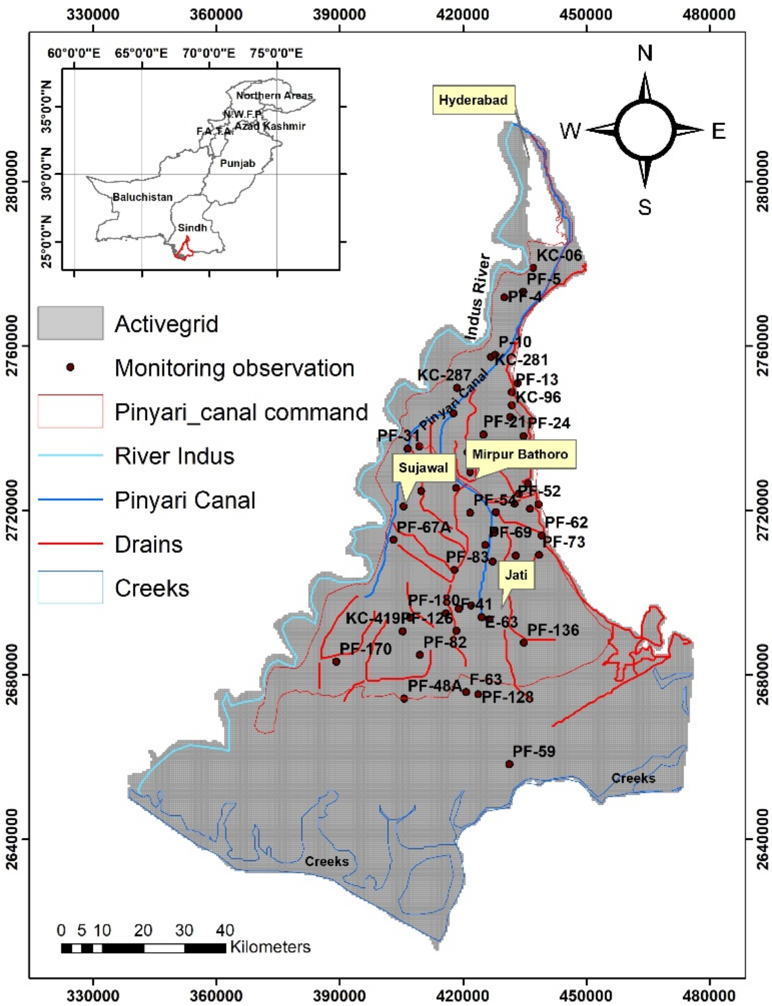


Figure 13: Description of Sujawal model

4.3. Aquifer Geometry

The purpose of a numerical groundwater model is to allow the various elements of the groundwater flow system to be quantified so that the impact of changes to or stresses on parts of the system can be estimated. The groundwater flow system has two directional components – horizontal and vertical. To accommodate the horizontal component of flow, the groundwater system is formed of a series of layers, each given a mathematical representation of the aquifer characteristics for that layer. A grid is overlaid on the layers to allow spatial characterisation of aquifer parameters and facilitate the simulation of the vertical component of flow.

To define the top surface of the model, we used the Merit digital elevation model (DEM), a modified version of DEM, which was created after removing all available bias in other digital elevation models, such as SRTM NASA (Chai et al., 2022). Merit DEM uses a 90-metre resolution, which is upscaled by averaging the number of 90 metre grid values to obtain values for the 500 metre model grids. Upscaling causes the loss of refined information; however, the flat topography of Sindh minimises errors due to upscaling.

4.4. Aquifer Parameters

MODFLOW computes the conductance components of the finite difference equation, which determines flow between adjacent cells. It also computes the terms that determine the water movement rate to and from storage. The aquifer geometry, leakage between layers, and the properties of the aquifer system need to be specified. The aquifer parameters that need to be specified are hydraulic conductivity (kh) and specific yield (Sy) for Layer 1, and kh and specific storage (Ss) for Layers 2 and 3. This section describes how these properties were estimated.

The top layer is 35m thick. This assumes that the river and other surface features are defined in the first 35 metres of the aquifer. The base of the aquifer is inferred from the bore log data. Examples of bore logs are shown in Figure 14. Shallow bores that are not representative of the thickness of the deeper layers were removed. The remaining deep logs were used to interpret the bottom of the third layer. The basement of the model was then identified by tagging the layers with shale, limestone, or a sequence of cemented clay and sand layers. These elevations were noted and then interpolated to generate the basement surface of the model (Figure 15) and imported into the model. The aquifer is shallow near the outcrop and becomes thicker as it moves towards the Indus River southwest of the model domain. As we move south, the aquifer becomes deeper towards the coast. Towards the south, the aquifer dips towards the east, and the depth of the aquifer increases towards the southeast.

The lithological composition of the research area, with an emphasis on the Tando Muhammad Khan region, can be better understood by analysing and visualising the data from the bore logs using Strater software. With its largest concentration of bore logs, Tando Muhammad Khan is particularly noteworthy as it provides extensive details on underlying structures. This region's stratified composition is revealed by the 83-metre average hole depth. There are differing amounts of sand and silt mixed in with the primarily clay upper layer (up to 35 metres). There is a mix of sand, silt, gravel, and clay in the second layer, which extends up to 55 metres. The bottom layer (up to 130 metres) is characterised by sand, gravel, limestone, and clay. Hydraulic conductivity ranges are 28–74 m/d for the top two layers and 23–59 m/d for the bottom layer (Figure 16). Specific storage ranges from 1.39×10^{-4}–2.73×10^{-3}, and 3.5×10^{-5}–6.84×10^{-4} for the bottom two layers (Figure 17). The variation in specific yield is from 0.00176–0.0304 and porosity from 0.132–0.228 (Figure 18). The subsurface hydrogeological conditions within the study area are facilitated by the visual representation of the spatial variation of these aquifer properties in Figure 16. Nonetheless, it is significant that very few borelogs are available for Hyderabad, Sujawal, and particularly the coastal zone, indicating possible gaps in our existing knowledge of the hydrogeological terrain in those areas.

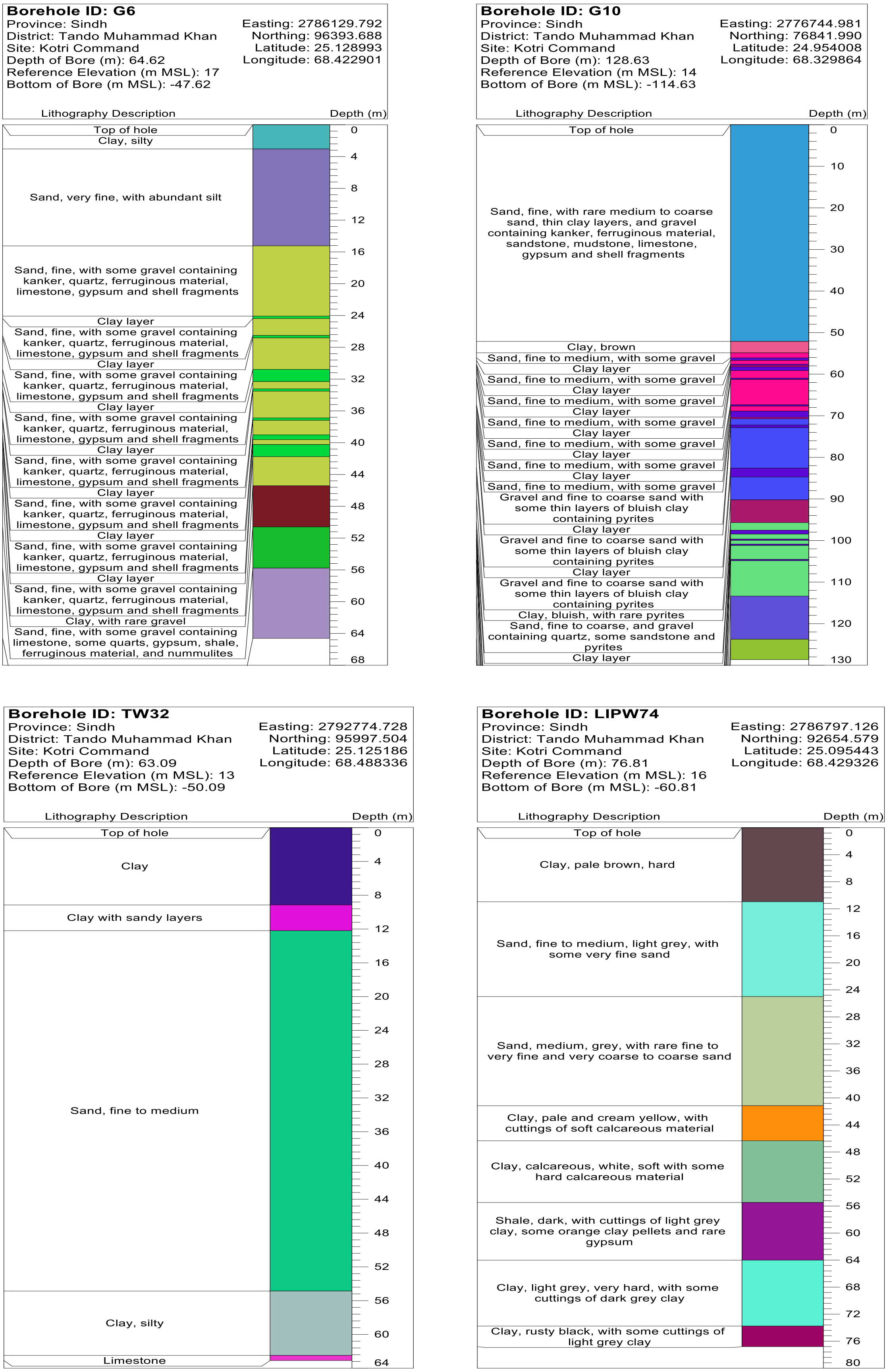


Figure 14: Lithological description of bore logs available in the study area

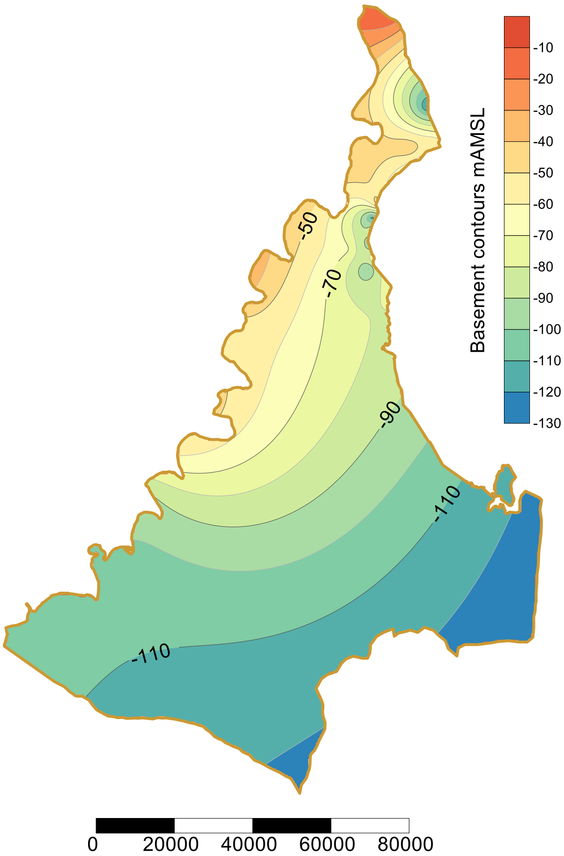


Figure 15: Basement contours for Sujawal (m-AMSL)

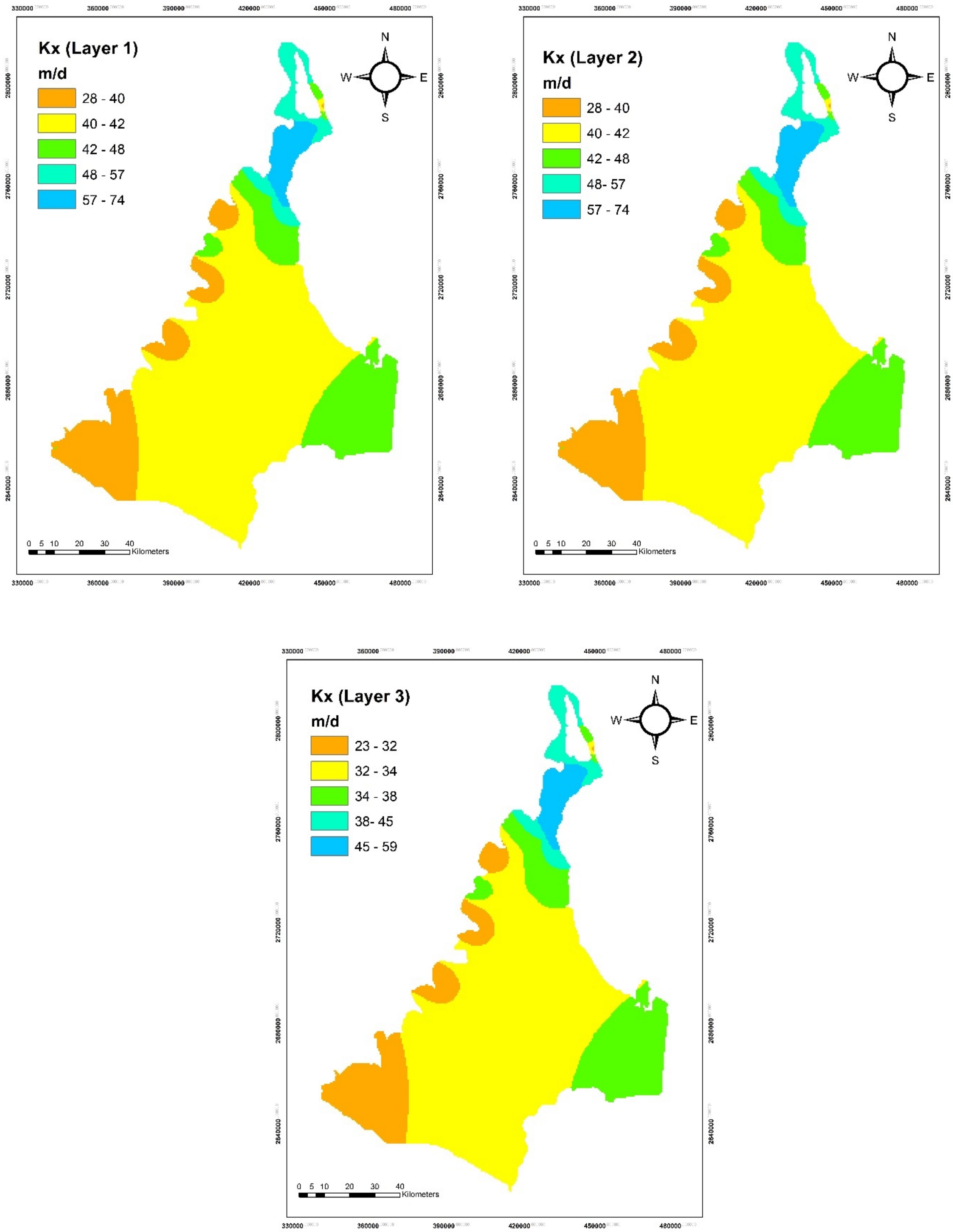


Figure 16: Spatial variation of hydraulic conductivity (m/d)

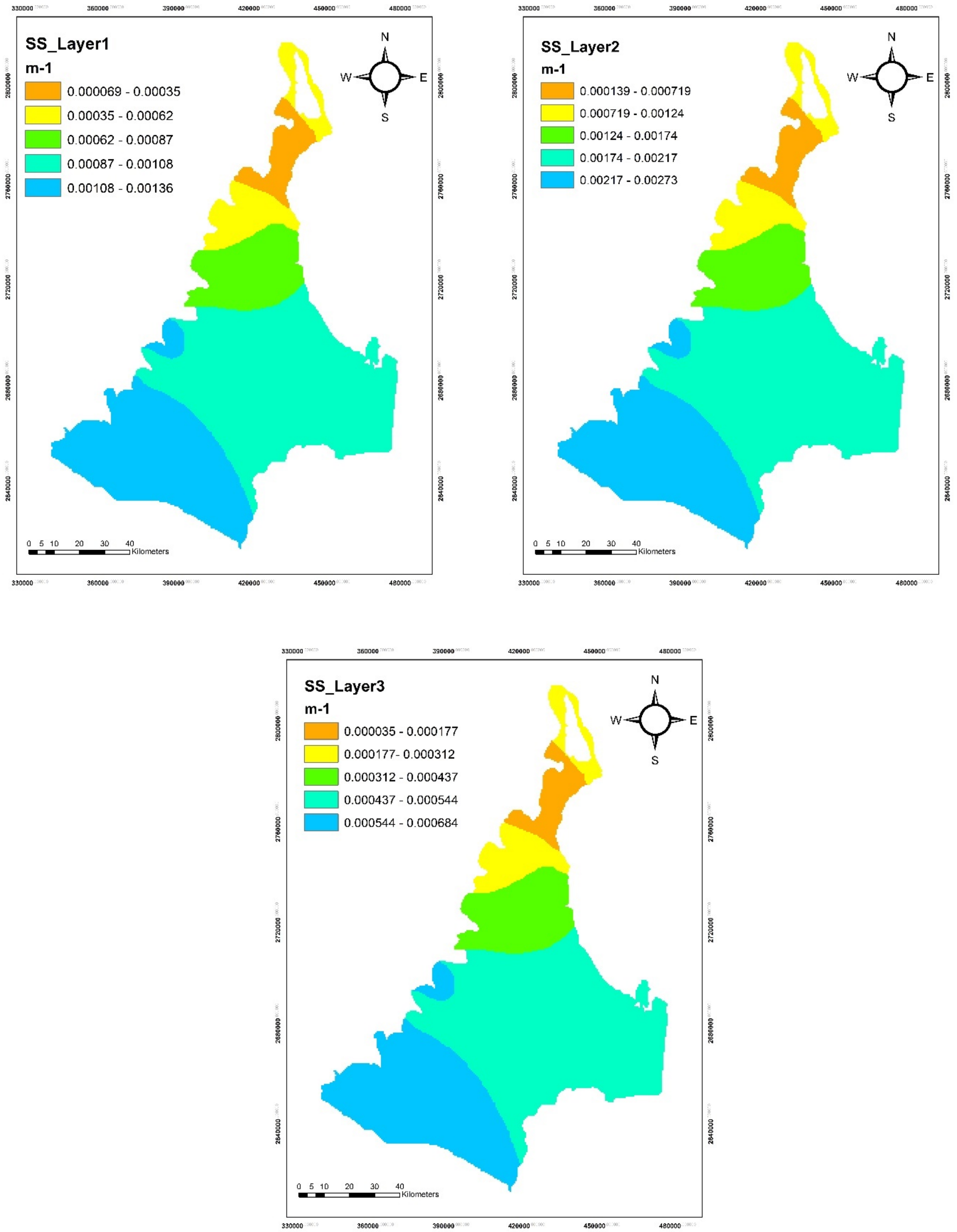


Figure 17: Spatial variation in specific storage (1/m)

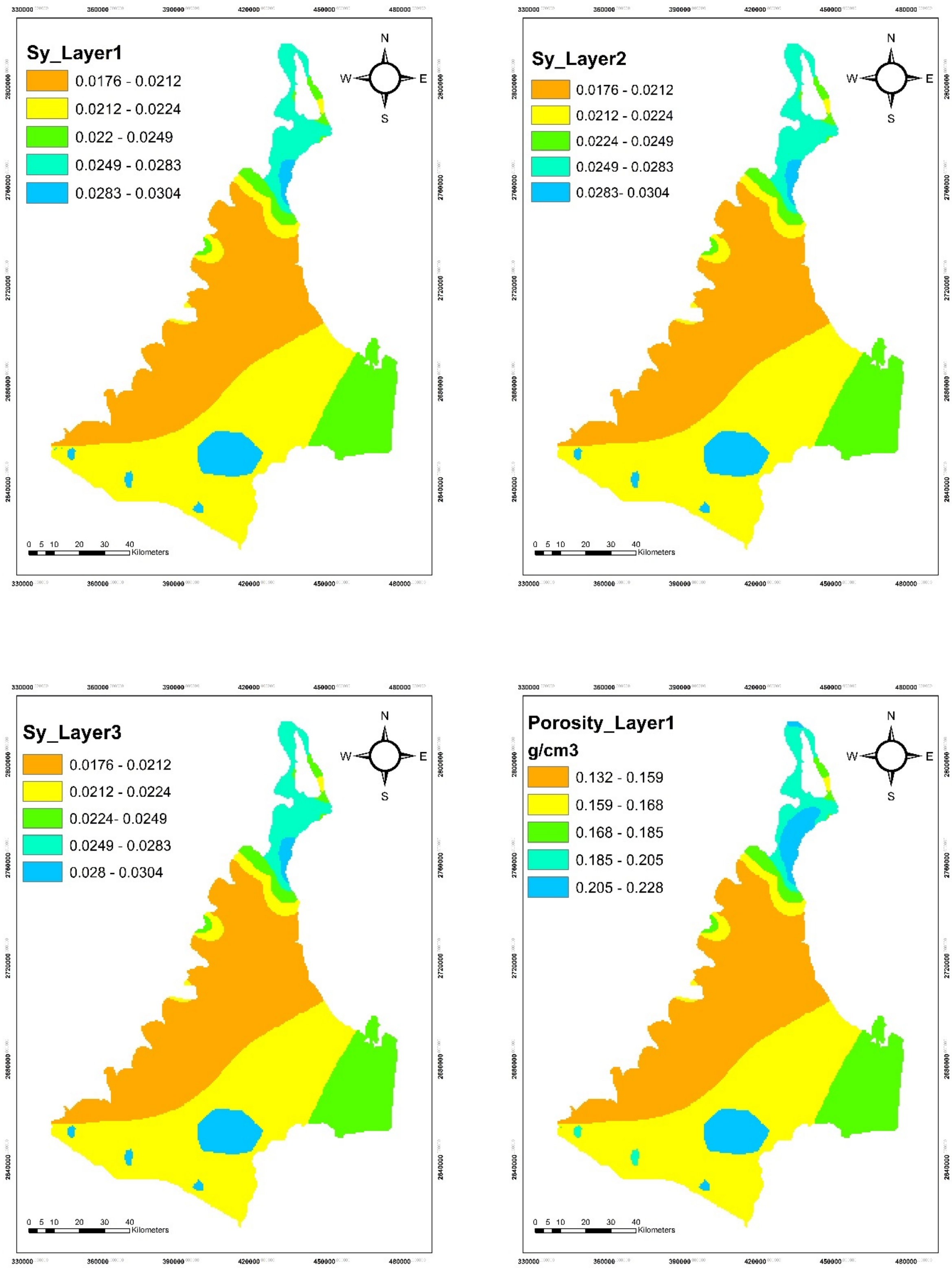


Figure 18: Spatial variation in specific yield and porosity

4.5. Indus River

The Indus River is a significant source of fresh water for the people of Pakistan, especially for those in the southern Indus Basin. It has a large delta area with a rich ecosystem and biodiversity. Most of its coastal area is covered by mudflats, marshes and scattered lakes and dhands. The study area includes the part of the Indus River below the Kotri Barrage, which intersects with the Arabian Sea. The Indus plays a significant role in contributing to groundwater recharge in the study area. The river package was divided into different reaches for calibration purposes. Stage data for the Indus River below the Kotri Barrage was acquired from the Kotri Barrage Authority, Hyderabad. The groundwater model calculates the amount of seepage from the river and canals based on the conductance and the difference in head between the river stage and the aquifer in a particular cell.

