Groundwater Policy Brief for Southern Sindh and the Coastal Zone

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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.[1] Agriculture in Pakistan has historically relied on its extensive canal network, which was designed for a cropping intensity of 67%. Surface water irrigation continues to play a crucial part in agricultural production; however, in Baluchistan, Punjab, and the freshwater regions of Sindh, the proportion of groundwater irrigation has grown dramatically in recent years. Access to groundwater has allowed farmers in the Indus Basin to increase cropping intensities to 120% and even more in some areas.[2] However, the quantum of fresh groundwater availability is not uniform across the basin. Farmers in Punjab can access thick freshwater lenses from accumulated seepage from canals, return flows, and rainfall. Farmers in Sindh must contend with thin freshwater lenses that overlie native saline groundwater, and, in many areas of lower Sindh, waterlogging and salinity are widespread.

Sindh is a lower riparian. Its flat topography, proximity to the coast, and shallow watertables makes these areas vulnerable to waterlogging and salinity. Shallow watertables, which result in waterlogging with 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 Canal

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[1] Young, W.J., Anwar, A., Bhatti, T., Borgomeo, E., Davies, S., Garthwaite III, W.R., . . . Saeed, B. (2019). *Pakistan: Getting more from water.* Washington DC: World Bank.

[2] Lytton, L., Ali, A., Garthwaite, B., Punthakey, J.F., & Basharat, S. (2021). *Groundwater in Pakistan's Indus Basin: Present and Future Prospects.* Wahington DC: World Bank.

Command Area (CCA) and the coastal zone south of the Pinyari CCA comprising the Indus Delta are particularly susceptible to waterlogging and salinity. These risks are compounded by rising sea levels and the subsequent ingress of seawater into coastal lands. In southern Sindh and its coastal zone, the underlying groundwater is marginal to brackish and is generally not used for irrigation. In these areas, there is an overwhelming preference for canal water for irrigation. The little groundwater use that occurs is limited to domestic and livestock needs from shallow hand pumps or tubewells at the village level. The challenge in these areas is to maintain productive agricultural enterprises by limiting the spread of waterlogging and salinity and making the best use of the limited fresh to marginal groundwater resources. With the impacts of climate change already affecting Pakistan, we can expect increased stresses on the availability of surface and groundwater for agriculture. Sea level rise driven by climate change poses a significant threat to the coastal zone, where encroachment from salinity intrusion has resulted in the loss of coastal lands and forced displacement of coastal communities, which is a significant concern for policymakers.

A key barrier to improved groundwater management is the need to build the technical capacity of institutions. Needs include improving monitoring systems, archiving and accessibility to groundwater data, modelling groundwater systems to understand the water budget and likely impacts of climate change, and groundwater planning and management. An in-depth understanding of the aquifer system is needed, along with community buy-in, to develop strategies on how best to manage groundwater depletion and, more importantly, the strategies required to adapt irrigation practices to the looming threat of climate change.

What has changed: Irrigated agriculture has played an important role in enhancing Pakistan's food security and economic sustainability. Surface water irrigation remained pivotal in agricultural production, but in recent decades, farmers in Sindh have increasingly been accessing groundwater to supplement shortfalls in surface water supplies. Much of Sindh is underlain by marginal to brackish groundwater, but seepage from the Indus River and from major canals such as the Rohri Canal has created pockets of freshwater lenses that allow farmers to access limited groundwater supplies. In these areas, the use of tubewells for irrigation has increased dramatically. Salinity and waterlogging are widespread in Sindh due to shallow watertables and high evapotranspiration rates, which increases salt transport into the crop root zone. The increased use of marginal quality groundwater for irrigation also contributes to salinity accumulation in the crop root zone.