4.6. Pinyari Canal and its Branches

The previous name for Pinyari Canal was the Old Phuleli Canal which offtakes from the Kotri Barrage along with two canals: New Phuleli Canal and Akram Wah in Hyderabad. Pinyari is the only canal in the study area. It is divided into different branch canals in the study area. The northern, middle, and lower parts of the study area are covered by the Main Pinyari Canal, Pinyari Lower Feeder, Daro and Pinyari Branches, respectively. Based on the command area of these canals and its subbranches, three zones were created for the recharge package: Main Pinyari Canal zone, Daro Branch zone and Pinyari Branch zone. Stage and design discharge data for Pinyari Canal and its branches were acquired from the Kotri Barrage Authority in Hyderabad and Pinyari Circle. The head and tail of each branch were used to interpolate the stage between reaches. The different zones for the Pinyari CCA are shown in Figure 19.

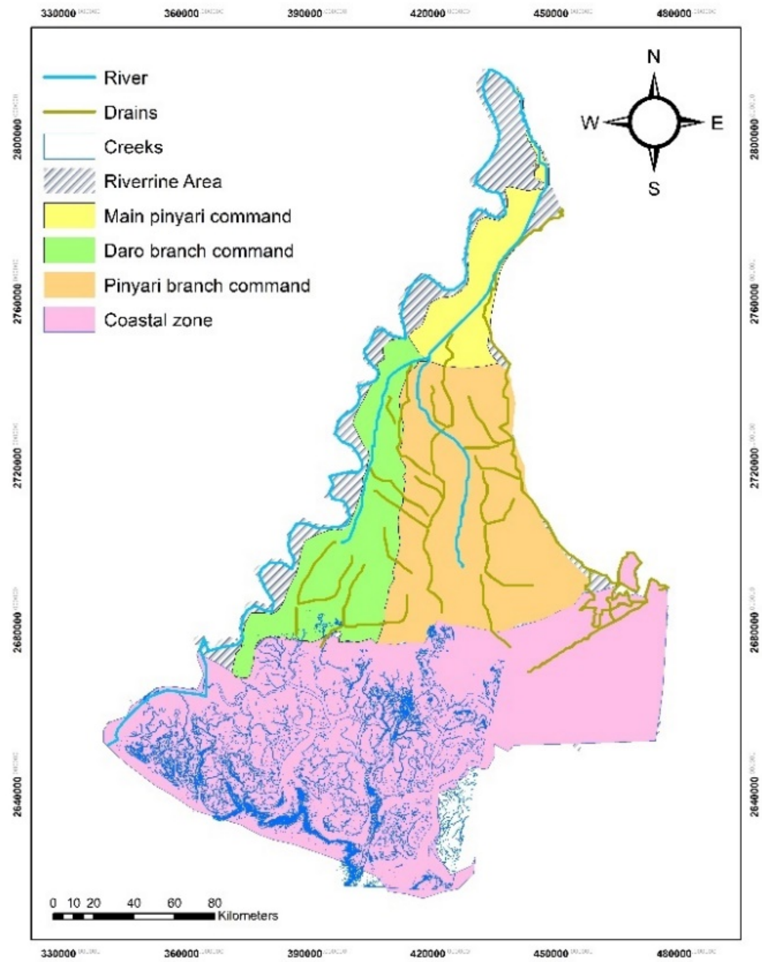


Figure 19: Distribution of the Pinyari CCA into different zones

4.7. Drain Package

In Sujawal, networks of drains are available which are distributed in the study area. Drains are also situated around Nareri Lake, which explains the density of drain packages in this area. Stage data and design data of drains were estimated as data for drains was unavailable. The main purpose of the drainage networks is to discharge saline groundwater into the Arabian Sea (Khaskheli et al., 2018).

4.8. Constant Heads

Multiple water bodies are situated in the study area, including lakes and creeks in the coastal areas to the south of the Pinyari CCA (Figure 20). Constant heads were assigned to these water bodies. Minor lakes situated in the model area are Gujju Dhand, Gadap Dhand, Kharar Lake, Mehbub Shah Dhand, Sareh Dhand, Paleji Lake and Nareri Lake. Also, minor and major creeks are also present in the coastal zone. These creeks can potentially enhance seawater intrusion in the study area.

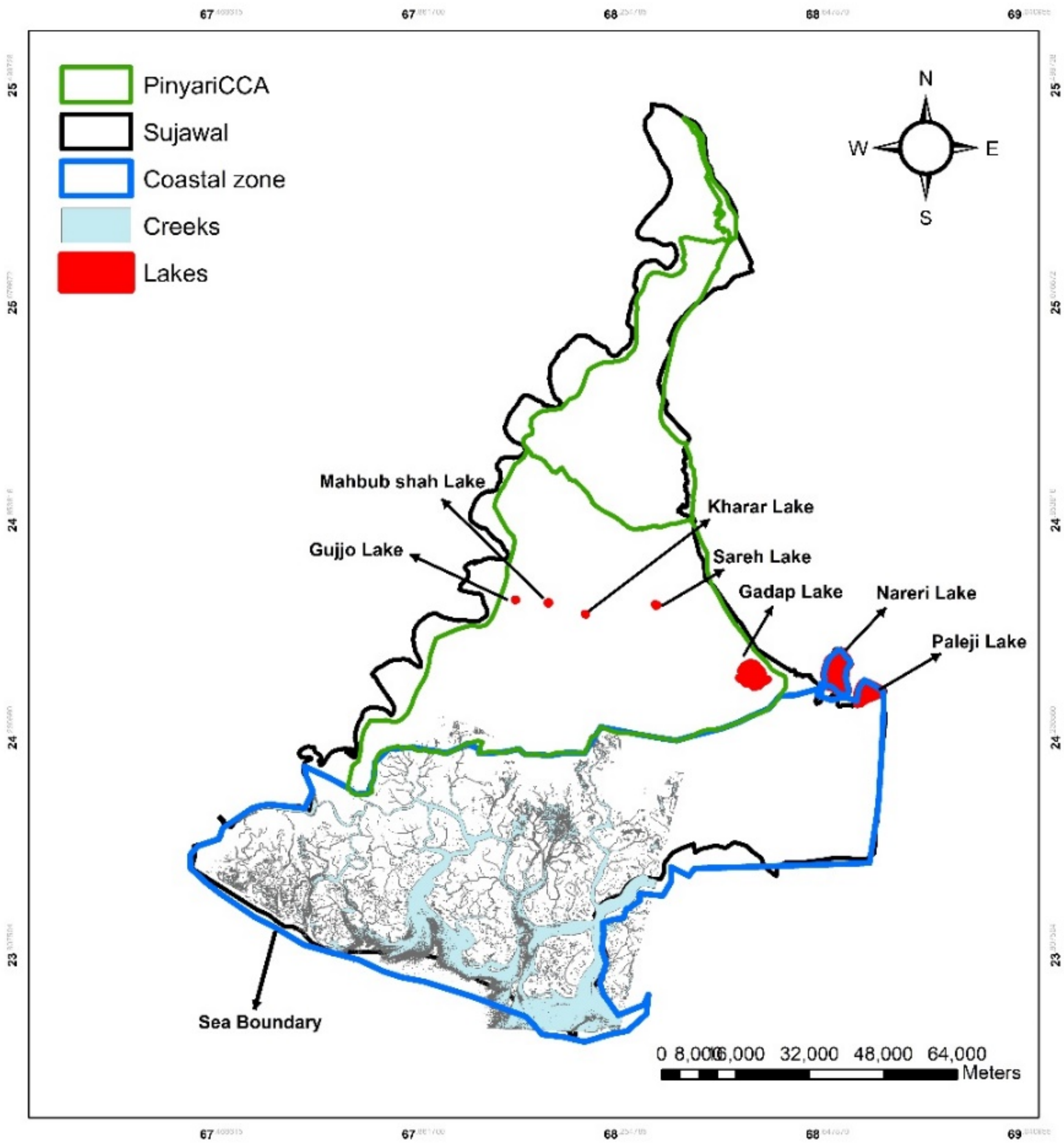


Figure 20: Description of lakes and creeks in study area

4.9. Coastal Belt of Sujawal

The Indus River flows into the Arabian Sea, forming one of the largest river deltas in the world. It is characterised by extensive mangrove forests and serves as an important habitat for various wildlife species. The delta is covered by mudflats, estuaries, and an extensive network of creeks. The Indus Delta has a variety of biodiversity and is home to a variety of fish species, including huge snakehead (*Channa marulius*), Indus Baril (*Barilius modestus*), Indus Garua (*Clupisoma naziri*), and Rita catfish (*Rita rita*). It is also a significant location for migratory water birds, ensuring the importance of the conservation of ecosystems in this region (WWF website). Mangroves are an indispensable species for this coastal zone providing essential nutrients for fish and crustaceans and stabilising the coastal area from erosion and tidal incursions. Moreover, coastal communities rely on mangroves for various goods like fuelwood, shellfish, and palms (Figure 21). Mangroves also provide essential ecosystem services by maintaining the productivity of estuarine dependent fisheries, regulating water quality, reducing flooding, and maintaining shoreline stability (Acharya, 2002). However, a lack of freshwater supply in the Indus Delta has impacted this region, resulting in increased salinity, waterlogging and inundation in the coastal zone. Seawater intrusion and coastal erosion have resulted from the sudden reduction in the sediment load and water discharge to the Arabian Sea, which has also enhanced the impact of waves and tides and hindered the growth of mangroves (Kanwal et al., 2020). In this study, we will simulate the impacts of climate change to improve our understanding of the likely impacts of rising sea levels in the coastal belt of Sujawal.

Figure 21: Mangroves in the coastal areas of Thatta

4.10. Recharge

Groundwater recharge includes the process by which water from different sources, such as precipitation and surface water resources, infiltrates into the ground and replenishes the aquifer. Precipitation data were acquired from remote sensing data processed by CSIRO. It was available from 2010 to 2020 in a raster dataset. Monthly spatial precipitation data were used for the active model grid.

The aquifer in this region is recharged by surface water bodies or seepage from irrigation return flows in the Pinyari CCA. Rainfall recharge plays a crucial role, although its impact is limited due to the relatively low rainfall. Irrigation recharge was computed using daily discharge data acquired from the non-perennial Pinyari Canal and its branches based on three predefined zones, accounting for a 15% conveyance loss from these canals. To estimate irrigation recharge, the canal flow was divided by each zone's area. The groundwater recharge was then assigned 45% of this irrigation recharge volume. This value was added with rainfall recharge, which constituted 15% of the total rainfall, to compute the final recharge for each grid in the zones. Irrigation recharge was calculated using Equation 4.1 below:

$$IR = 0.45\left[\frac{0.15\,Q}{A}\right] \qquad \text{Eq 4.1}$$

Where IR is irrigation recharge, Q is discharge for each branch of the Pinyari Canal, 0.15 is a factor for conveyance losses, A is the area of each zone and 0.45 is a factor for recharge from irrigation losses. This procedure was used to estimate monthly recharge for the transient model.

4.11. Evapotranspiration

The actual evapotranspiration (Eta) data (2010-2020) 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 500m resolution (Ahmad et al., 2023). Actual evapotranspiration data were initially computed on a 10-daily basis and then aggregated on an average monthly scale.

For the climate change scenarios, temperature data for the SSP2-4.5 and SSP5-8.5 scenarios were used to calculate reference evapotranspiration (ETo) using the Blaney-Criddle from 2010 to 2100. The crop factor (Kc) was computed using 10 daily cloud free composites of the EVI and GVMI obtained from the Google Earth Engine (GEE) from MODIS product. The data were spatially distributed for the model grid and imported into the groundwater vista.

5. Model Calibration and Sensitive Analysis

5.1. Sensitivity Analysis

Explicit representation of the groundwater system in hydrogeological modelling is essential for well-informed resource management since groundwater models traverse complex relationships between geological, hydrological, and hydraulic components, but their predictions are greatly impacted by unknown parameters. Sensitivity analysis is a process in which changes are applied to selected input parameters to check the impact on model output, which provides useful information to guide model calibration. Through this procedure, sensitive parameters can be known, which can potentially affect the accuracy of model outputs. Sensitivity analysis was accomplished by modifying the hydraulic conductivity, specific yield, recharge, and evapotranspiration parameters. Each input value was multiplied by a range of factors, to assess model calibration.

The following multipliers, 0.25, 0.5, 1.0, 1.5, and 2.0, were used for sensitivity analysis, including hydraulic conductivity (K), specific yield (Sy), specific storage (Ss), and recharge. The acceptable bounds for the aquifer parameters (K, Sy, and Ss) were cross-checked using field data and published literature.

Table 3 shows the sensitivity analysis of different parameters in the model. Decreasing the hydraulic conductivity improves the model calibration statistics and decreases the absolute residual mean to 0.76 and 0.79 from 0.82, indicating hydraulic conductivity is a moderately sensitive parameter affecting model performance, while specific storage (Ss) and specific yield are much less sensitive. Recharge shows the optimal calibration is achieved with a multiplier of 1, indicating there is no need to change the recharge rate.

Table 3: Sensitivity analysis results of hydraulic conductivity, specific storage, specific yield, and recharge

Multiplier	Absolute residual mean (m)			
	Hydraulic conductivity (Kx)	Specific storage (Ss)	Specific yield (Sy)	Recharge
0.25	0.76	0.826	0.82	1.03
0.5	0.79	0.826	0.81	0.92
1	0.82	0.827	0.82	0.82
1.5	0.84	0.828	0.83	0.83
2	0.86	0.829	0.86	1.77

5.2. Model Calibration

The calibration approach adopted in this study involved varying aquifer parameters within a probable range until a reasonable agreement was achieved between observed and simulated heads. The procedure involved adjusting aquifer hydraulic properties, storage, boundary conditions, and system stresses such as recharge, evapotranspiration and river and canal-aquifer interaction such that the model is capable of simulating both spatial and temporal responses.

The strategy we adopted for calibration in this study includes the following steps: We analysed available bore logs to estimate hydraulic conductivity and storage for Sujawal, as indicated earlier in Section 4.4. Initial estimates of aquifer hydraulic properties were adjusted progressively during model calibration.

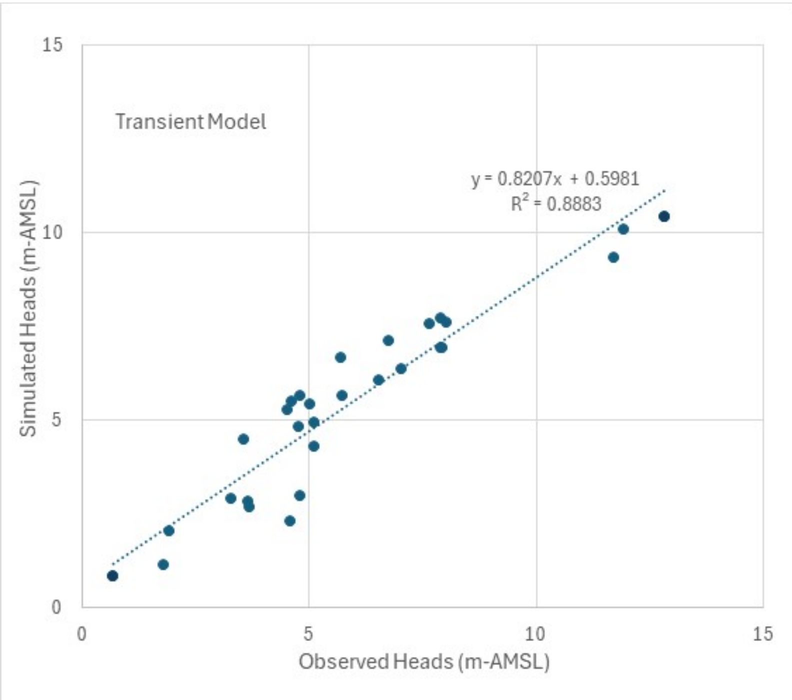
The model domain was divided into four zones for recharge. Three zones were assigned to the Pinyari CCA, and a fourth zone was assigned to the coastal and estuarine areas south of the Pinyari CCA. A multiplier was assigned for each parameter to adjust the sink and source terms in each zone, which includes recharge and evapotranspiration.

The river package was divided into different reaches. A total of eleven reaches were assigned to assist in calibration. The model calibration involved adjusting river conductance in each reach. Constant heads were assigned along the sea boundary and creeks in the coastal zone.

Water level data of 29 observation wells were acquired from the SCARP Monitoring Organization (SMO) for calibration purposes. The model was simulated for 120 monthly stress periods. The calibration period extended from October 2010 (post-monsoon) to September 2020. The steady state model provided initial heads for October 2010, which were used as starting heads for transient simulation.

5.3. Steady State Model

A steady state model was developed for Sujawal to estimate initial heads for post-monsoon October 2010. Boundary conditions, including constant heads, river and drain packages, were specified. The Merit digital elevation model was used to specify the topography as it was found to be superior to SRTM data. Twenty-nine observation wells were used in models for calibration. The absolute residual mean for the steady state model was 0.82, which is an acceptable calibration of the simulated heads over the model domain. The results of the steady state model show good agreement between observed and computed values, as shown in Figure 22.

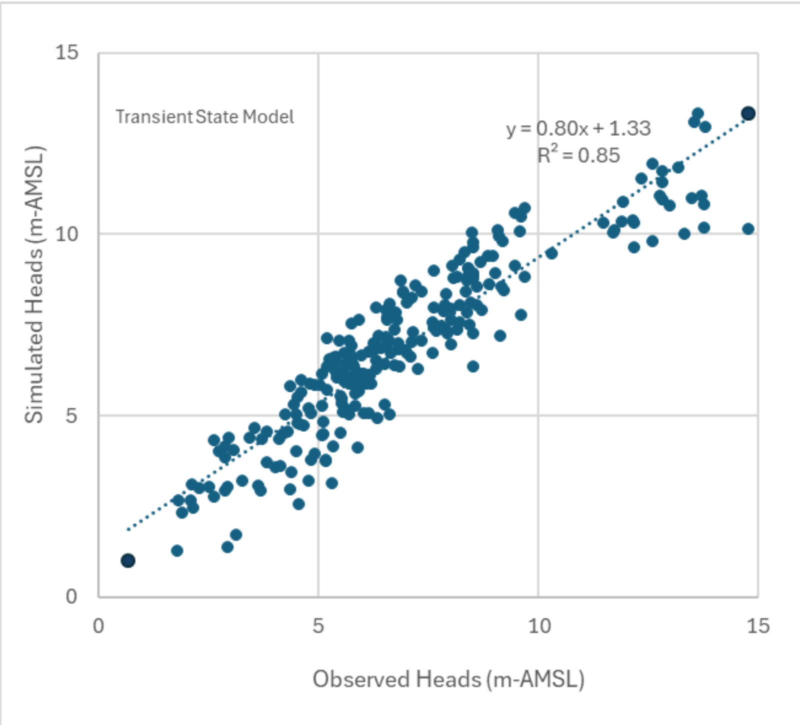


Residual Mean	0.45
Absolute Residual Mean	0.82
Residual Std. Deviation	0.97
Sum of Squares	33.21
RMS Error	1.07
Min. Residual	-0.95
Max. Residual	2.39
Number of Observations	29

Figure 22: Observed vs simulated heads and calibration statistics for the steady state model

5.4. Calibration of the Transient Model

The transient model was developed over ten years using 120 stress periods corresponding to monthly periods. The model was calibrated using 29 observation wells which are monitored biannually (pre- and post-monsoon). Model calibration was performed for 120 stress periods from Oct-2010 to Sep-2020, where data were available. Observed heads were arranged for pre- and post-monsoon seasons for each year from 2010 to 2020. Figure 23 and Figure 24 show spatial calibration for 29 observation points obtained at the end of the model calibration period (Sep-2020) and shows the head distribution at the end of the calibration period. The location of the 29 observation points in study area are shown in Figure 25. The absolute residual mean shown in Figure 23 is 0.85, which depicts a strong relationship between observed and computed values. The residuals range from -1.92 to 4.68, which indicates differences in some observed and computed values. Monitoring can be improved by instrumenting key monitoring sites with loggers to provide information on daily and weekly trends, which would also allow for an improved understanding of groundwater dynamics in the coastal areas of Sindh.



Residual mean	0.03
Absolute Residual Mean	0.85
Residual Std. Deviation	1.09
Sum of Squares	295.1
RMS Error	1.09
Min. Residual	-1.92
Max. Residual	4.68
Number of Observations	250

Figure 23: Observed vs simulated heads and calibration statistics of transient state model

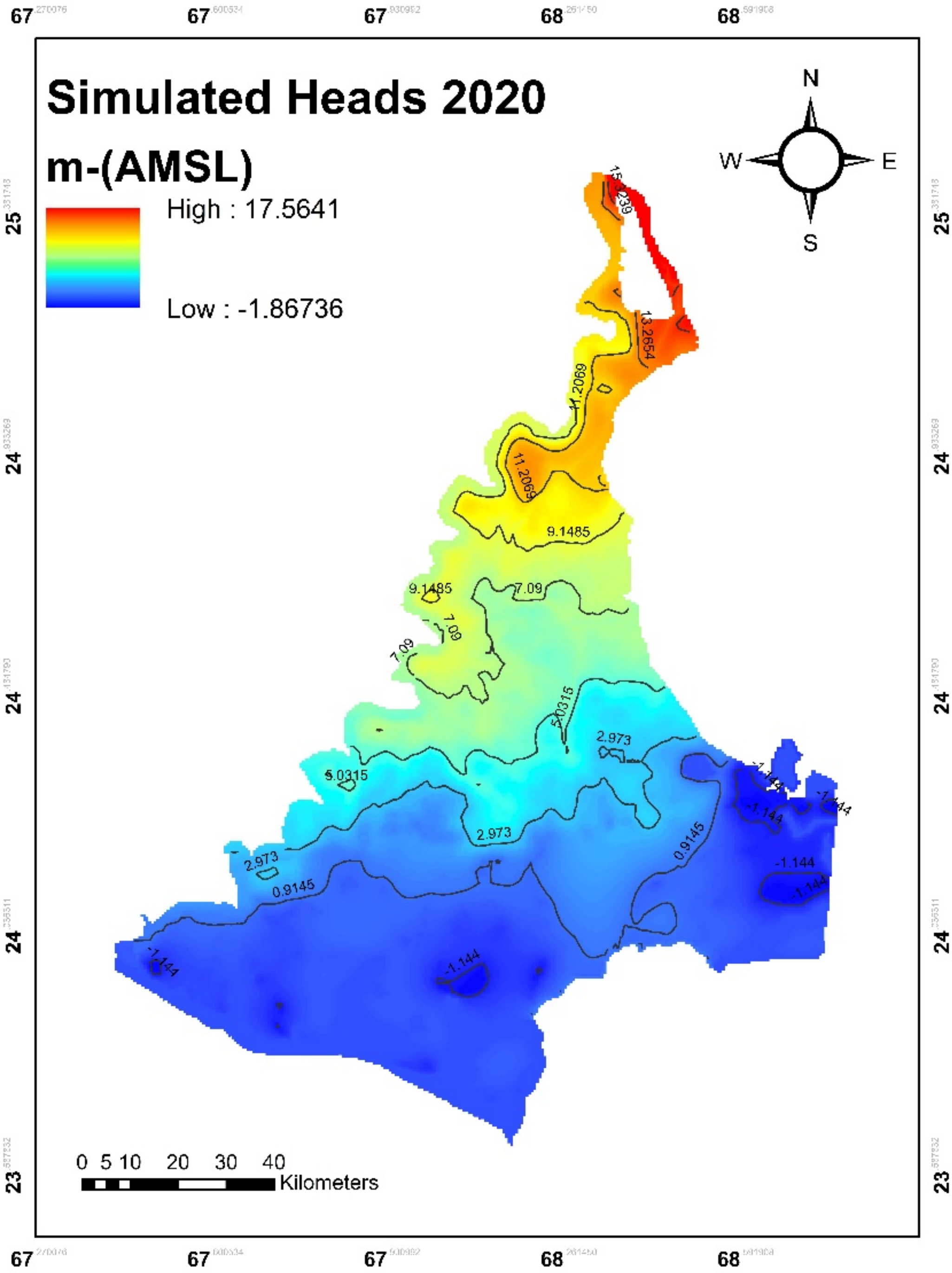


Figure 24: Simulated heads (m-AMSL) for Oct-2020

5.5. Hydrographs

The SCARP Monitoring Organization (SMO) measures depth to watertable (DTW) twice a year during the pre- and post-monsoon seasons, whereas the model simulates monthly head values. The head targets for the 29 SMO wells in the study area (Figure 25) were compared with model simulated heads. The hydrograph response of observed versus simulated heads in Figure 26 shows that the model replicates the response to external stresses, and simulated trends that follow the temporal observed trend.

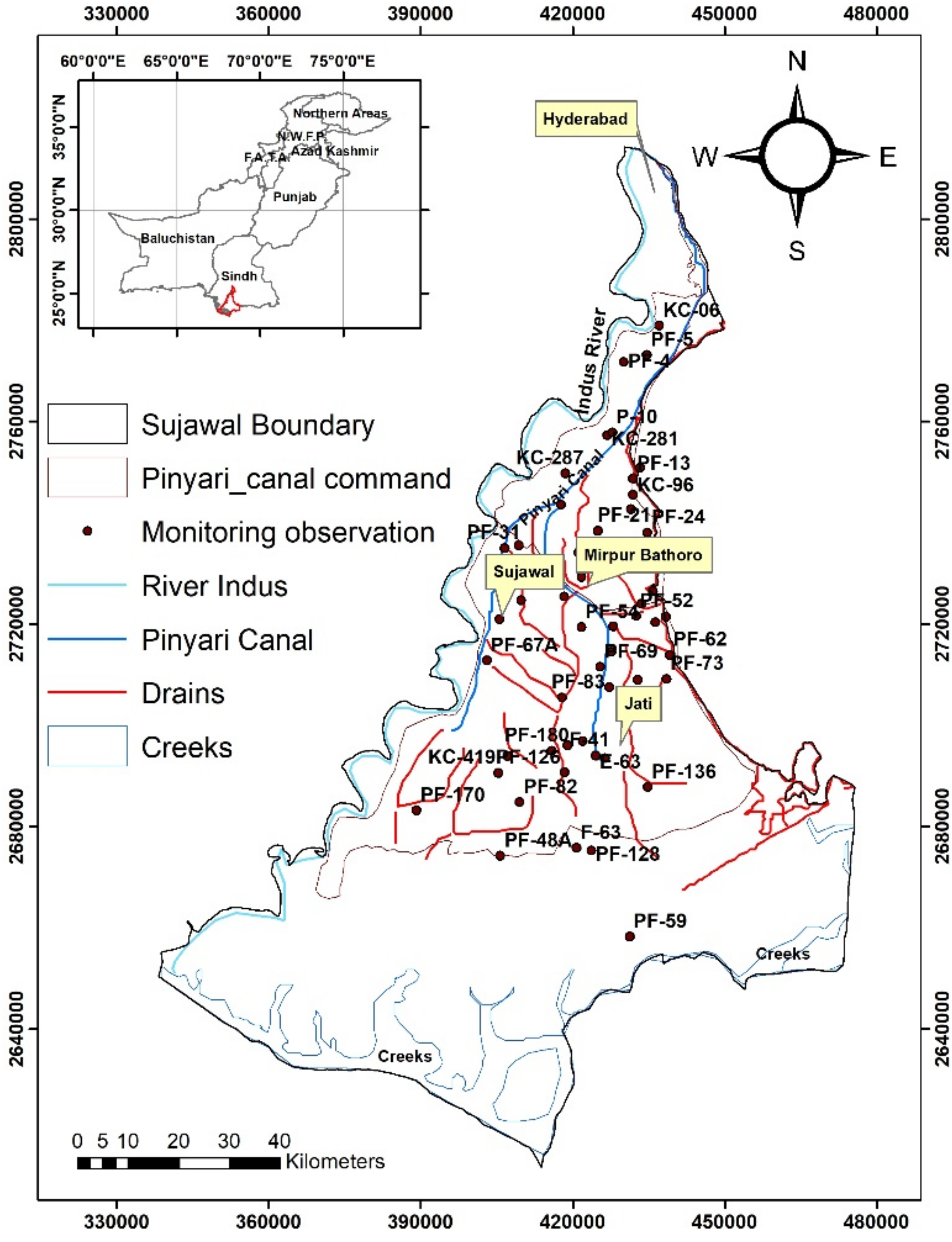


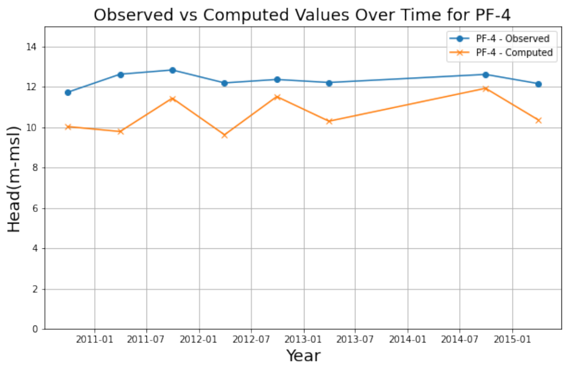
Figure 25: Locations of SMO observed data in the Pinyari CCA.

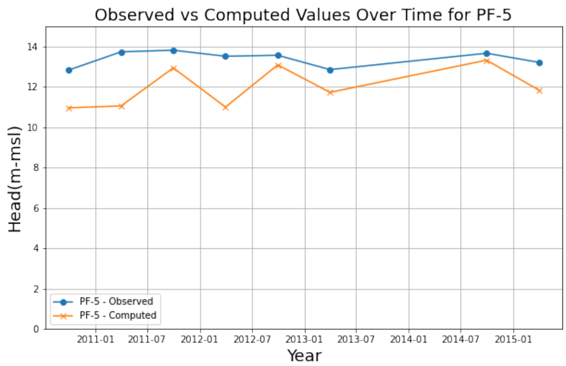
Simulated heads for bores PF-4 and PF-5 show the model underpredicts observed heads as starting heads from the steady state model are lower than observed heads; however, the trends are reproduced with good accuracy. The initial starting heads from the steady state model are somewhat lower, which may contribute to the overall underprediction. These monitoring bores are in the Main Pinyari CCA. Bores PF-19, PF-21, and

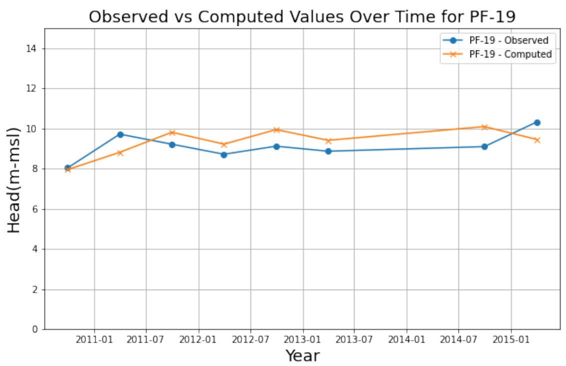
PF-24 reproduce the observed values and trends accurately. These bores are located within the Pinyari CCA in the upper portion of the Pinyari Branch zone.

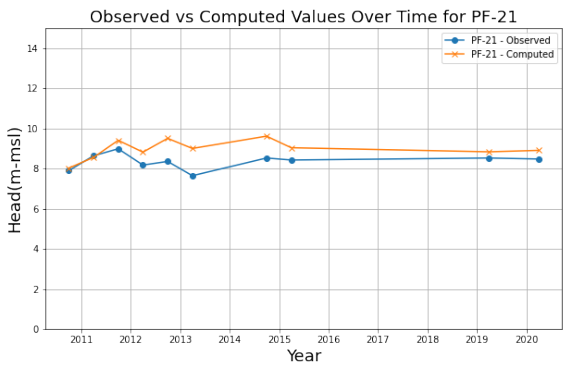
Simulated heads for bore PF-36 are reproduced reasonably, other than in Oct-2014, when observed heads show an increase in heads. A possibility is that the processed rainfall dataset used to estimate recharge does not pick up a late monsoon rainfall event. Simulated heads for PF-42, PF45, PF-46, and PF-48 in the Pinyari Branch zone show good agreement with observed heads and trends, although the head response in PF-46 and PF-48 is somewhat subdued compared to observed heads, indicating lower recharge and possibly due to the distance away from the nearest canals. Bores PF-42 and PF-45 are close to canals and show good agreement with observed heads and trends. Bores PF-51, PF–54, PF-59, and PF-62 reproduced observed heads and trends accurately. These bores are situated in the southern region of the Pinyari CCA, close to the coastal zone.

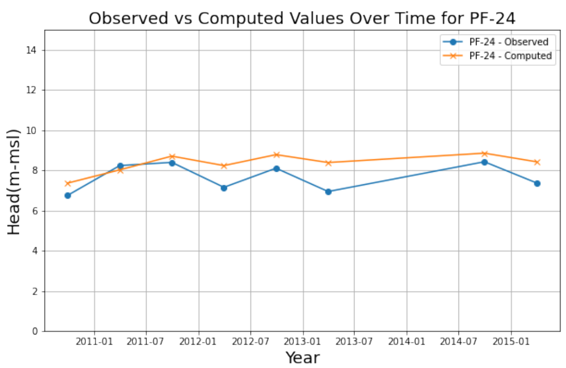
Simulated heads for KC-96, KC-303, and KC-328, which are situated at the intersection of the Pinyari and Daro Branches, show good agreement with observed heads. The observation bores KC-408 and KC-419 are located at the tail end of the Pinyari CCA. Both bores show good agreement with observed data and also reproduce temporal changes in heads accurately.

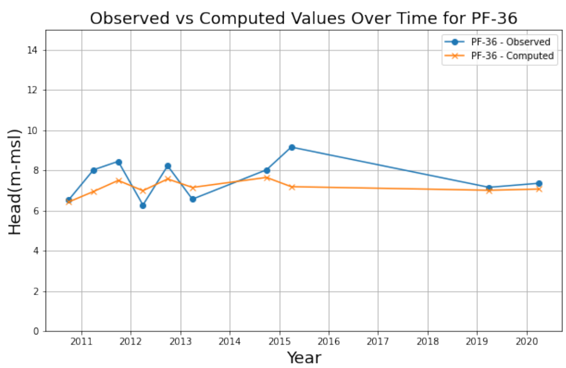


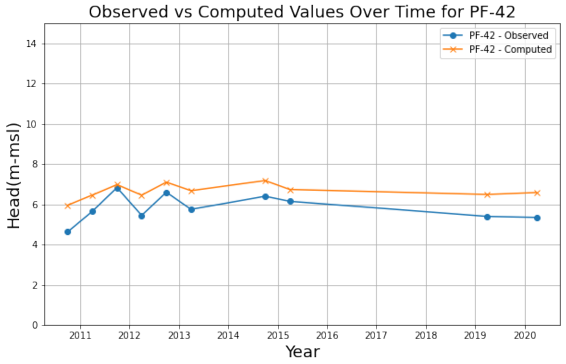


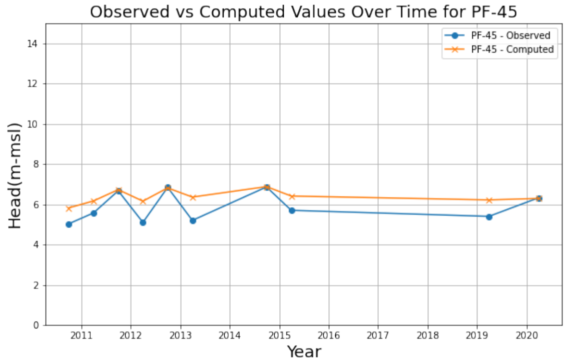


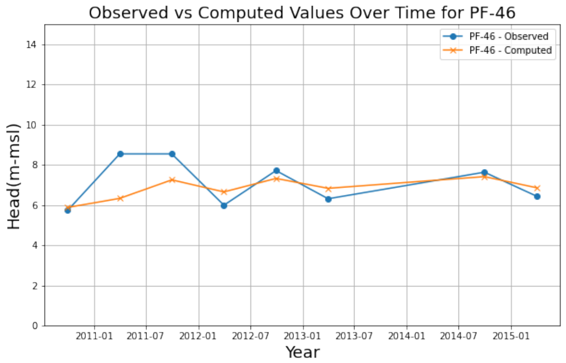


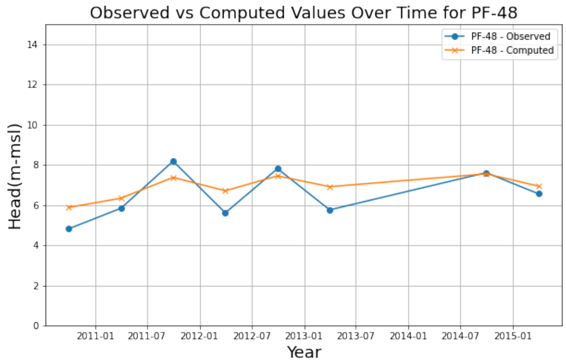


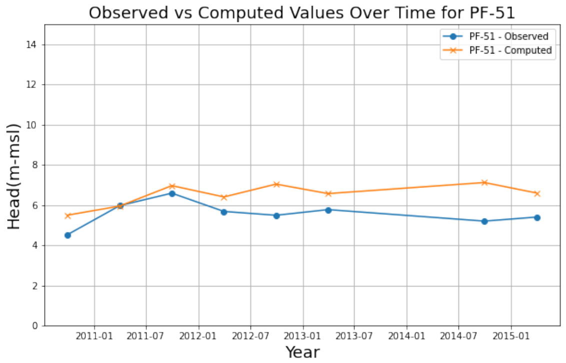


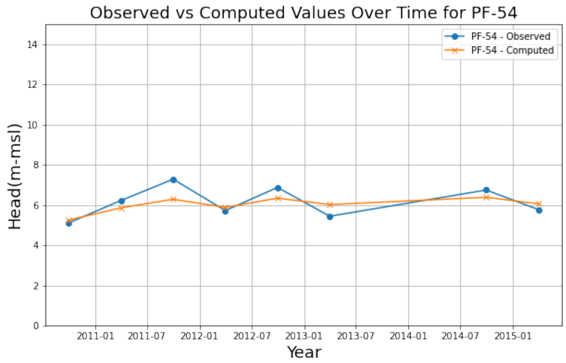

Observed vs Computed Values Over Time for PF-42
PF-42 - Observed
PF-42 - Computed
Head(m-msl)
Year
0 2 4 6 8 10 12 14
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

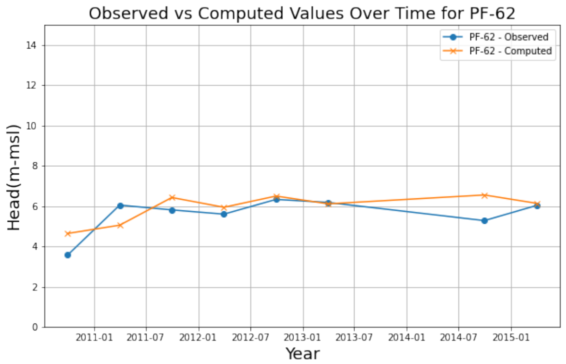

Observed vs Computed Values Over Time for PF-45
PF-45 - Observed
PF-45 - Computed
Head(m-msl)
Year
0 2 4 6 8 10 12 14
2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

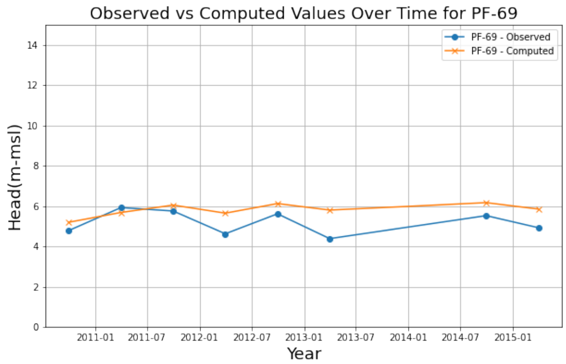

Observed vs Computed Values Over Time for PF-46
PF-46 - Observed
PF-46 - Computed
Head(m-msl)
Year
0 2 4 6 8 10 12 14
2011-01 2011-07 2012-01 2012-07 2013-01 2013-07 2014-01 2014-07 2015-01

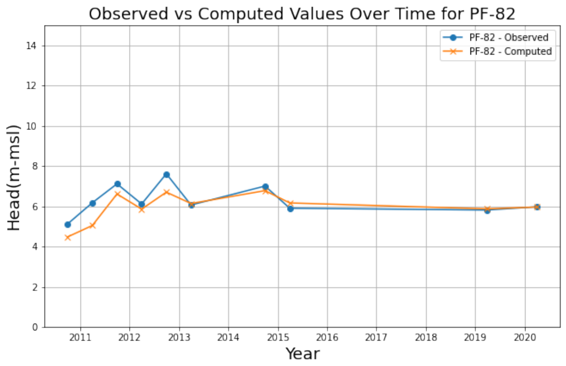

Observed vs Computed Values Over Time for PF-48
PF-48 - Observed
PF-48 - Computed
Head(m-msl)
Year
0 2 4 6 8 10 12 14
2011-01 2011-07 2012-01 2012-07 2013-01 2013-07 2014-01 2014-07 2015-01