In the coastal districts of Sindh, shallow groundwater and associated waterlogging and salinity impacts on soils and cropping systems are of particular concern for farmers. Nowhere are the impacts of salinity felt more than in large parts of southern Sindh where canal water supplies are non-perennial, available only during the kharif season. The sole reliance on canal water has far-reaching consequences for farming communities, increasing the vulnerability of smallholder farmers. Salinity intrusion is also prevalent in coastal Sindh due to 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 affecting coastal villages, with some settlements being abandoned.[3,4]

In Sindh, the monitoring, mapping, and modelling of groundwater resource use has largely been ignored other than some early studies in the 1960s and a recent study on improving groundwater management for the Lower Indus Basin.[5] The network of bores with biannual monitoring of depth to groundwater and EC measurements used in this study has been undertaken by the SCARP Monitoring Organisation (SMO). There are, however,

[3] Siyal, A.A. (2018). *Climate change: Assessing impact of seawater intrusion on soil, water and environment on Indus delta using GIS and remote sensing tools.* Jamshoro, Pakistan: US—Pakistan Center for Advanced Studies in Water (USPCAS-W), MUET.

[4] Kalhoro, N. A., He, Z., Xu, D., Faiz, M., Yafei, L. V., Sohoo, N., & Bhutto, A. H. (2016). Vulnerability of the Indus River Delta of the North Arabian Sea, Pakistan. *Global Nest Journal, 18*(3), 599–610. https://doi.org/10.30955/gnj.001912

[5] Ahmed, W., Ahmed, S., Punthakey, J.F., Dars, G.H., Ejaz, M.S., Qureshi, A.L., & Mitchell, M. (2024). Statistical Analysis of Climate Trends and Impacts on Groundwater Sustainability in the Lower Indus Basin. *Sustainability, 16,* 441. https://doi.org/10.3390/su16010441

significant data gaps and many monitoring bores have been abandoned or are not monitored due to funding constraints. The Sindh Irrigation Department (SID) does not have a monitoring network in place, and significant institutional capacity constraints need to be addressed to implement the directives in the Sindh Water Policy. What is needed then is not a simple *one-size-fits-all solution or policy.* What is needed is a paradigm shift in how we monitor and manage groundwater levels and quality, where management approaches are varied to suit specific situations, demand for groundwater, and with adaptation options developed together with affected water users and communities. Adaptive and flexible groundwater management in an era of climate change with a strong focus on community awareness and consultation will be key aspects for managing groundwater quantity and quality for a sustainable future. It was on this premise and understanding that the ASSIB project was designed.

The ASSIB project: The *Adapting to Salinity in the Southern Indus Basin (ASSIB)* project *(LWR/2017/027),* led by Charles Sturt University together with national and international partners, aims to develop and investigate adaptation options and strategies with people living in salinity-affected agricultural landscapes in the southern Indus Basin. The project is multidisciplinary and incorporates a strong social research component working closely with affected communities, together with remote sensing and groundwater modelling. The two study areas include the Southern Bari doab in South Punjab and the coastal district of Sujawal in Sindh. Groundwater declines and emerging water quality issues are widespread in Southern Punjab, whereas in Sujawal, shallow watertables, high salinities, and seawater intrusion in the Indus Delta regions are significant issues affecting coastal communities.

In this study, a groundwater model of the southern coastal district of Sujawal was developed to simulate scenarios and allow an understanding of how climate change and sea level rise will impact waterlogging and salinity. The groundwater model covered the districts of Sujawal and parts of Hyderabad and Tando Muhammad Khan (Figure 1). 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), which drains saline water into the Arabian Sea. The model area encompassed the Pinyari Canal Command Area (CCA), covering 4,441 km^2 and the coastal belt south of Pinyari CCA, with an area of 5,416 km^2.