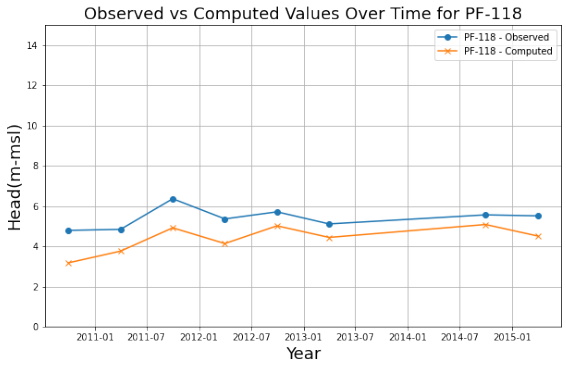

Observed vs Computed Values Over Time for PF-51
PF-51 - Observed
PF-51 - Computed
Head(m-msl)
Year
0 2 4 6 8 10 12 14
2011-01 2011-07 2012-01 2012-07 2013-01 2013-07 2014-01 2014-07 2015-01

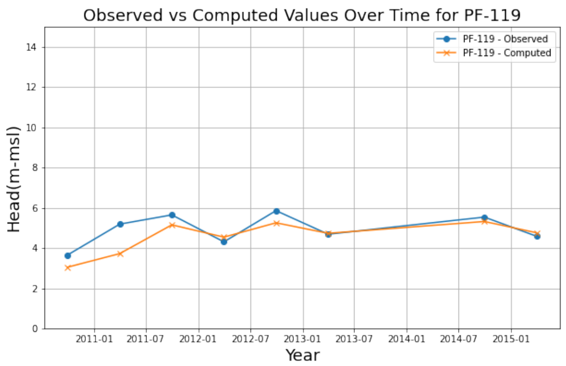

Observed vs Computed Values Over Time for PF-54
PF-54 - Observed
PF-54 - Computed
Head(m-msl)
Year
0 2 4 6 8 10 12 14
2011-01 2011-07 2012-01 2012-07 2013-01 2013-07 2014-01 2014-07 2015-01

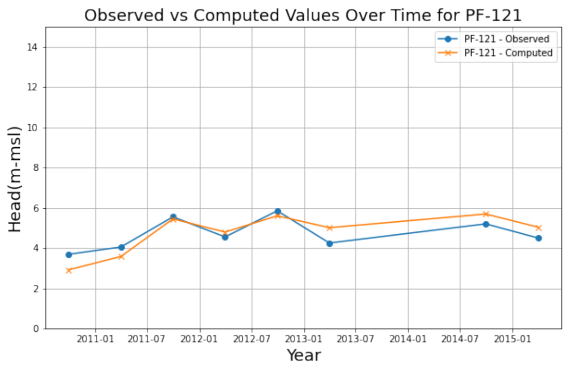

Observed vs Computed Values Over Time for PF-62
PF-62 - Observed
PF-62 - Computed
Head(m-msl)
Year
0 2 4 6 8 10 12 14
2011-01 2011-07 2012-01 2012-07 2013-01 2013-07 2014-01 2014-07 2015-01

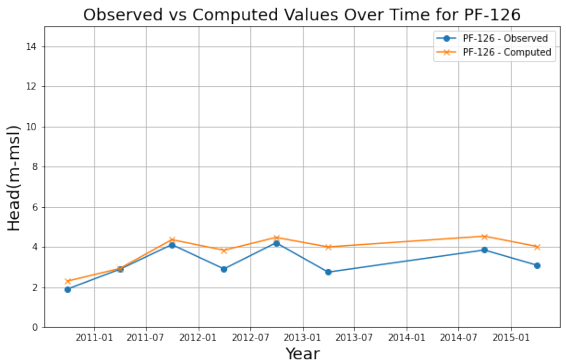

Observed vs Computed Values Over Time for PF-69
PF-69 - Observed
PF-69 - Computed
Head(m-msl)
Year
0 2 4 6 8 10 12 14
2011-01 2011-07 2012-01 2012-07 2013-01 2013-07 2014-01 2014-07 2015-01

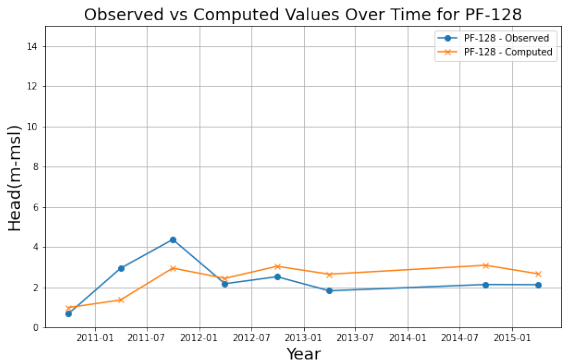

Observed vs Computed Values Over Time for PF-82
PF-82 - Observed
PF-82 - Computed
Head(m-msl)
Year

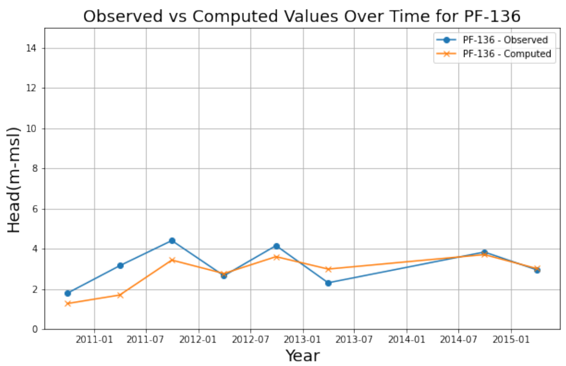

Observed vs Computed Values Over Time for PF-118
PF-118 - Observed
PF-118 - Computed
Head(m-msl)
Year

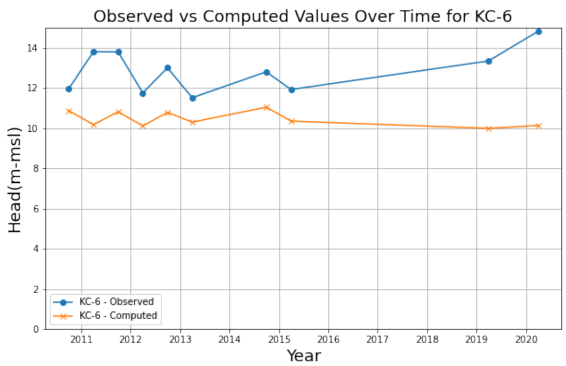

Observed vs Computed Values Over Time for PF-119
PF-119 - Observed
PF-119 - Computed
Head(m-msl)
Year


Observed vs Computed Values Over Time for PF-121
PF-121 - Observed
PF-121 - Computed
Head(m-msl)
Year


Observed vs Computed Values Over Time for PF-126
PF-126 - Observed
PF-126 - Computed
Head(m-msl)
Year


Observed vs Computed Values Over Time for PF-128
PF-128 - Observed
PF-128 - Computed
Head(m-msl)
Year


Observed vs Computed Values Over Time for PF-136
PF-136 - Observed
PF-136 - Computed
Head(m-msl)
Year


Observed vs Computed Values Over Time for KC-6
KC-6 - Observed
KC-6 - Computed
Head(m-msl)
Year

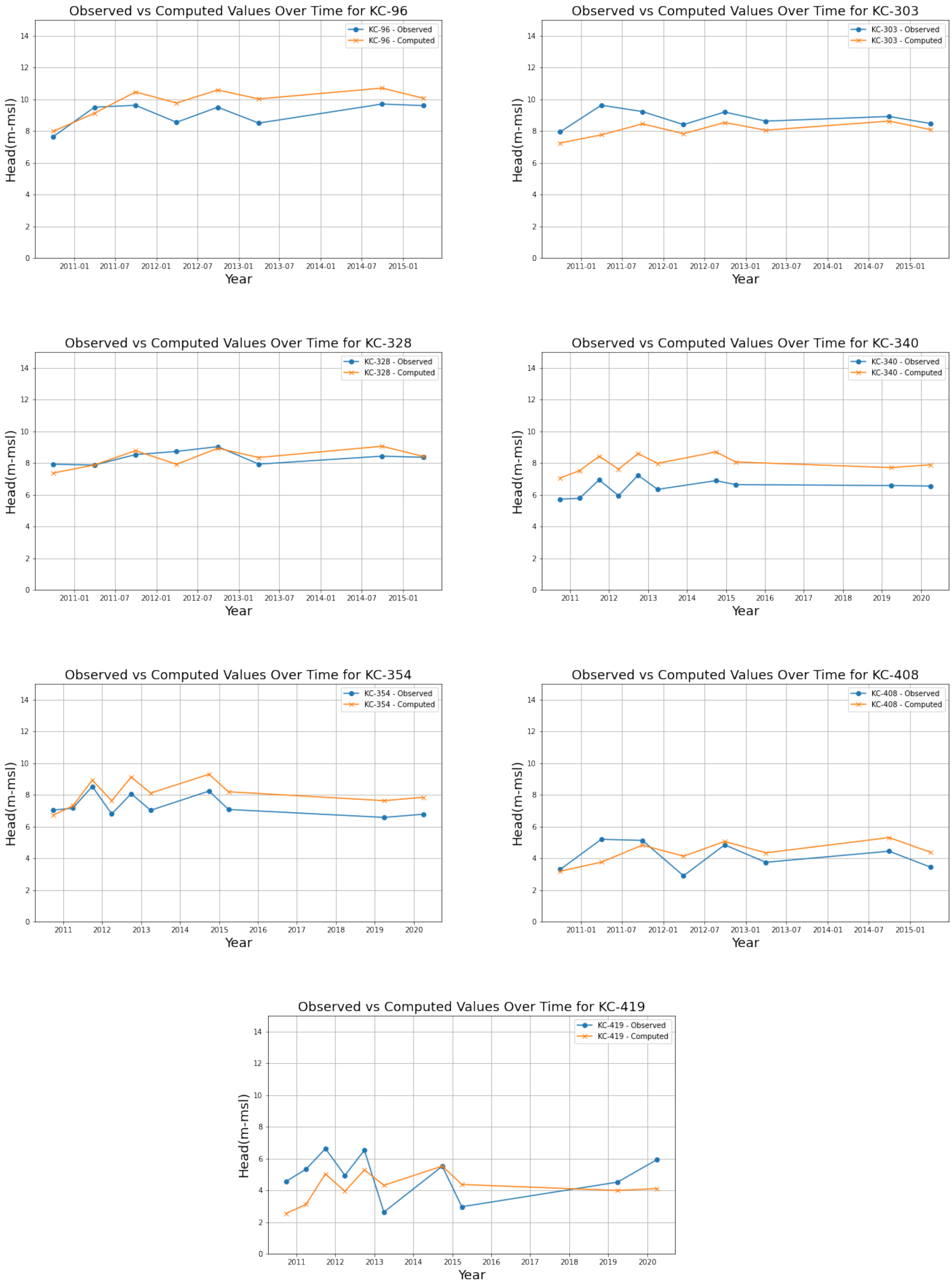


Figure 26: Simulated versus observed head (m) for piezometers in the study area

6. Water Balance for the Pinyari CCA

The water budget includes the inflows, outflows, and changes in storage for the aquifer. This provides an understanding of the impact of stresses on the groundwater system and allows an assessment of how waterlogging and salinity management can be improved. Water budgets can also be undertaken for irrigation districts or zones experiencing groundwater level declines to assess groundwater usage for districts or zones. The Indus River and the underlying aquifer are a highly connected system. There is considerable seepage from the Indus to the aquifer, particularly during the kharif season. Seepage from the Pinyari Canal, along with its branches Daro and Pinyari, also contributes to recharging the groundwater system in kharif as the Pinyari is a non-perennial canal. Along with the river and canal systems, precipitation and irrigation recharge play an important role in recharging the aquifer.

Major outflows from the model area are evapotranspiration and drainage. Evapotranspiration is a significant outflow from the groundwater systems due to the shallow water levels, high summer temperatures and the arid climate of lower Sindh. In Sujawal, due to extreme variations in temperature, the rate of evapotranspiration is especially high during the pre-monsoon dry season. A network of drains is available in the study area, which serves to discharge saline groundwater into the delta and the sea. The Left Bank Outfall Drain (LBOD) forms part of the eastern model boundary of our study area. It collects saline water, industrial effluents, and Indus River basin floodwater from two million hectares of irrigated land of the Shaheed Benazirabad, Sanghar, Mirpurkhas and Badin districts and disposes the drainage effluent into the Arabian Sea via a 41km long Tidal Link Canal.

6.1. Water Balance Analysis of the Steady State Model (October 2010)

The water balance for the steady state model in Table 4 indicates inflows from recharge and the river and canal system comprised about 78% of all inflows; the remaining inflows came from constant head boundaries along the coast. The contribution of inflows from the constant head boundaries is 268.2 MCM/yr, indicating the occurrence of seawater intrusion along the coastal boundary with the sea. Net inflows from the river and canals were 633.6 MCM/yr, indicating the river was recharging the aquifer. This is typical in the monsoon season when river levels are relatively higher – enhancing recharge from the river to the aquifer. By far the largest outflow was evapotranspiration, which comprised about 81% of all outflows. The significant outflow from the groundwater systems via evapotranspiration is expected due to the shallow water levels and high summer temperatures of lower Sindh.

Table 4: Annual average groundwater balance of steady state model

Source	Inflow (MCM/yr)	Outflow (MCM/yr)	Net (MCM/yr)
Recharge	294.9	0	294.9
River	690.9	-57.3	633.6
Evapotranspiration	0	-1,021.3	-1,021.3
Drain	0	-60.8	-60.8
Constant heads	268.2	-114.6	153.6
Total	**1,254.0**	**-1,254.0**	**0**

6.2. Water Balance Analysis of the Transient State Model

The water balance of the calibrated model in Table 5 indicates that the river and canal contribute 720.4 MCM/yr, and recharge from other sources, such as irrigation recharge and precipitation recharge, is 2,246.3 MCM/yr, which amounts to 22% and 68% of the total inflows to the aquifer, respectively. Significant inflows along the coastal boundary of 316.7 MCM/yr indicate the area south of the Pinyari CCA is at risk of seawater intrusion, particularly during the dry season when rainfall and river flows are very low. The major outflow from the aquifer is evapotranspiration at 2,199.8 MCM/yr due to high summer temperatures and shallow watertables underlying Sujawal. Outflows to the Indus River along the western model boundary are 610.7 MCM/yr and net flows are 109.7 MCM/yr, indicating this section of the river is highly connected to the aquifer. The net gain in aquifer storage during this period is 87.63 MCM/yr, indicating a net gain in storage in the aquifer which over time is contributing to high watertables in Sujawal.

Table 5: Annual average groundwater balance of the transient state model

Source	Inflow (MCM/yr)	Outflow (MCM/yr)	Net (MCM/yr)
Recharge	2,246.3	0	2,246.3
River	720.4	-610.7	109.7
Evapotranspiration	0	-2,199.8	-2,199.8
Drain	0	-114.5	-114.5
Constant heads	316.7	-270.8	45.9
Total	**3,283.4**	**-3,195.8**	**87.6**

6.3. Water Balance Analysis in Different Layers

Water reaches the uppermost layer (Layer 1) from four sources: recharge from rainfall and irrigation return flows, seepage from the Indus River and Pinyari Canal and its branches, inflows of 276.7 MCM/yr from constant head flows, and inflows of 1,022.3 MCM/yr from Layer 2 underlying Layer 1. The outflows from Layer 1 to Layer 2 are 1,280.9 MCM/yr, which results in a net downward flow of -258.6 MCM/yr, indicating irrigation, seepage and rising water levels are enhancing downward flows. The inflows to Layer 1 from the river are 720.4 MCM/yr and outflows back to the river are 610.7 MCM/yr, showing a high degree of river-aquifer connectivity. By far the largest outflow of -2,199.8 MCM/yr is via evapotranspiration, which is driven by shallow watertables in the district of Sujawal. The high rate of evapotranspiration and marginal to brackish watertables in Sujawal increases the risk of salinity transport into the crop root zone, which is often manifested as surface salinity (see Figure 27).

The transient simulation indicates the net inflow from constant heads along the coast is 240.4 MCM/yr. As sea levels rise due to climate change, we can expect increased seawater ingress into the coastal belt below the Pinyari CCA. The water budget for Layer 1 shows outflows of 114.5 MCM/yr via the LBOD and tidal link. Sea level rise will likely impact the operation and management of the drainage network. In the middle layer (Layer 2), the inflows from the top layer (Layer 1) were 1,280.9 MCM/yr and from the deeper Layer 3 were 421.6 MCM/yr, while outflows to Layer 1 and Layer 3 were -1,022.3 and 457.6 MCM/yr, respectively. The net outflow from the constant head boundary in Layer 2 was -172.9 MCM/yr; however, there are inflows of 28.77 MCM occurring along sections of the constant head boundary, which has implications for rising water levels and increasing salinity in the deeper parts of the aquifer along the coast. This layer also shows a net gain in storage of 49.9 MCM/yr.

For the deepest aquifer layer (Layer 3), the total inflow from Layer 2 was 457.6 MCM/yr and the outflow was 421.6 MCM/yr. Inflows from constant head boundaries were 11.2 MCM/yr with a net gain in the storage of 14.5 MCM/yr, as shown in Figure 28.

Figure 27: The presence of salinity from shallow groundwater in Jongo Jalbani village in Shah Bandar taluka, Sujawal, Sindh

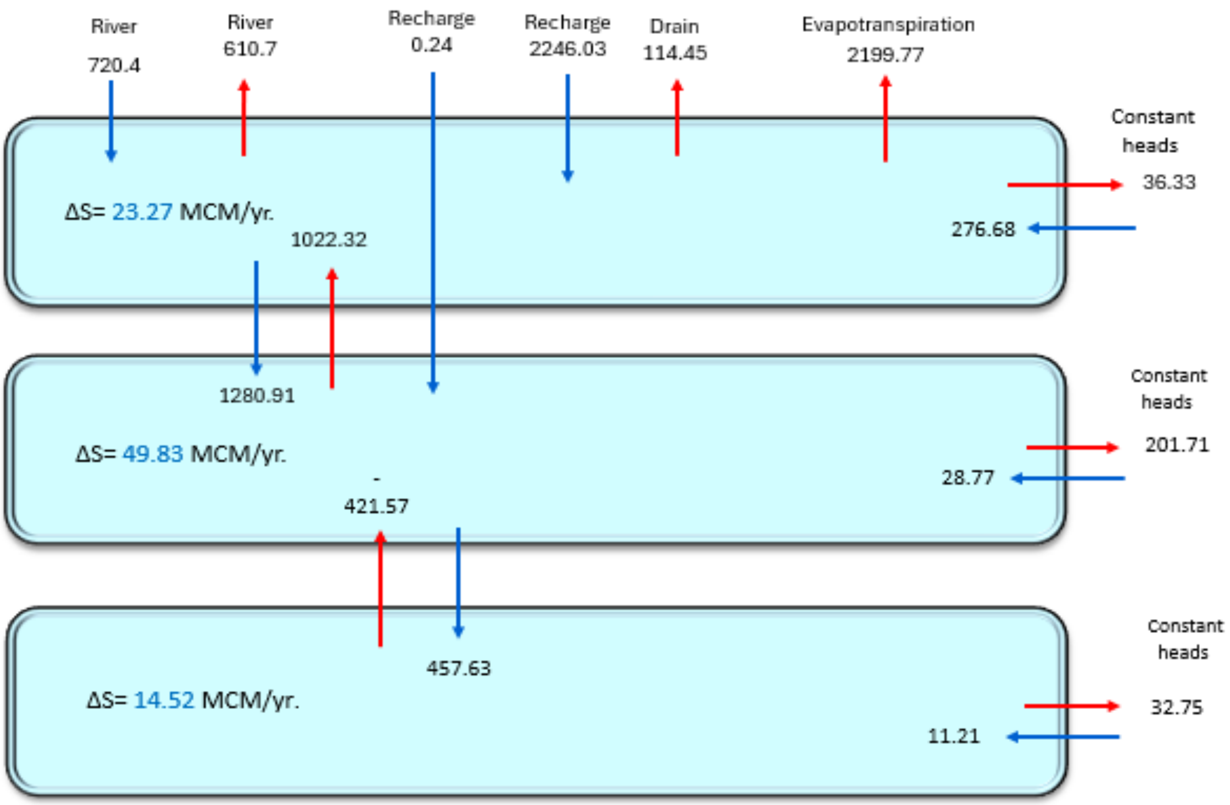


Figure 28: Groundwater balance for different layers during 2010–2020

7. Scenario Modelling

Scenario modelling allows evaluation of the impact of stresses on a groundwater system over the long term. It also guides policymakers in formulating a sustainable framework for managing surface and groundwater resources. The scenarios shown in Table 6 were developed in consultation with the Sindh Irrigation Department and stakeholders to understand the likely impacts on the aquifer under a changing climate. The first two scenarios were run from October 2010 to September 2060, while the climate change scenarios SSP2-4.5 (intermediate greenhouse gas emission) and SSP5-8.5 (very high greenhouse gas emission) apply from October 2010 to September 2100. The overall groundwater balance for each scenario is represented in Table 7.

Table 6: List of the proposed modelling scenarios for the coastal district of Sujawal

Scenario Title	Scenario Description
Scenario 1: Baseline (no change in current practices)	All the hydrological stresses remain the same as 2010–2020 and sea levels remain at 2020 levels
Scenario 2: Decrease in surface water supplies in the Pinyari CCA	Cropping intensity remains the same, water demand increases in future while canal supplies decrease and sea levels remain at 2020 levels
Scenario 3: Climate change scenario-SSP2-4.5	Shared Socio-economic Pathway SSP2-4.5 with sea levels rise projected under the SPP2-4.5 scenario
Scenario 4: Climate change scenario-SSP5-8.5	Shared Socio-economic Pathway SSP5-8.5 with sea levels rise projected under the SSP5-8.5 scenario

Two sets of four scenarios were simulated: managerial scenarios and climate change scenarios. These scenarios were developed to inform stakeholders about the impact of reduced surface water supply and the impacts of climate change on groundwater conditions in the Sujawal district. The initial head conditions in October 2010 were considered the starting point for these scenarios and for guiding the development of a policy brief for coastal Sindh.

7.1. Scenario 1: Baseline Scenario

The Baseline scenario simulates future projections demonstrating the system's behaviour should stresses on the aquifer remain similar to those in 2010–2020. To create a Baseline scenario until September 2060, 600 stress periods were created, each with 30.4 days. The variations in ET, recharge, and river flows were repeated using data for the calibrated model from 2010–2020. For computational ease, zones were created for evapotranspiration and recharge packages for scenario modelling. Two zones were created for evapotranspiration: the Pinyari CCA and the coastal zone. For recharge and canal seepage, the model domain was further subdivided into four zones – the Main Pinyari zone, the Daro Branch zone, the Pinyari Branch zone, and the coastal zone. Additionally, hydrological stresses remained the same as 2010–2020 and sea levels remain at 2020 levels. The water balance from 2010–2060 for the Baseline scenario shows results similar to the calibrated model shown in Table 8.

Table 7: Water balance for different scenarios

Inflows	Baseline scenario	Reduced Flow scenario	SSP2-4.5	SSP5-8.5
Simulation Period	**2010-2060**	**2010-2060**	**2010-2100**	**2010-2100**
Recharge	2,246.3	1,844.7	1,902.9	1,927.3
River	714.9	618.9	506.8	495.1
Constant heads	315.3	312.7	262.6	284.8
Total Inflows	**3,276.5**	**2,776.3**	**2,672.3**	**2,707.2**

Outflows	Baseline	Reduced Flow	SSP2-4.5	SSP5-8.5
River	614.7	524.2	594.0	612.2
ET	2,255.4	1,899.7	1,849.5	1,871.9
Constant heads	272.7	236.2	104.3	96.4
Drain	115.4	98.1	112.2	114.5
Total Outflows	**3,258.2**	**2,758.2**	**2,659.9**	**-2,695.0**
Net	**18.3**	**18.1**	**12.4**	**12.3**

Table 8: Water balance for the Baseline scenario (2010–2060)

Source	Inflow (MCM/yr)	Outflow (MCM/yr)	Net (MCM/yr)
Recharge	2,246.3	0	2,246.3
River	714.9	-614.7	100.2
Evapotranspiration	0	-2,255.4	-2,255.4
Drain	0	-115.4	-115.4
Constant heads	315.3	-272.7	42.6
Total	**3,276.5**	**-3,258.2**	**18.3**

The layer water balance for the Baseline scenario simulated from 2010 to 2060 (Figure 29) shows net storage in the top layer decreased from 23.27 MCM/yr for Layer 1 (2010–2020) to 5.39 MCM/yr, indicating that should conditions remain the same as 2010–2020, the aquifer will eventually reach an equilibrium. The layer water balance indicates significant flows between Layers 1 and 2 and, to a lesser extent, between Layers 2 and 3. Interlayer leakage shows net flows are occurring from Layer 1 to Layer 2 and similarly from Layer 2 to Layer 3, which is important to maintain as reversal of gradients will result in increased waterlogging and the spread of salinity. A significant inflow of 275.2 MCM from the sea boundary into the top layer indicates that areas adjacent to the sea and tidal rivers are at risk of waterlogging and salinity. Preserving Pakistan's coastline in the future will require a rethink of how coastal ecosystems can be protected and made productive.

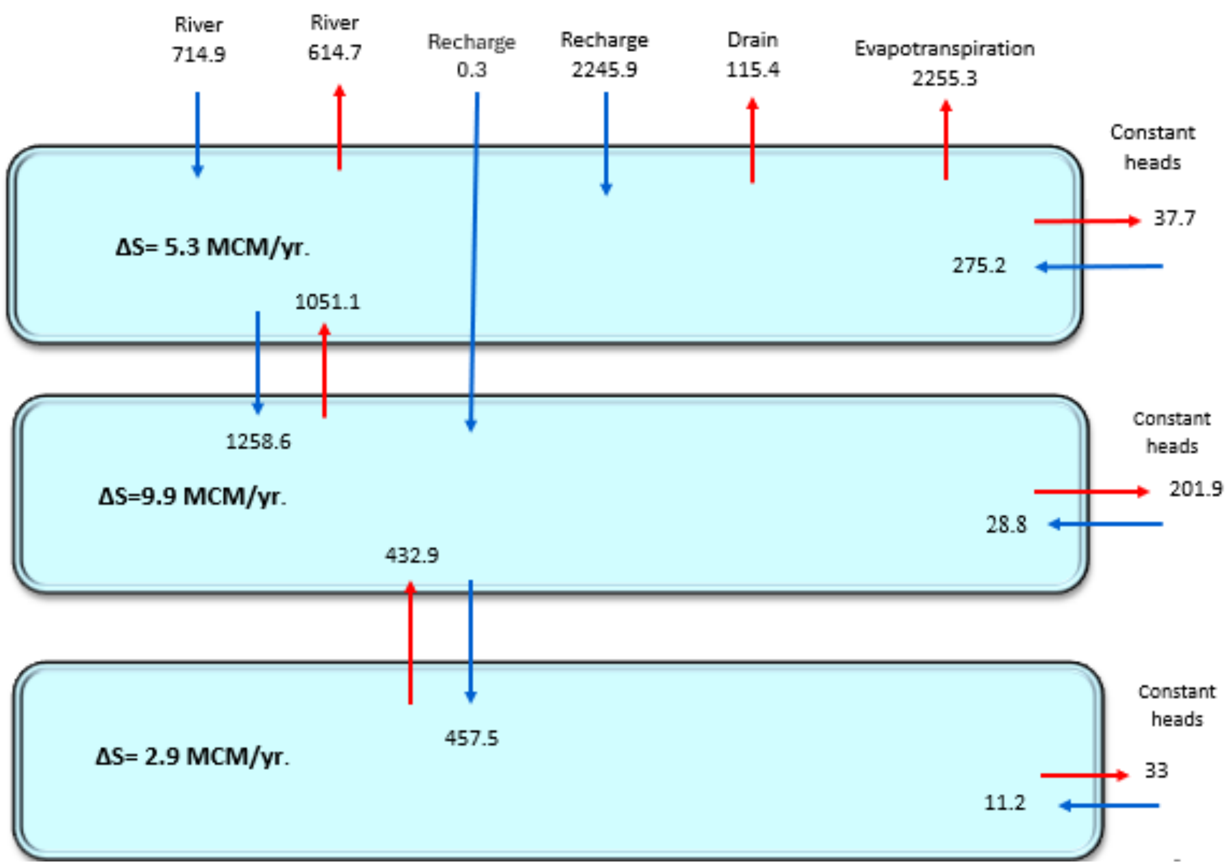


Figure 29: Groundwater balance for the Baseline scenario (2010–2060)

7.2. Scenario 2: Reduced Flow Scenario

We used the Standardised Streamflow Index (SSI) to compare streamflow observations to the long-term average conditions. The SSI method is a common approach for drought identification. The standardised anomaly is first calculated as the difference between the observed streamflow for a specific period (X) and the mean streamflow (μ). Divide this difference by the standard deviation (σ), which gives the standardised anomaly (Z):

$$Z = (X - \mu) \div \sigma \ldots\ldots Eq\ 7.1$$

The standardised anomaly (Z) obtained from equation 1 is multiplied by 0.577 to convert it to the Standardised Streamflow Index (SSI):

$$SSI = Z \times 0.577 \ldots\ldots Eq\ 7.2$$

The SSI is a standardised value that indicates how extreme a specific streamflow value is compared to the long-term mean and variability. Positive values of SSI indicate above normal streamflow, while negative values indicate below normal streamflow. In our case, monthly data from 2003 to 2020 were used to determine the duration of droughts. The five years with the lowest stream flow and record drought occurred from 2008–2012. A moving average with a five-year lag was also calculated; it also determined the lowest flows occurred from 2008–2012. The decrease in stream flows was estimated at 19% compared to the average surface water flows between 2010 and 2020. The river flows and canal flows from 2010 to 2020 were decreased by 19% to simulate a Reduced Flow scenario, which was then replicated to 2060.

A reduction in surface water flows also impacts the availability of canal water for irrigation. The canal flows were segregated into the three zones corresponding to Main Pinyari, Daro Branch and Pinyari Branch and the return flows were estimated based on reduced canal water availability. The monthly estimates of rainfall recharge and monthly estimates of irrigation return flow provided an estimate of the total recharge, which was used for simulating the Reduced Flow scenario.

The water balance for the Reduced Flow scenario in Table 9 shows a decrease in inflows from the river and canal network to the aquifer of 13.6% compared to the Baseline scenario. The decrease in inflows has a compensatory effect as outflows from the aquifer to the river also decrease by 14.6% in response to declining water levels near the river. The resulting net inflows to the aquifer from the Indus River and Pinyari Canal network decrease slightly from 100.2 MCM to 94.8 MCM. The decline in surface water flows available for irrigation results in a 17.9% decrease in irrigation recharge, resulting in a small decline in water levels in the aquifer. This decline in water levels also decreases evapotranspiration by 15.8% compared with the Baseline scenario and the drain outflow by 15%. This result indicates that areas affected by shallow watertables and salinity can be reduced if water efficient crops are introduced along with improved water and land management.

Pakistan’s water security is a significant concern for policymakers. Competition for water from a growing population and industrial base will likely result in marked reductions in surface water flows, which will be the key driver in transforming cropping patterns to less water intensive crops. Due to the high summer temperatures in Sujawal and the shallow groundwater table, a reduction in evapotranspiration rates which allows salinity to manifest on the soil surface can be reduced, which can improve agricultural production in areas prone to salinity and waterlogging. There are also additional benefits for reducing waterlogging, such as reduced flooding, as a small increase in the depth to water will allow greater infiltration of monsoon rains that would normally result in inundation and loss of cropping land.

In the coastal zone, the results from the reduction in surface water supplies in the Pinyari CCA show that inflows from constant heads are reduced marginally by 0.8% compared to the Baseline scenario. However, outflows to the sea decrease by 13.4%, resulting in an increase in net inflows from the sea boundary from 42.6 MCM for the Baseline scenario to 76.5 MCM, which could increase the risk of seawater intrusion. To minimise this risk, green barriers and engineering solutions may also be required to manage an encroaching sea boundary, particularly as sea levels rise in response to climate change.

Table 9: Water balance for the Reduced Flow scenario

Source	Inflow (MCM/yr)	Outflow (MCM/yr)	Net (MCM/yr)
Recharge	1,844.7	0	1,844.7
River	619	-524.2	94.8
Evapotranspiration	0	-1,899.7	-1,899.7
Drain	0	-98.1	-98.1
Constant heads	312.7	-236.2	76.5
Total	**2,776.4**	**-2,758.2**	**18.2**

A significant change from the Baseline scenario is the decrease in evapotranspiration from 2,255.3 MCM to 1,899.7 MCM, resulting in reduced capillary rise from the shallow watertable and reduced mobilisation of salts to the surface. The layer water balance for the Reduced Flow scenario in Figure 30 indicates a small decrease in net storage of 1 MCM/yr in Layer 1, which is beneficial in reducing shallow watertables in the top layer. As expected, there is a decrease in vertical flows from Layer 1 to Layer 2, but this is compensated by a decrease in upward flows, resulting in a net downward flow of 173.7 MCM. Inflows from the constant head boundary in Layer 1 show a marginal decline to 273.3 MCM, indicating new thinking will be required to manage salinity and inundation, and loss of biodiversity in the coastal zone south of the Pinyari CCA.

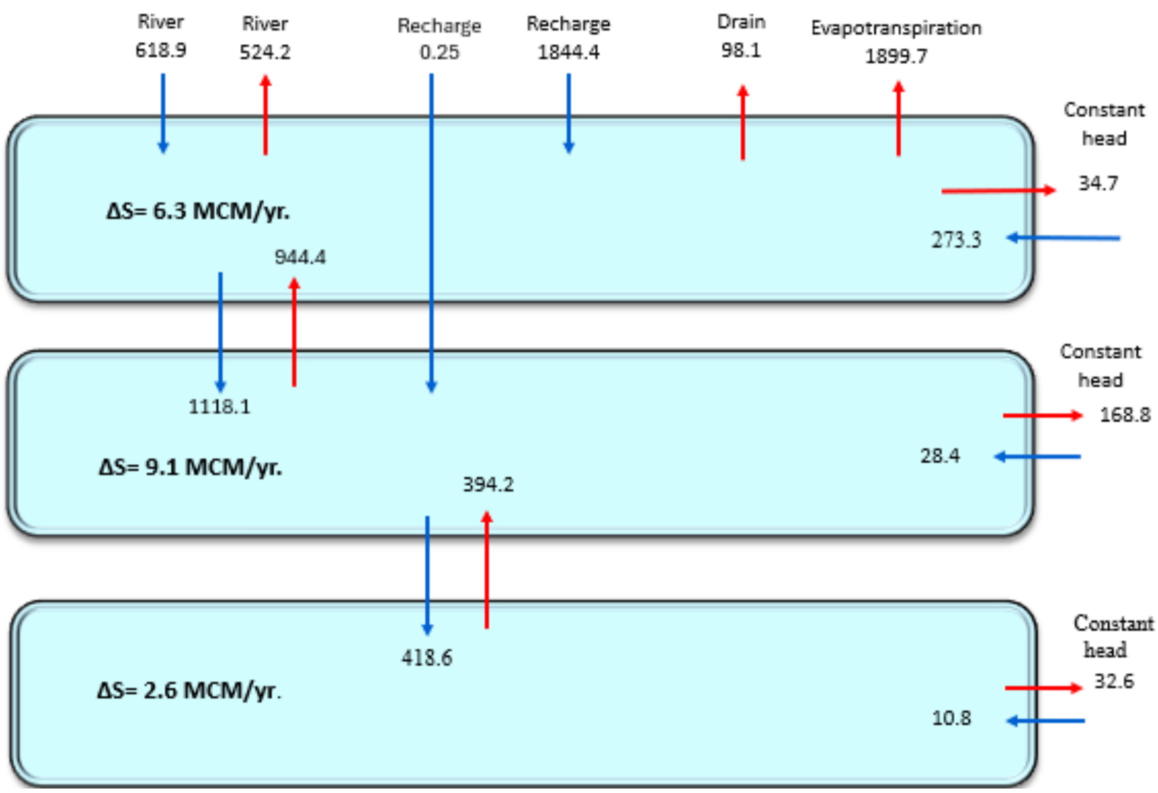


Figure 30: Groundwater balance for the Reduced Flow scenario (2010–2060)

7.3. Climate Change Scenarios

Shared socio-economic pathways (SSP) climate scenarios are part of global climate models, forecasting climatic parameters for the future. The SSP scenarios forecast climatic parameters based on greenhouse gas concentrations, economic development, population growth and societal choices. Coupled Model Intercomparison Project Phase 6 (CMIP-6) is a project responsible for designing, comparing and simulating future climate models under different forcing scenarios. The Earth System Grid Federation (ESGF) is a platform for accessing CMIP-6 data. Quantile mapping was applied for bias correction for projected SSP rainfall datasets to compare with locally observed rainfall data from 2010–2020. We simulated two scenarios using precipitation and temperature data for SSP2-4.5 and SSP5-8.5 corresponding to medium and high emission scenarios to simulate the likely impact of climate change on groundwater resources.

Precipitation data from 2021–2100 for both SSP2-4.5 and SSP5-8.5 were used to estimate the rainfall recharge and irrigation recharge to the aquifer. Only rainfall recharge was assigned for the coastal belt, as this area lies outside the Pinyari CCA.

The mean temperature (T mean) data under SSP2-4.5 and SSP5-8.5 scenarios from 2021–2100 were used to calculate evapotranspiration using the Blaney-Criddle method in Equation 7.3. Actual ET was calculated by multiplying the potential ET with the crop coefficient for each month.

$$Et_o = P(0.46 \times T_{mean} + 8) \ldots\ldots Eq\ 7.3$$

Where, Eto is the reference crop evapotranspiration (mm/day), T*mean* is mean daily temperature, and P is the mean daily percentage of annual daytime hours.

Coastal areas of Sindh are expected to experience a significant rise in sea levels. The projected sea level rise for the SSP2-4.5 and SSP5-8.5 scenarios with a medium confidence level is shown in Figure 31. These scenarios indicate that by 2100, the likely sea level rise is expected to be 0.56m for the SSP2-4.5 and 0.77m for the SSP5-8.5 climate condition (projections by NASA).[1] Additionally, projections by NASA advise that the low-confidence scenarios indicating the potential effect of low-likelihood, high-impact ice sheet processes

[1] https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool?psmsl_id=204&data_layer=scenario

cannot be ruled out. Under the high-impact scenarios, sea levels can be expected to rise to 0.7m in 2100 and 1.22m by 2050 for the SSP2-4.5 scenario. For the SSP5-8.5 scenario, the high-impact scenario is projected to result in a sea level rise of 1.01m in 2100 and 1.86m in 2150. The simulations we have undertaken look at the likely impact of the medium confidence level case for the SSP2-4.5 and SSP5-8.5 climate scenarios.

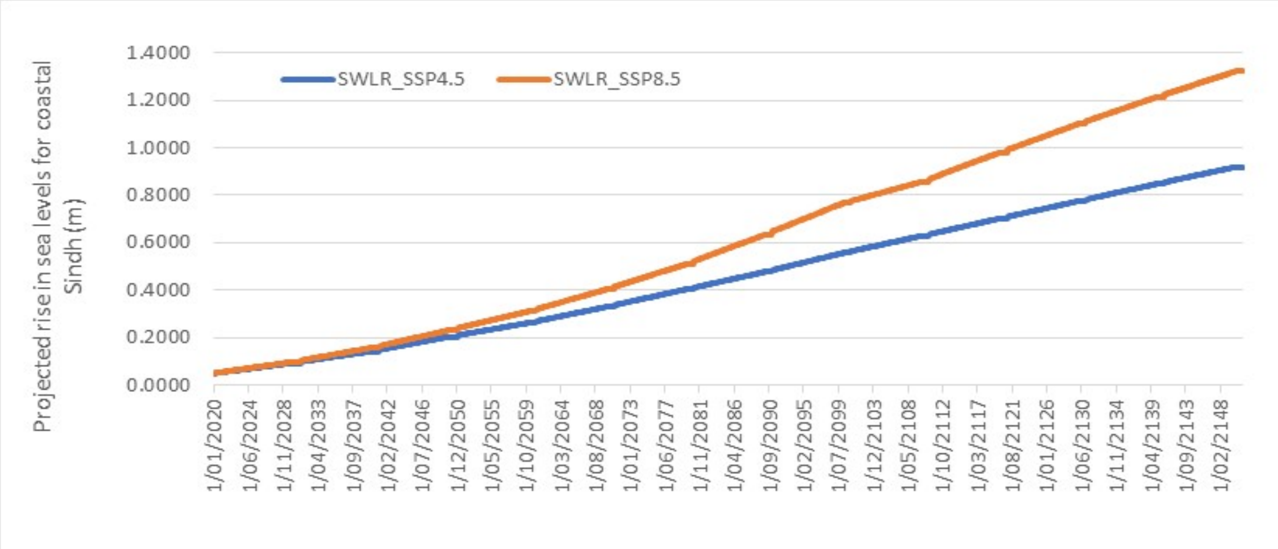


Figure 31: Projected sea level rise for coastal Sindh

7.4. Scenario 3: Climate Change Scenario SSP2-4.5

The projected rainfall and evapotranspiration for the SSP2-4.5 scenario, assuming reduced flows in the Pinyari Canal, were used to simulate groundwater conditions to 2100. The water balance for the SSP2-4.5 scenario in Table 10 indicates recharge has increased to 1,902.9 MCM compared to 1,844.7 MCM per year. However, recharge was significantly less than the Reduced Flow scenario due to the reduction in flows in the river and canal system. Outflows to the river increased whereas inflows from the river to aquifer have declined, thus reversing gradients compared to the Reduced flow scenario. The river now acts as a gaining stream with net flows from the aquifer of 87.2MCM compared to a losing stream with flows from the river to the aquifer of 100.2 MCM for the Baseline scenario and 94.8 MCM for the Reduced Flow scenario. It appears that climate change will significantly impact agriculture and livelihoods in the coastal zone, even under the medium emission scenario. The higher temperatures also result in evapotranspiration of 1,849.5 MCM, which is about 18% lower than the Baseline scenario but 2.6% lower than the Reduced Flow scenario. Additionally, the projected sea level rise for the SSP2-4.5 scenarios with a medium confidence level indicates a doubling of inflows along the sea boundary. These inflows may be expected to be greater when density is considered and as sea levels continue to rise beyond 2100.

Table 10: Water balance for the SSP2-4.5 scenario (2010–2100)

Source	Inflow (MCM/yr)	Outflow (MCM/yr)	Net (MCM/yr)
Recharge	1,902.9	0	1,902.9
River	506.8	-594.0	-g87.2
Evapotranspiration	0	-1,849.5	-1,849.5
Drain	0	-112.2	-112.2
Constant heads	262.6	-104.3	158.3
Total	**2,672.3**	**-2,659.9**	**12.4**

The layer water balance for the SSP2-4.5 scenario in Figure 32 shows downward flows from Layer 1 to Layer 2 of 964.3 MCM and upward flows of 960.1 MCM, indicating the top and middle layer are almost in balance. However, the significant amount of upwards flows indicate that these areas are likely to be affected by waterlogging and salinity mobilisation.

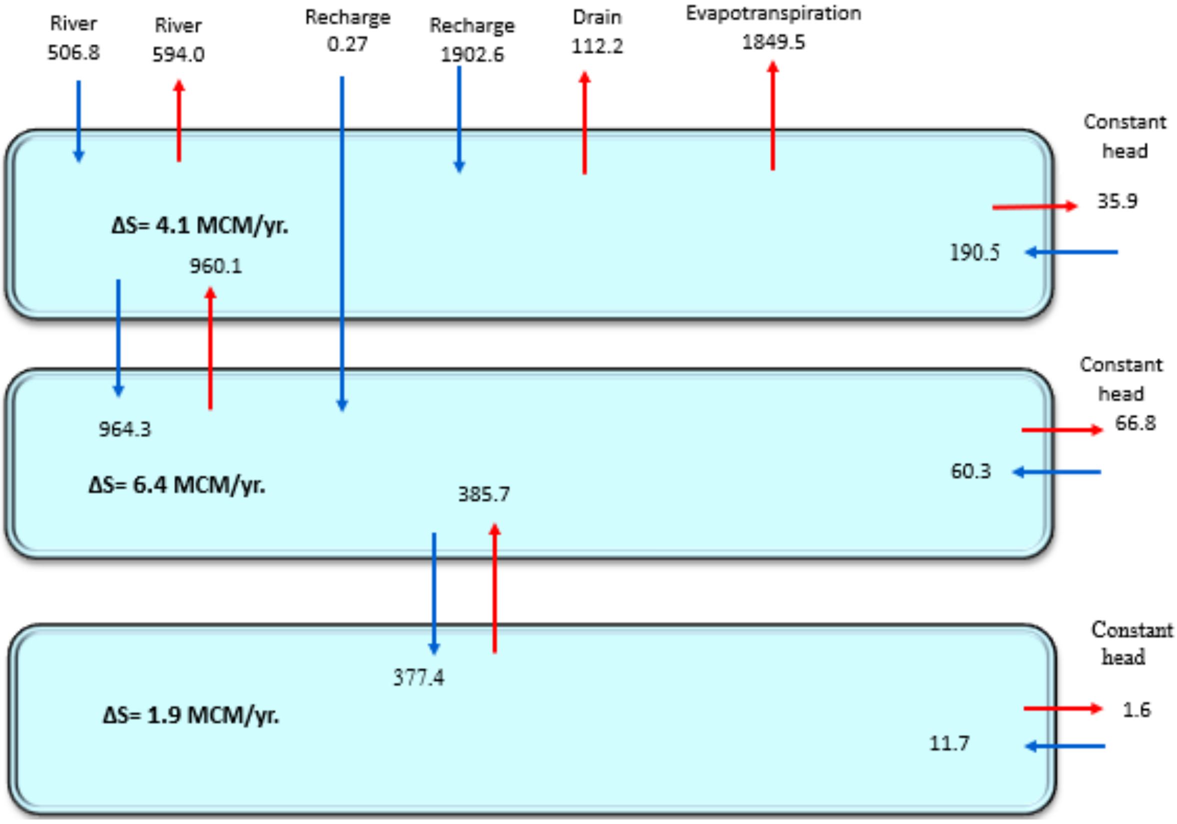


Figure 32: Layer water balance under climate change SSP2-4.5 scenario

7.5. Scenario 4: Climate Change Scenario SSP5-8.5

The projected rainfall and evapotranspiration for the SSP5-8.5 scenario, assuming reduced flows in the Pinyari Canal, were used to simulate groundwater conditions to 2100. The water balance for the SSP5-8.5 scenario in Table 11 indicates a marginal increase in rainfall recharge, and a marginal increase in evapotranspiration compared to the SSP2-4.5 scenario. A significant increase occurs in boundary inflows from the sea due to the rising sea levels between 2010 and 2100, resulting in a significant increase in net inflows of 42.6 MCM for the Baseline scenario, 76.5 MCM for the Reduced Flow scenario, 158.3 MCM for the SSP2-4.5 scenario, and 188.4 MCM for the SSP5-8.5 scenario. The simulated increase in net inflows from the sea boundary is expected to continue to increase post-2100 as sea levels continue rising to 1.86m to 2150, or under the potential effect of low-likelihood, high-impact ice sheet processes, the net inflows and coastal inundation are expected to be even greater.

The results of the layer water balance for the SSP5-8.5 scenario (Figure 33) are similar to the SSP2-4.5 scenario with some important differences. The SSP5-8.5 scenario shows downward flows from Layer 1 to Layer 2 of 964.8 MCM and upward flows of 987 MCM, indicating a reversal of gradients will occur under these climatic conditions. The net upward flow of 22.2 MCM is significantly higher than for the SSP2-4.5 scenario, with a similar net upward flow from Layer 3 to Layer 2 of 8.7 MCM, which will result in upward mobilisation of salinity from the deeper layers where salinities are significantly higher. The mobilisation of salts from the deeper layers to the top layer is likely to impact agricultural productivity in the region.

Table 11: Water balance for the SSP5-8.5 scenario (2010–2100)

Source	Inflow (MCM/yr)	Outflow (MCM/yr)	Net (MCM/yr)
Recharge	1,927.3	0.0	1,927.3
River	495.1	-612.2	-117.1
Evapotranspiration	0.0	-1,871.9	-1,871.9
Drain	0.0	-114.5	-114.5
Constant heads	284.8	-96.4	188.4
Total	**2,707.2**	**-2,695.0**	**12.3**

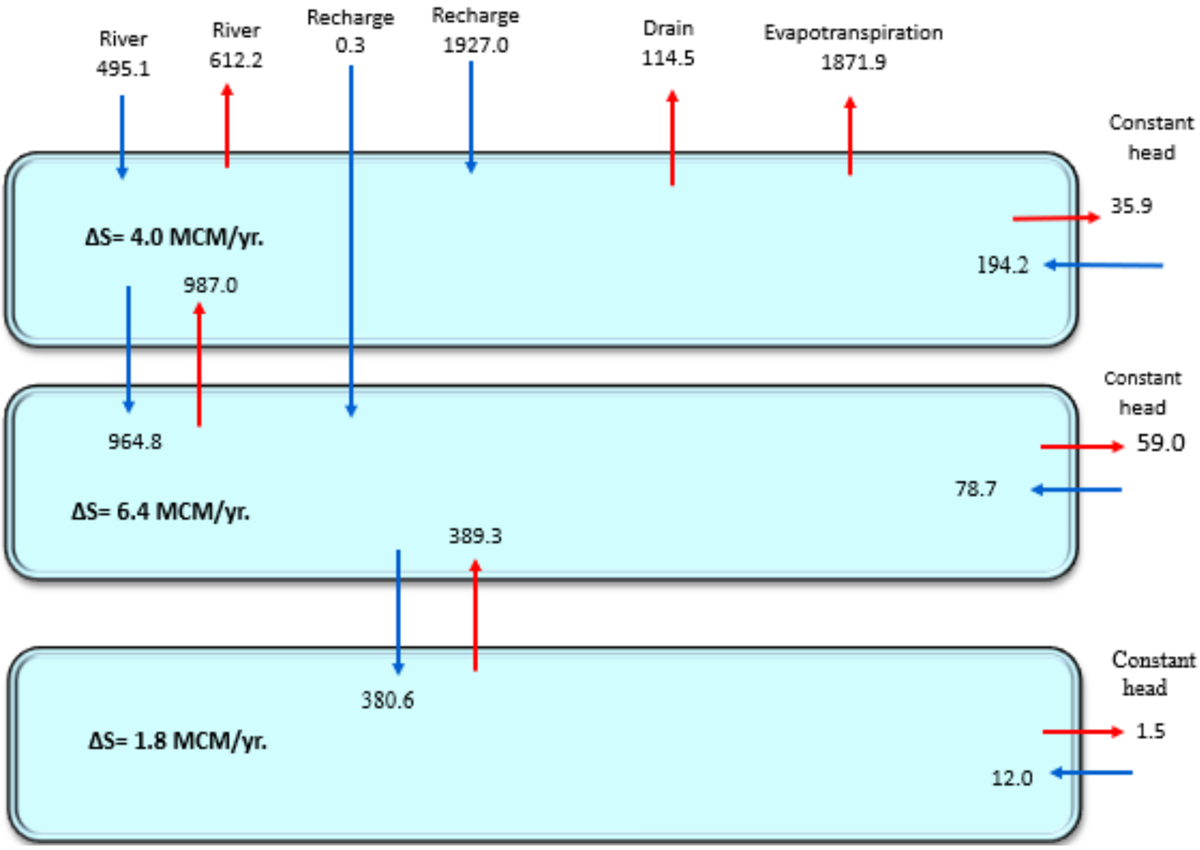


Figure 33: Layer water balance under climate change SSP5-8.5 scenario

7.6. Comparative Analysis of Hydrographs for Scenarios

The hydrographs for the Baseline and Reduced Flow scenarios are similar; however, differences in amplitude exist for the Reduced Flow scenario.

The hydrograph PF-4 varies between 10 and 13 metres above mean sea level (m-AMSL) for both the Baseline and Reduced Flow scenarios, showing greater fluctuation in water levels due to its proximity to the Indus River and Main Pinyari zone (Figure 34). Hydrographs PF-21 and PF-24 were located at the head of the Pinyari Branch zone; however, water level fluctuation is slightly subdued due to their proximity to the drain network. The piezometers KC-340 and PF- 45 are located in the Daro Branch and Pinyari Branch, respectively. The water level response was generally between 5 to 7 m-AMSL. The water levels in PF-128 fluctuate between 2 and 3 m-AMSL as this monitoring bore is located near the coastal zone near Jati, indicating that water levels are close to the surface in the coastal zone.

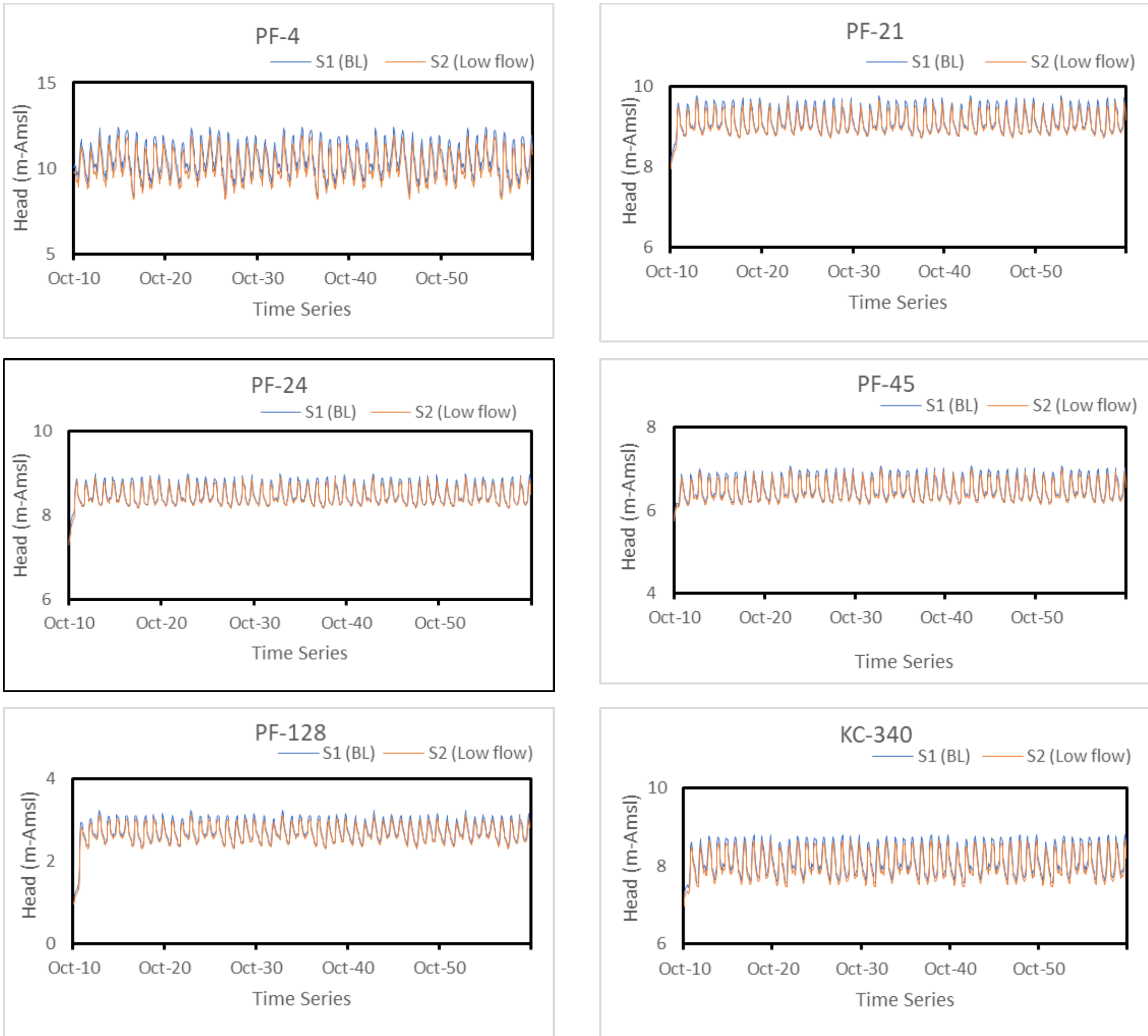


Figure 34: Simulated heads for the Baseline and Reduced Flow scenarios

The water levels in piezometers PF-4 and PF-21 show higher amplitudes than others, as these bores are located within the Main Pinyari zone, close to the Indus River (Figure 35). Interestingly, the amplitude in water levels for the SSP5-8.5 scenario (high emission scenario) is much greater than for the SSP2-4.5 scenario (medium emission scenario). This pattern is similar for the remaining hydrographs. Fluctuations in PF-24, PF-45, and PF-380 are somewhat subdued as these bores are further away from the river, and the main recharge source is from canal seepage and irrigation return flows. Bore PF-128 is near the coastal zone near Jati and is important to continue monitoring as it is the only bore located relatively close to the coast. Rising water levels in this bore would be of concern as it would indicate seawater intrusion. However, when designing a monitoring strategy for Sujawal, we recommend additional bores closer to the coast to provide early warning of the impacts from seawater intrusion.

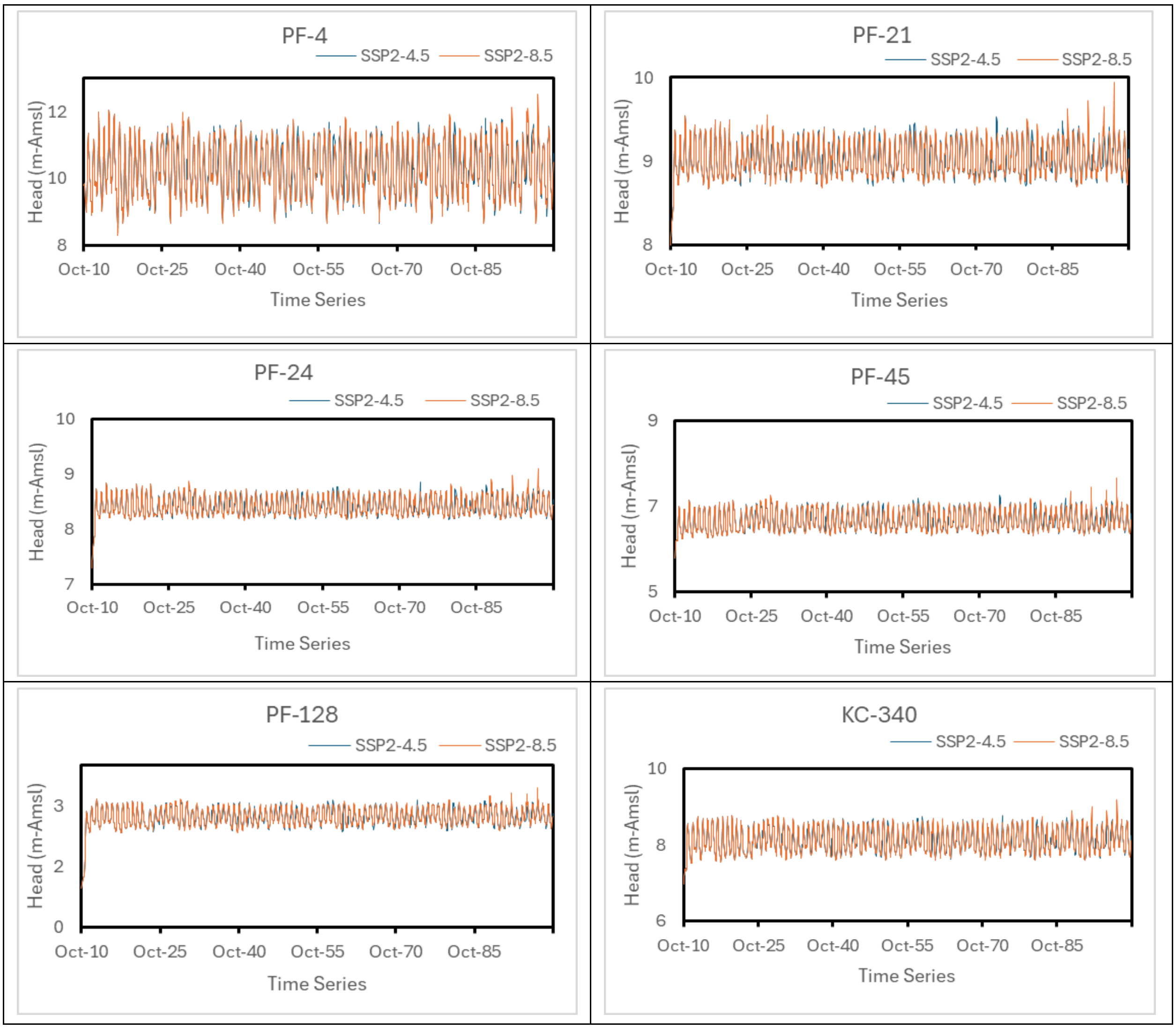


Figure 35: Simulated heads for the SSP2-4.5 and SSP5-8.5 climate scenarios

7.7. Guidance Developed from Scenario Analysis

There are no records of production bores for irrigation in the Pinyari CCA. However, with recharge from surface water irrigation and annual monsoon rains, there are likely isolated shallow lenses that are relatively fresh and may be suitable for livestock and some domestic uses and for small-scale agricultural activities at the household level. Mapping these lenses and assisting farmers to adopt skimming wells may provide benefits of lowering the watertable and providing supplementary water when surface water supplies are reduced or unavailable. However, adopting skimming wells will require financial assistance and significant knowledge transfer to participating farmers.

Groundwater usage in the coastal areas is limited to hand pumps and a few shallow bores tapping pockets of freshwater. However, a few farmers tap the freshwater lens for market gardens, which essentially relies on the transmissive nature of the aquifer and rainfall and on seepage from irrigation return flows. This is likely unsustainable as salinity will increase over the long term. Much of the groundwater in the deeper layers of the coastal zone is likely to be brackish too, and in some cases, salinity levels exceed the seawater concentration.

Additionally, groundwater is susceptible to seawater intrusion and upconing from deeper saline layers. Thus, the limited opportunities for accessing shallow marginal quality groundwater require careful management to allow use by coastal communities. The heterogeneity of the aquifer and the variation in interlayered sand and clay layers are important considerations for monitoring and managing groundwater resources in the coastal area (Lytton et al., 2021).

There are other options for controlling waterlogging in Sujawal. With a good network of drains, one option could be using solar-powered tubewells to pump deeper saline groundwater for disposal into the drainage network, which is transported via a tidal link to the sea. A word of caution: this option may work only for a few decades until rising sea levels impact the drainage system. Agriculture in Sujawal comprises smallholder farmers and impacts on agricultural productivity will have significant impacts on livelihoods, which will likely result in out-migration to cities for employment opportunities. In many of the coastal areas of Sindh, educational opportunities are limited, which suggests that youth are at the most risk of declining opportunities due to a low skill base. Policy experts in agriculture, irrigation and rural development will be required to develop an integrated solution for coastal agricultural communities.

The layer water balance indicates significant inflows from the coastal boundary in response to rising sea levels, which will primarily impact the coastal zone below Pinyari CCA and with rising sea levels beyond 2100, sea level rise under the SSP5-8.5 scenario is likely to reach between 1.25 and 1.86m by 2150, which may impact the southern areas of the Pinyari CCA.

7.8. Designing Adaptation Options for Coping with Climate Change in Sindh Coastal Areas

Sindh being a lower riparian district, with its flat topography, proximity to the coast, and shallow watertables, makes these areas vulnerable to waterlogging and salinity. Shallow watertables resulting in waterlogging and the underlying marginal to saline groundwater are detrimental to cropping systems in southern Sindh. The areas most at risk are the districts of Thatta, Sujawal and Badin. In the Sujawal district, the Pinyari CCA and the coastal zone to the south of the Pinyari command comprising the Indus Delta are particularly susceptible to water logging and salinity. These risks are compounded by rising sea levels and the subsequent ingress of seawater into coastal lands. The supply of freshwater in Pinyari is restricted to the kharif season as it is a non-perennial canal system. With little or no access to fresh groundwater for irrigation, farmers and cropping systems are susceptible to reduced canal flows in kharif and a lack of rainfall during the dry rabi season, which limits agricultural activities to the availability of water. Groundwater use is limited in the Pinyari CCA as farmers are reluctant to use marginal to brackish groundwater for irrigation and prioritise limited surface water for agriculture. Due to the lack of alternative freshwater sources, some communities exploit these marginal aquifers to meet potable and domestic needs.

In this environment, it is difficult for communities to expand their agricultural enterprises or increase cropping intensities. Thus, farmers need to adopt alternative strategies that allow for the diversification of livelihoods. Suitable adaptation strategies are also required to allow farming communities to *"live with salinity"*. Adaptation strategies and financing to mitigate these impacts will become increasingly important as climate change intensifies. Although much of the agriculture activities are within the Pinyari CCA due to the availability of canal water supplies during the kharif season, traditionally, there was subsistence farming in the coastal zone, such as harvesting mangroves for fodder and other small-scale agriculture such as growing betel leaf and musk melon (Khushk & Lashari, 2008). These activities have been largely abandoned due to the extent of seawater ingress and increased salinity in the coastal zone. Even the thriving fishing industry has suffered from smaller catches and the abandonment of coastal fishing villages.

7.8.1. Change to water efficient crops

The distribution of rice and sugarcane, which are the major kharif crops in the Pinyari Canal command, are shown in Figure 36; both are high-water demand crops irrigated with water supplied from the Pinyari Canal. These major cash crops for the farming community require sufficient canal water supplies. To manage the widespread shallow watertables and reduce salinity impacts on agricultural land, we have designed a mix of adaptation options, which include changes to cropping systems and nature-based solutions to guide farming communities and institutional actors on possible strategies to reduce the risk of land salinisation and seawater intrusion in the coastal district of Sujawal. The following adaptation strategies were adopted for simulating outcomes for the high emission climate change scenario SSP5-8.5. The first adaptation option included replacing 25% of the rice crop with sunflower and 25% of the sugarcane crop with mustard to replace these high delta crops with water efficient crops. Both mustard and sunflower are grown in the area; there is increasing demand for oilseed crops (pers. comm. Prof Latif Qureshi).

To determine suitable areas for replacing rice and sugarcane, we used the crop mask data for the kharif season processed by joint collaboration of FAO with Suparco and then mapped the rice and sugar crops for the Pinyari CCA, as shown in Figure 36 (FAO, 2017). Next, we mapped depth to water and EC for the Pinyari CCA to delineate areas with shallow watertables and high salinities. We identified areas where the depth to watertable was less than 1.5m (high risk of waterlogging), as shown in Figure 37.

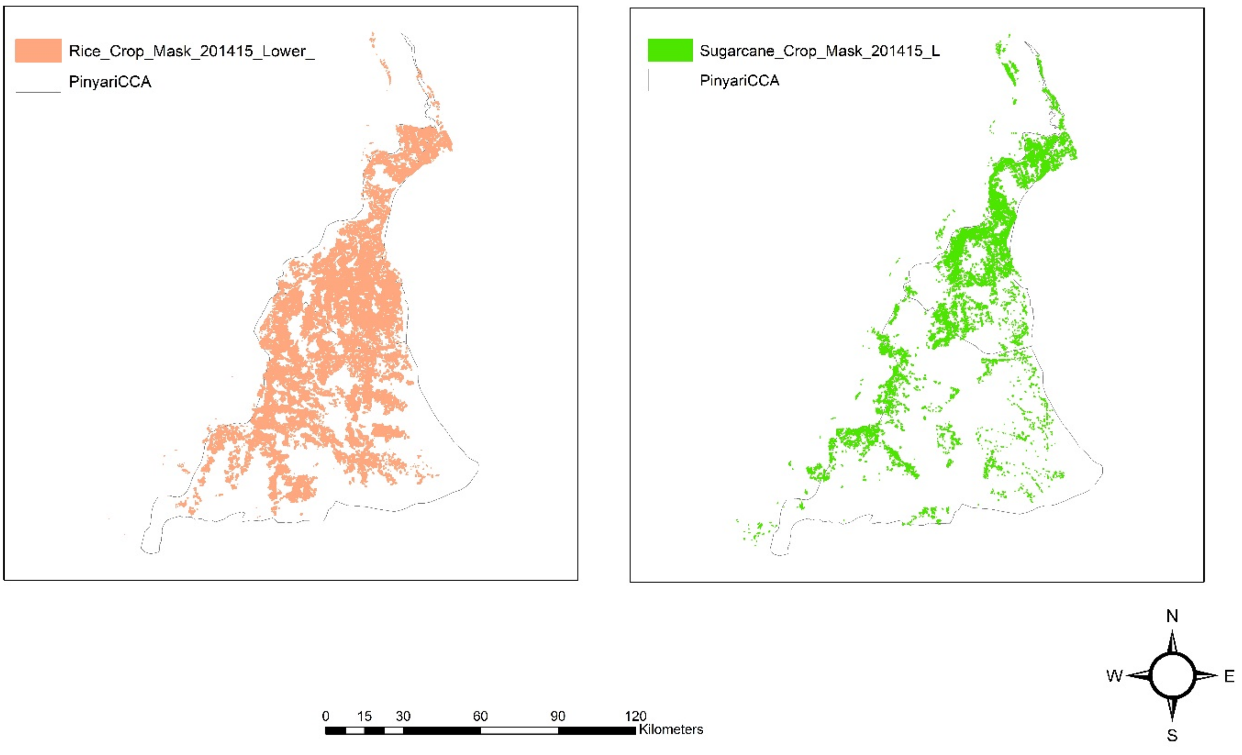


Figure 36: Crops classification map for rice and sugarcane in the Pinyari CCA

We divided the Pinyari CCA into six zones to identify shallow watertables and replace a portion of the rice and sugarcane crop with mustard and sunflower in each zone. We recommend replacing rice and sugarcane crops with sunflower and mustard in zones 5, 6 and 7, where the watertables were close to the surface (Figure 38). The average depth to water in post-monsoon 2020 was 0.82, 1.14, and 0.84m in zones 5, 6, and 7, respectively. Similarly, the average EC in post-monsoon 2020 was 1,857, 2,775, and 2,048 µS/cm in zones 5, 6, and 7, respectively. We estimated that replacing 25% of the rice and sugarcane crops with water efficient crops will reduce irrigation recharge by 20% in the designated zones.

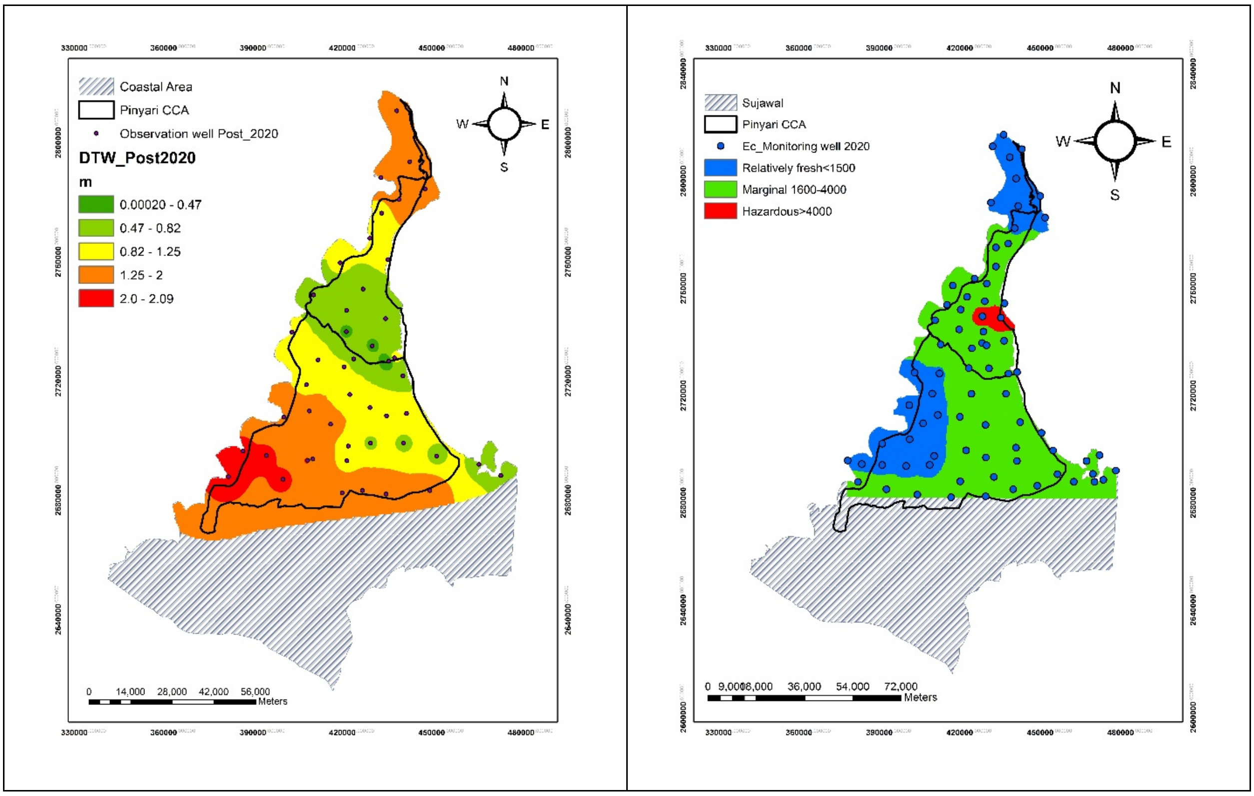


Figure 37: Spatial variation of depth to water (m) and EC (µS/cm), post-2020

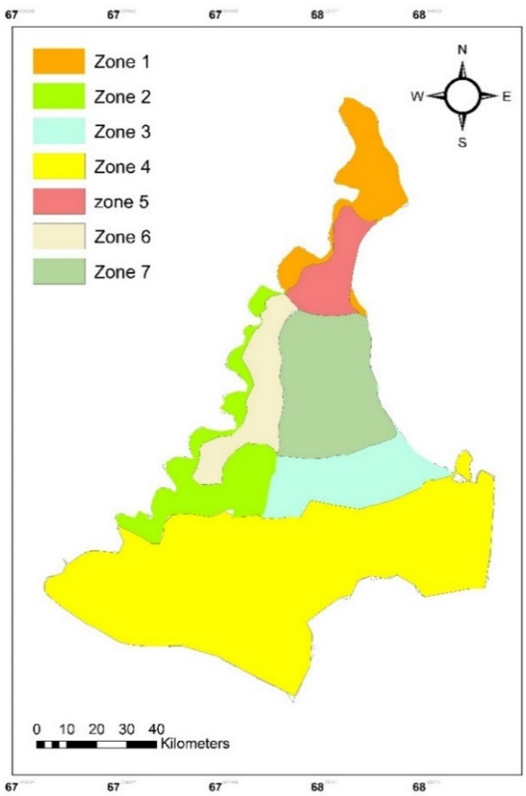


Figure 38: Zones delineation based on depth to watertable variation

7.8.2. Green barriers a nature-based solution

Seawater intrusion from rising sea levels and high tides typically experienced during the monsoon season and storm surges are resulting in the loss of land from inundation and degrading coastal ecosystems, including fisheries. To mitigate the impacts of seawater intrusion in the medium to long term, we proposed nature-based solutions which would be beneficial for reducing some of these risks for coastal areas and communities. We identified three zones in the coastal zone for environmental amelioration. In the coastal zone along the southern border of the Pinyari CCA, we identified a zone with ECs extending to an upper limit of 5,000 µS/cm (Figure 39), which would be suitable for planting native trees, including fruit and medicinal trees. This could provide economic returns for coastal communities. Examples of native salt tolerant species include Babbur (*Acacia nilotica*), this tree is the most dominant and occurs in thick forests along the Indus banks. Other native tree species include Nim (*Azadirachta inidica*), Ber (*Ziziphus vulagaris*) or Jujuba, Lai (*Tamarix orientalis*), Kirrir (*Capparis aphyla*) and Kandi (*Prosopis cineraria*). Establishing native tree plantation that are adapted to the local environment would also increase evapotranspiration in this zone, reduce the extent of shallow watertables, and provide alternative food and income sources if they can be communally managed.

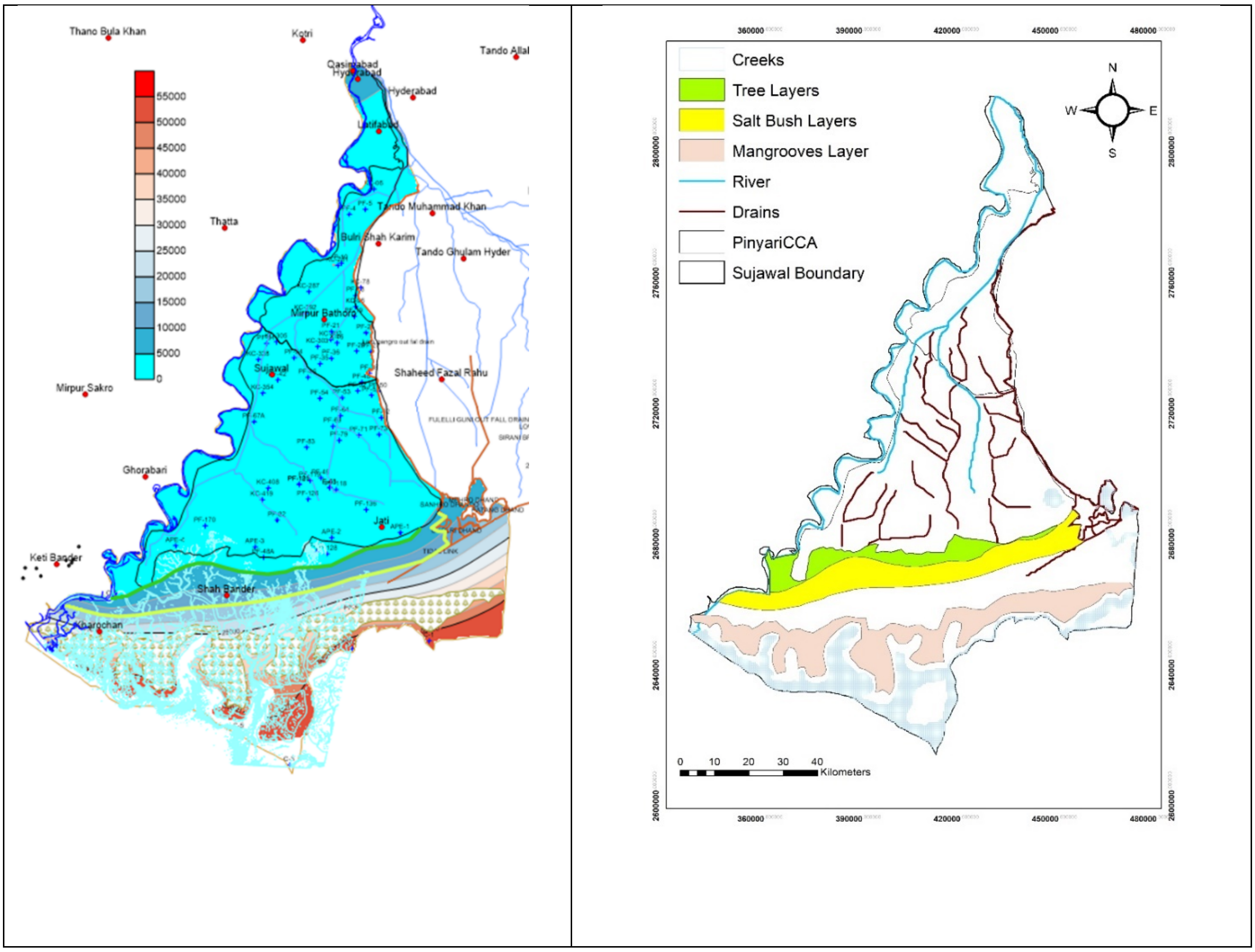


Figure 39: Salinity distribution in Sujawal (µS/cm) and proposed green barriers in the coastal zone in Sujawal

The second green barrier we proposed extends below the tree zone where we have suggested planting saltbush and other halophytic species. In this zone, salinity varies from 5,000 to 15,000 µS/cm. River saltbush (*Atriplex Amnicola)* and Old Man saltbush (*Atriplex nummularia*) are recommended as they are suitable in the coastal zone in Sindh (pers. comm. Dr Ed Barrett-Lennard).

River saltbush (*Atriplex Amnicola)*

River saltbush is a highly salt tolerant species used in Australia in the rehabilitation of saline areas. It has the best long-term survival and growth of any saltbush particularly when it is grown in saline soil. It may be a suitable species in coastal Sindh as it is fairly drought tolerant and can tolerate waterlogging well once it reaches maturity. Studies in Australia indicate it is highly favoured by sheep and recovers well from grazing. However, in coastal Sindh, grazing with goats will require a higher degree of controlled grazing. Additionally, studies in Australia have shown that the meat of sheep grazed on river saltbush is high in Vitamin E and has high “consumer appeal”. The disadvantages include a low volunteering rate and difficulties establishing by direct seeding.

Old Man saltbush (Atriplex nummularia)

Old Man saltbush (Atriplex nummularia) is the most commonly used forage shrub in Australia. It is a perennial halophyte species that is hardy and thrives in harsh environments, such as saline and alkaline lowlands. It is the largest species of Australian saltbush and can grow 2–4m wide and 3m high and can grow on saline, low-lying clay soils such as floodplains, but it is highly adaptable and can grow in most soils. Old Man saltbush can survive in harsh environments subject to flooding, drought and high salinity levels. It would be particularly useful in the coastal zone of Sindh as it is palatable for livestock and beneficial due to the elevated mineral content in its leaves. The seeds from the plant are a traditional food source for many Australian Aboriginal communities. It is also used as a windbreak, stock shade, crop shelter belt, erosion control and soil binder, particularly for stabilising sand dunes as well as rehabilitating eroded soils. The Noongar people of Australia traditionally searched for grubs in the roots, which were eaten either raw or roasted, and the leaves and roots were mashed and boiled with water to bathe skin sores, wounds and burns, indicating it may provide multiple uses and benefits for coastal communities.

Sources:

https://agriculture.vic.gov.au/farm-management/water/saltbush-for-saline-land

https://keys.lucidcentral.org/keys/v3/pastures/Html/River_saltbush.htm 1/

https://www.agric.wa.gov.au/soil-salinity/saltbushes-dryland-salinity-management-western-australia

Planting sea grasses such as Sea Asparagus or Sampire (*Tecticornia lepidosperma*) and Saltmarsh-grasses (*Puccinellia maritima*) in the coastal mud flats with its network of small creeks between the saltbush and the mangroves zone will further improve the ecosystem in the delta areas and help mitigate the continuing degradation in this zone. This zone falls in the estuarine plain and may require trials with different saltbush varieties and grasses for selection and establishment. Seagrasses can play a role in mitigating the adverse impacts of climate change and promote ecosystem conservation. They act as carbon sponges that trap and store carbon while also providing crucial support to various marine life forms and sustaining ecosystem balance.[2] Establishing seagrasses in this coastal zone faces risks from multiple stressors at the ecosystem scale, particularly extreme climate events and global warming. Significant research for developing an improved understanding of seagrass establishment, restoration and resilience will be required to manage these underwater habitats in the coastal zone of Sindh.

The mangroves zone was demarcated along the southern creeks to act as a green barrier for coastal erosion and seawater intrusion. These green barriers were simulated by modifying the extinction depth in these zones. The extinction depth for the tree zone was estimated at 5m, saltbush 3m, and mangroves 0.8m.

7.8.3. Implementing adaptation options for the SSP5-8.5 climate change scenario

The water balance for the SSP5-8.5 scenario with adaptation options for the Pinyari command shows a significant decrease in recharge from 1,927.3 MCM/yr without adaptation to 1,787.4 MCM/yr with adaptation, which will reduce the risk of waterlogging and salinity in zones 5, 6 and 7 within the Pinyari CCA (Table 12). The increase in river inflows from 496.1 without adaptation to 569.1 MCM/yr with adaptation indicates increased freshwater flows from the Indus, recharging the aquifer and replacing some of the reduced recharge from irrigation. It also shows that implementing the proposed adaptation options allow increased river inflows, which will be beneficial for creating a freshwater lens along the banks of the Indus. The water balance for the

[2] https://hlw.org.au/news/seagrass-a-vital-ally-in-climate-regulation-and-ecosystem-conservation#gsc.tab=0

adaptation scenario shows a small increase in net inflows along the constant head boundaries. Analysis of evapotranspiration for the tertiary barrier (tree zone) was 166 MCM/yr, for the secondary barrier (saltbush zone) 89.4 MCM/yr, and for the primary barrier (mangroves zone) 70.5 MCM/yr. Increased evapotranspiration from these zones will decrease water levels in the secondary and tertiary barrier zones. The establishment of mangroves will provide a primary barrier to coastal erosion. The secondary and tertiary barriers provide added protection to the southern areas of the Pinyari CCA.

The water balance for the coastal zone showed river inflows were 327.6 MCM/yr for the Pinyari CCA, while river inflows for the coastal zone had reduced to 182.7 MCM/yr. Mitigating seawater intrusion into the Indus Delta will require increased flow releases below the Kotri Barrage. Our suggested options will play an important role in mitigating waterlogging and salinity intrusion risks in the medium to long term. Still, these alone will not mitigate the overarching risk of rising sea levels and climate change. Mitigating the adverse impacts of sea level rise will need a rethink of additional adaptation strategies to address politically sensitive issues, such as the additional allocation of freshwater to the Indus River for release below the Kotri Barrage, and physical barriers such as dikes or polders, drainage of shallow saline groundwater and extensive land reclamation.

Table 12 Adaptation option for the SSP5-8.5 scenario (2010–2100)

Source	Inflow (MCM/yr)	Outflow (MCM/yr)	Net (MCM/yr)
Recharge	1,787.4	0	1,787.4
River	569.1	-577.1	-8.0
Evapotranspiration	0.0	-1,875.5	-1,875.5
Drain	0.0	-100.4	-100.4
Constant heads	296.9	-91.9	205
Total	**2,653.4**	**-2,644.9**	**8.48**

8. Groundwater Policy and Governance

In 2023, the Government of Sindh promulgated the Sindh Water Policy, which states unequivocally that a backlog of urgent problems such as contaminated water supplies, extensive land under waterlogging and salinity, unserved drinking water needs, dry tail-end areas and disappearing wetlands are resulting in economic insecurity and stress at the family level, impacting stability and household relations. These issues, particularly contaminated water supplies, waterlogging and salinity, significantly impact resource conditions and access to water that is fit for irrigation, and domestic and industrial needs.

The water policy in Sindh highlights the significance of managing water resources holistically, emphasising the need to achieve a more sustainable use of groundwater. One of the main goals is to control groundwater use to avoid depletion. To this end, a committee to oversee the commercial use of groundwater has been created. The establishment of a specific department for groundwater management within the Sindh water resources management department is intended to coordinate efforts to address issues such as waterlogging and salinity in the region. Programs like the Hydro-Agro Informatics Centre play a crucial role in strengthening monitoring systems for groundwater, and regulations pertaining to tubewells ensure that extraction is carried out safely and in accordance with aquifer conditions.

Moreover, improved conjunctive use and management are needed to reduce waterlogging and salinity levels while maintaining freshwater replenishment. Building small dams helps store groundwater, while protective measures like constructing unlined canals and using selective drainage protect freshwater reserves in rural regions. Licensing regulations, educational campaigns, and improved monitoring systems all play a role in supporting sustainable groundwater management and encouraging the joint use of water resources throughout Sindh.

8.1. Identifying Information Gaps

To date, the monitoring, mapping, and modelling of groundwater resource use and uses has largely been ignored. The network of bores with biannual monitoring of depth to groundwater and EC measurements used in this study have been undertaken by the SMO. There are, however, significant data gaps, and many monitoring bores have been abandoned or not monitored due to funding constraints. The Sindh Irrigation Department (SID) does not have a monitoring network in place, and significant institutional capacity constraints exist. With the growing demand for increasing food production, farmers in Sindh have been accessing groundwater to supplement shortfalls in surface water supplies in areas where there are fresh groundwater lenses, e.g., in the districts of Khairpur, Sukkur, Naushero Feroze, and Shaheed Benazirabad. A recent study of the Lower Indus Basin indicates groundwater extractions in Sindh have increased from 1.6 BCM to 19 BCM (Salam et al., 2023). This is concerning as increased pumping from the freshwater lenses is unmanaged and as these lenses get depleted, the risk of saline intrusion and upconing increases. The continued use of marginal quality groundwater has implications for salt accumulation in or near the crop root zone, which may impact agricultural productivity in these areas.

The significant gap in institutional capacity to monitor and manage groundwater resources will need to be addressed to allow the SID to transition into the role of resource management. This will require significant multidisciplinary skills encompassing hydrogeological modelling, water quality monitoring and modelling, and strengthening skills in social and community engagement to reach out to groundwater irrigators to improve resource use management.

The dearth of information about Sindh's groundwater and the institutional capacity constraints in SID is a significant barrier to better groundwater management. Although the institutional capacity to manage Sindh's groundwater resources has not been developed, it is recognised in the Sindh Water Policy that groundwater resources need to be monitored and managed as they are vital for food production and farming livelihoods and an important source of potable water for rural communities.

8.2. Establishing a Water Resources Directorate

From an institutional perspective, SID plans to create an internal division devoted to groundwater mapping, modelling, and management. Continuous monitoring loggers that provide reliable monitoring of groundwater will allow assessment of the condition of the aquifer and help with informed decision-making.

We would encourage SID to establish a Water Resources Directorate with the specific mandate to improve the monitoring and management of surface and groundwater resources in Sindh and focus on an integrated water resource management approach. The districts of Sujawal, Thatta, and Badin will require an approach suited for the coastal areas where tidal incursions and seawater intrusion impact coastal communities. The Water Resources Directorate would need to integrate water management to ensure it provides benefits for irrigation, domestic needs, industries, the environment and coastal protection.

A major commitment has been made in this project as well as other recent projects, such as the ACIAR-funded *Improving Groundwater Management to Enhance Agriculture and Farming Livelihoods in Pakistan* project (LWR/2015/036), for developing groundwater models to improve our understanding of impacts in these areas. A team from SID and the Sindh Irrigation and Drainage Authority (SIDA) 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 allow for expertise in surface and groundwater modelling to be developed in-country and to 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. This project has trained more than 20 SID engineers, MUET students, and engineers from SMO Sindh in groundwater monitoring and modelling, marking the initial steps towards capacity building in Sindh. It is crucial to build on these efforts to monitor and manage groundwater resources to benefit Sindh's groundwater users in the future.

The Water Resources Directorate would be responsible for maintaining a strategic groundwater monitoring program and data management, groundwater models, and conducting hydrogeological and water resource assessments on which to base policy settings. The interface of this group with existing monitoring groups such as the SMO and SIDA would be useful to ensure that the monitoring, collection and management of groundwater data is undertaken efficiently and provides open access to the Water Resources Directorate. Improved monitoring systems would allow the water resources team to produce an annual groundwater status report and define allocation limits for Groundwater Management Zones based on modelling results, identify stressed zones, and set extraction limits to ensure freshwater sources are used sustainably without loss in quality. We further recommend the Water Resources Directorate establish links with various national and international water research centres and national universities as well as other government agencies, community groups, irrigators, and stakeholders.

8.3. Groundwater Monitoring and Management

An important recommendation is investment in collecting, storing, and making monitoring data on water levels, salinity and other water quality parameters available online by capitalising on investments in data portals by the World Bank, ADB and ACIAR. Improved monitoring of groundwater resources is also advised in the new Sindh Water Policy document. We understand that SIDA is already monitoring water levels and salinity below the Kotri Barrage. However, we recommend that the monitoring program be upgraded with water level and salinity loggers at strategic sites not only in agricultural areas but also in the other coastal regions. The disparate monitoring efforts by researchers on specific projects and by the SMO need to be consolidated in a single Water Resources Information Management System.

There are no records of groundwater pumping in Sujawal or the other coastal areas as groundwater usage is not being monitored. We recommend metering tubewells at strategic locations within these areas to provide good spatial coverage of groundwater extractions and identify screen lengths so that it can be ascertained from which depth groundwater is being pumped. An excellent example is the geotagging of 1.2 million tubewells in Punjab being undertaken by the Water Resources Zone of the Punjab Irrigation Department.

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 future groundwater studies and policymakers. Establishing Groundwater Management Zones needs to be designated in Sindh to ensure that groundwater extractions do not degrade the freshwater lens to preserve Sindh's fresh groundwater areas for future users. In Sindh, tail-end farmers are being forced to use marginal quality groundwater to supplement a shortage in surface water. The inequity in canal water supplies increases the use of marginal to brackish groundwater and increases the risks of land salinisation and sodicity and deteriorates soil structure. Farmers must be made aware of these risks and their potential impact on crop productivity and soil health. However, to minimise salinity impacts from marginal quality groundwater for irrigation, SID and the Sindh Agriculture Department will need to offer farmers extension services in improved conjunctive use practices, farm scale monitoring of groundwater quality, and ultimately increased surface water supply for tail-end farmers through equitable resource sharing and promoting crops that are water efficient along with extension services for improved irrigation, crop and land management practices.

8.4. Institutional Policy, Licensing, Pricing

Based on existing studies and where required, targeted studies would need to be commissioned to develop a policy framework for managing both groundwater and surface water resources to include resource monitoring and mapping, groundwater modelling, conjunctive management, and environmental water allocation to improve ecosystem function. Soon, a system of licensing high volume groundwater users needs to be considered to control excessive depletion in stressed zones for protecting Sindh freshwater lenses. A mechanism needs to be developed such that information on new bores drilled in Sindh is provided to SID for archiving the bore depths, screen lengths and depth of production bores. A program to train and license drillers in bore logging and SID/SIDA hydrogeologists to log bores and prepare drilling reports will improve understanding of the underlying aquifer.

8.5. Water Saving Technologies

Introducing water saving technologies among progressive farmers needs to be encouraged and for this, SID needs dedicated staff with up-to-date knowledge of modern water savings technologies. Adaptation options suited for different zones in Sindh need to be co-developed with farming communities accompanied by investments in farmer awareness training, and training in apps developed in the ASSIB project, which integrates remote sensing of crops, soils and crop water requirements with a land capability framework (Khan et al., 2024).

The groundwater storage underlying the freshwater zones in Sindh represents a tremendous resource which can be tapped judiciously. Where feasible, accurate mapping of the underlying deposits and their hydraulic properties would need to be undertaken to ensure the effective location and operation of managed aquifer recharge schemes, particularly in areas with relatively deep watertables. Mapping of groundwater resources is essential to manage freshwater zones and devise strategies for conjunctive use of canals and marginal groundwater to benefit farmers in Sindh.

8.6. Capacity Building and Development

Skills need to be enhanced in the following areas:

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

9. Conclusion and Recommendations

In the district of Sujawal, watertables are generally shallow and elevated groundwater salinities make it unsuitable for irrigation. The primary source of irrigation water is from the Pinyari Canal, which is non-perennial. Surface water is available in the kharif (wet) season; however, waterlogging and salinity are widespread in parts of the command. In the rabi (dry) season, agricultural activities are marginal and rainfall dependent. Thus, the productivity of agriculture in the kharif season is significant in maintaining the livelihoods of smallholder farmers. Along the coast, inflows from constant head boundaries pose a risk to coastal ecosystems and in the future, possibly by 2150, these risks may extend to the southern edge of the Pinyari CCA due to sea level rise and extreme climate events such as the rains in 2022 and also possibly tidal surges which are experienced during peak monsoon.

9.1. Conclusions

Monitoring groundwater resources: There are a limited number of monitoring bores within the Pinyari CCA. The water levels monitored from 2010–2015 indicated shallow watertables within a few metres of the surface with a maximum depth to water of 5.4m. EC values in the Pinyari CCA indicated the groundwater was of marginal quality and farmers generally only access the shallow groundwater with hand pumps for domestic uses. The absence of monitoring bores in the coastal belt south of the Pinyari CCA is a significant gap in data and knowledge of groundwater conditions. The Sindh Irrigation Department will need to establish a monitoring network for the canal commands as well as the coastal zone due to the adverse impact this zone is having on productive agriculture and coastal lands.

Understanding the water budget: The water budget for the calibrated model from October 2010 to September 2020 indicated rainfall recharge and irrigation from field applications are the main sources of recharge to the aquifer, contributing 2,246.3 MCM. Seepage from the Pinyari Canal network and the Indus River also account for significant inflows to the aquifer. Evapotranspiration of 2,199.8 MCM is by far the major outflow from the aquifer owing to shallow watertables and high temperature in southern Sindh. The high rate of evapotranspiration and marginal to brackish watertables in Sujawal increase the risk of salinity transport into the crop root zone and is often manifested by surface salinity.

The top layer of the aquifer: Water inflows to the top layer of the aquifer (Layer 1) are from rainfall recharge and irrigation return flows, seepage from the Indus River and Pinyari Canal along with its branches, inflows from constant head boundaries along the coastline, and upward flows from Layer 2 underlying Layer 1. There are also substantial outflows from Layer 1 to Layer 2, which results in a net downward flow of 258.6 MCM/yr, indicating irrigation, canal seepage and rising water levels are enhancing downward flows. The inflows to Layer 1 from the river are 720.4 MCM/yr and outflows back to the river are 610.7 MCM/yr, showing a high degree of river-aquifer connectivity.

The Baseline and Reduced Flow scenarios: The layer water balance for the Baseline scenario simulated from 2010 to 2060 shows that net storage decreased from 23.27 MCM/yr for Layer 1 (2010–2020) to 5.39 MCM/yr, indicating that should conditions remain the same as for 2010–2020, the aquifer will eventually reach an equilibrium. The layer water balance indicates significant flows between Layers 1 and 2 and, to a lesser extent, between Layers 2 and 3. Interlayer leakage shows net flows are occurring from Layer 1 to Layer 2 and similarly from Layer 2 to Layer 3, which is important to maintain as reversal of gradients will result in increased waterlogging and the spread of salinity. The inflow of 275.2 MCM from the sea boundary into the top layer indicates that areas adjacent to the sea and tidal rivers are at risk of waterlogging and salinity. Preserving Pakistan's coastline in the future will require a rethink of how coastal ecosystems can be protected and made productive.

The water balance for the Reduced Flow scenario results in a decrease in seepage from the river and canal network and in recharge, and a corresponding decrease in evapotranspiration due to declining water levels. This result indicates that areas affected by shallow watertables and salinity can be reduced if water efficient crops are introduced along with improved water and land management. Water security in Pakistan's future is a significant concern for policy makers and in particular competition for water from a growing population and industrial base will likely result in marked reductions in surface water flows which will be the key driver in transforming cropping patterns to less water intensive crops.

Climate change scenarios: We simulated two scenarios using precipitation and temperature data for SSP2-4.5 and SSP5-8.5 corresponding to medium and high emission scenarios to simulate the likely impact of climate change on groundwater resources. The increased rainfall for the SSP2-4.5 and SSP5-8.5 scenarios result in increased recharge in comparison to the low flow scenario. The resulting increase in water levels decreases flows from the river to the aquifer by18% and 20% for the SSP2-4.5 and SSP5-8.5 scenarios and correspondingly results in higher outflows from the aquifer to the river. The river now acts as a gaining stream with net flows from the aquifer to the river of 87.2 MCM, compared to a losing stream for the reduced flow scenario of 94.8 MCM.

The climate change scenarios indicate a substantial increase in boundary inflows from the sea due to the rising sea levels between 2010 and 2100. The resulting net inflows from the sea boundary are 158.3 MCM for the SSP2-4.5 scenario and 188.4 MCM for the SSP5-8.5 scenario, compared to 43.6 MCM for the Baseline scenario. It appears that climate change will significantly impact agriculture and livelihoods in the coastal zone, even under the medium emissions scenario. The simulated increase in net inflows from the sea boundary is expected to continue to increase post-2100 as sea levels continue rising. Under the potential effect of the low-likelihood, high-impact ice sheet processes, sea level rise could be as much as 1.22m for SSP2-4.5 and 1.86m for the SSP5-8.5 scenarios, with resulting net inflows and coastal inundation expected to be even greater. Under these conditions, the adaptation options being investigated may not be adequate, which will compel the Government of Sindh to rethink new strategies which may include engineered sea barriers and injection wells to act as barriers amongst other adaptation strategies.

Adaptation strategies for the SSP5-8.5 scenario: Coastal areas of Sindh are expected to experience a significant rise in sea levels. We selected the SSP5-8.5 scenario to simulate a range of adaptation strategies, including changing cropping patterns in areas with high watertables and relatively high groundwater salinities. We also simulated nature-based solutions by demarcating zones to act as primary (mangroves), secondary (saltbush) and tertiary (native trees) green barriers. The water balance for SSP5-8.5 low flow scenario with adaptation options in the Pinyari CCA shows a significant decrease in recharge from 1,927.3 MCM/yr without adaptation to 1,787.4 MCM/yr with adaptation, which will reduce the risk of waterlogging and salinity in zones 5, 6 and 7 within the Pinyari CCA. The net increase in river inflows from -117.1without adaptation to -8 MCM/yr with adaptation indicates increased freshwater flows from the Indus recharging the aquifer and shows that implementing the proposed adaptation options will increase inflows from the river to the aquifer and decrease outflows from the aquifer to the river which. will be beneficial for creating a freshwater lens along the banks of the Indus. The green barriers do not significantly alter inflows from the sea boundary as sea levels rise to 0.71m under the medium confidence level scenario. However, once these green barriers are established, the mangroves will provide a primary barrier to coastal erosion. The secondary and tertiary barriers consisting of saltbush and native trees will provide added protection to the southern areas of the Pinyari CCA. Mitigating the adverse impacts of sea level rise will require a rethink of additional adaptation strategies, which will need institutional support and financing to protect lands and communities along Sindh's coastline.

9.2. Recommendations

Improve data collection and monitoring: The exploitation of freshwater lenses will require prudent management to ensure the salinity of these lenses remains within a usable range. Overexploitation will increase salinity due to lateral intrusion from saline areas surrounding these freshwater lenses, and the risk of upconing from deeper saline groundwater. This will require the Sindh Irrigation Department (SID) to implement a robust monitoring strategy encompassing marginal quality zones in Sindh and develop guidelines in conjunction with communities on strategies for the long-term use of these lenses. A robust monitoring approach would allow informed decisions for improving sustainable groundwater management. SID will require dedicated funding to establish a monitoring network with an initial focus on the freshwater areas and extending to areas with shallow watertables and the coastal areas of Sindh.

The design of the monitoring network is essential rather than a random approach (ee, for example, the network design approach by Ahmed et al. (2020), which was undertaken for two irrigation divisions, Dad and Moro in the Northern Rohri canal command). Monitoring can be improved by instrumenting key monitoring sites with loggers to provide information on daily and weekly trends, which would also allow for an improved understanding of groundwater dynamics in the coastal areas of Sindh.

Monitoring in the coastal zone of Sindh: The Pinyari CCA is generally underlain by shallow marginal quality lenses. There may be isolated shallow lenses that are relatively fresh and may be suitable for livestock and some domestic uses. Mapping these lenses along with intensive knowledge sharing with communities on best practices in exploiting these marginal quality lenses will provide opportunities for salt tolerant vegetables and livestock rearing and help improve livelihood outcomes. The coastal zone has already lost about 2.95 million acres (1.194 hectares) due to seawater intrusion and inundation (Khaskheli et al., 2018). Additionally, Siyal (2018) indicated that approximately 80 acres (32.4 hectares) of delta land is being lost daily due to seawater intrusion. This is huge loss of land which could have provided livelihoods for coastal communities struggling to find alternate livelihood opportunities. A specialised monitoring program is required to improve our understanding of the impacts on the unique coastal ecosystems in Sindh. These areas will require sentinel bores for early warning of sea level rise and to develop strategies for protecting coastal ecosystems and make these systems productive.

Rethinking resource management in the coastal zone: High watertables and salinity in the Indus Delta and rising sea levels have already displaced many coastal communities, forcing them to move further inland as the sea reclaims the land. Over the decades, continued irrigation from the canal supply network and annual monsoon rains have created isolated shallow lenses that are relatively fresh and may be suitable for livestock and some domestic uses and for small-scale agricultural activities at the household level. Mapping these lenses and assisting farmers to adopt skimming wells may provide supplementary water when surface water supplies are reduced or unavailable. However, adopting skimming wells will require financial assistance and significant knowledge transfer to participating farmers. Climate financing will be required to allow stakeholders, including groundwater users, the opportunity to adopt new technologies and improve how groundwater is used and managed for the coastal regions in Sindh.

The coastal zone contributes to the marine ecosystem, including shrimps and fisheries, as well as providing livelihood opportunities for coastal communities. The loss of agricultural lands and livelihoods in the coastal districts of Thatta, Sujawal and Badin is a cause for significant concern. Adaptation measures such as the series of green barriers proposed in this study, including planting trees, saltbush and other salt tolerant plants in the coastal belt, are needed to make this ecosystem productive and healthy and maintain biodiversity. Although politically challenging, an important consideration for the Government of Sindh is legislating minimum flow requirements in the Indus River downstream of the Kotri Barrage for ecosystem maintenance and to prevent accelerated degradation of the delta and minimise the impacts of sea level rise.

Rethinking adaptation strategies in the coastal zone: Several options exist for controlling waterlogging in the Pinyari CCA. With a good network of drains, one possible option could be using solar-powered tubewells to pump deeper saline groundwater for disposal into the drainage network, which is transported via a tidal link to the sea. A word of caution: this option may work only for a few decades until rising sea levels impact the drainage system. Our suggested options will play an important role in mitigating waterlogging and salinity intrusion risks in the medium to long term, but these alone will not mitigate the overarching risk posed by rising sea levels and climate change. The adverse impacts from sea level rise will need additional adaptation strategies that will need to address politically sensitive issues, such as the additional allocation of freshwater to the Indus River for release below the Kotri Barrage, and physical barriers such as dikes or polders, drainage of shallow saline groundwater and extensive land reclamation.

Farmers will need to adopt alternative strategies that allow for the diversification of livelihoods. Suitable adaptation strategies are also required to allow farming communities to “live with salinity”. Adaptation strategies and financing to mitigate these impacts will become increasingly important as climate change intensifies. Agriculture in Sujawal comprises smallholder farmers and impacts on agricultural productivity will significantly impact livelihoods, likely resulting in out-migration to cities for employment opportunities. In many of the coastal areas of Sindh, educational opportunities are limited, which would suggest that youth are most at risk due to a lower skill base. Policy experts in agriculture, irrigation and rural development will be required to develop an integrated solution for coastal agricultural communities.

Institutional capacity: A recent study of the Lower Indus Basin indicates groundwater extractions in Sindh have increased from 1.6 BCM to 19 BCM (Salam et al., 2023). This is concerning as there is a shortage of information about Sindh’s groundwater and the lack of technical capacity in SID is a significant barrier to better groundwater management. Although the institutional capacity to manage Sindh’s groundwater resources has not been developed, it is recognised in the Sindh Water Policy that groundwater resources need to be monitored and managed as they are vital for food production and farming livelihoods. From an institutional perspective, SID is planning to create an internal division devoted to groundwater mapping, modelling, and management. Continuous monitoring loggers that provide SID with updates can be used for monitoring, which will allow accurate spatial and temporal assessment of the condition of the aquifer.

Although this project has trained more than 20 SID engineers, MUET students and engineers from the SMO in groundwater monitoring and modelling, marking the initial steps towards capacity building, it is crucial to build on this initial investment for the sustainability of Sindh's groundwater resources and to support the Sindh Water Policy. Close cooperation and working on groundwater studies with various stakeholders indicates a definite need to continue improving the capacity of stakeholders, the farming community and groundwater users in improved groundwater management practices. This will enhance the professional capacity of SID, SIDA and the Sindh Agricultural Department to monitor, map, model and manage groundwater resources and the impact of waterlogging and salinity.

Knowledge networks for co-developing strategies with groundwater users: Co-developing a shared understanding for managing the depletion of freshwater lenses, managing waterlogging and salinity, using marginal groundwater resources, and conjunctive use strategies will be a cornerstone for achieving sustainability for various groundwater uses. Knowledge transfer to communities increasingly relying on groundwater for irrigation is required to allow sufficient time to adapt to the changing conditions brought on by shortfalls in surface water supplies, climate change and the need to adjust crop selection for the Lower Indus Basin and the coastal zone of Sindh.

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