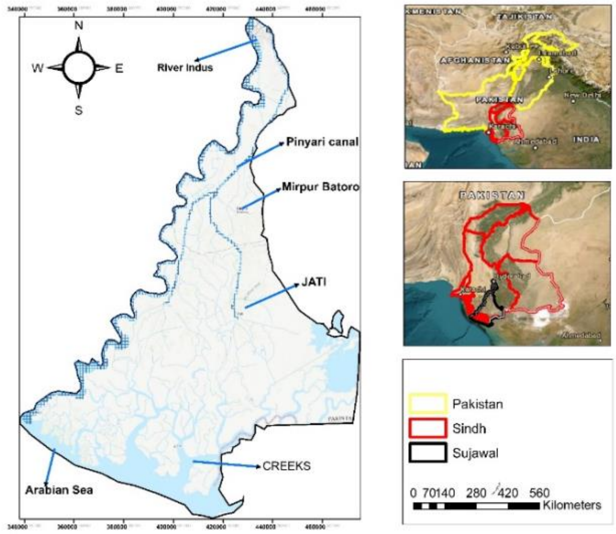

Figure 1. Sujawal district and coastal zone

We undertook scenarios under reduced surface flow conditions and SSP2-4.5 and SSP5-8.5 scenarios. Additionally, we simulated adaptation strategies which will be useful for policymakers to consider. Understanding the behaviour of the aquifer to system stresses will allow institutional actors to develop strategies for improving the management and governance of groundwater resources for coastal Sindh.

Groundwater model development: The groundwater model was developed in consultation with SID for Pinyari CCA and the Indus Delta in Sindh. Irrigated agriculture comprising mostly rice and sugarcane, and small amounts of sunflower, mustard, and vegetables are grown in the kharif when canal water supplies are available. In the winter rabi season, rainfed wheat and winter forage are grown but dependence on limited rainfall results in variable and low production. The model development consisted of a three-layered aquifer system extending up to the coastline along the Arabian Sea. The conceptual model of Sujawal district and the coastal zone is shown in Figure 2.

The Indus River flows into the Arabian Sea, forming one of the largest river deltas in the world, characterised by mudflats, estuaries, and an extensive network of creeks. It has extensive mangrove forests and is home to a variety of fish species, including the huge snakehead (*Channa marulius*), Indus Baril (*Barilius modestus*), Indus Garua (*Clupisoma naziri*), and Rita catfish (*Rita rita*).

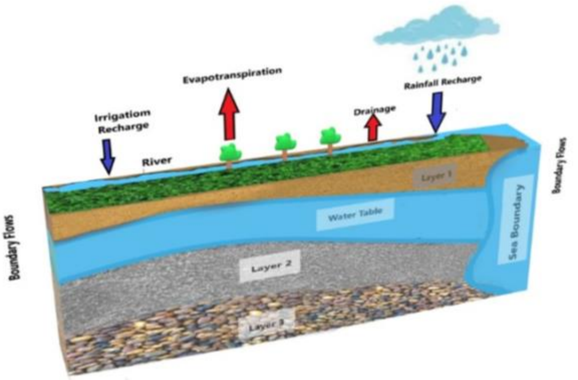

Figure 2. Conceptual model for Sujawal district and coastal zone.

It is also a significant location for migratory water birds, ensuring the importance of preserving the region's ecosystems. The extensive mangroves in the coastal zone provide essential nutrients for fish and crustaceans and stabilise the coastal area from erosion and tidal incursions. Many subsistence communities along Sindh's extensive coastline rely on mangroves for various goods like fuelwood, shellfish, and palms.

Mangroves also provide essential ecosystem services by maintaining the productivity of estuarine-dependent fisheries, regulating water quality, reducing flooding, and maintaining shoreline stability (Figure 3).[6]

Figure 3. Mangroves in the coastal areas of Thatta, Sindh.
Photo courtesy Ms Ifrah N Malik

However, a lack of freshwater supply in the Indus Delta has impacted this region, resulting in increased salinity and waterlogging, and inundation in the coastal zone. Seawater intrusion and coastal erosion have resulted from a sudden reduction in 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.[7] In this study, we simulated the impacts of climate change to improve our understanding of the likely impacts of waterlogging and salinity in the Pinyari CCA and rising sea levels in the coastal belt of Sujawal.

Groundwater modelling outcomes: An analysis of the water balance from the groundwater model indicated the average annual river and canal seepage over the ten years from 2010 to 2020 was 720.4 MCM/year, while recharge from rainfall and field application losses of canal supplies was 2,246.3 MCM/year. Inflows along the coastal boundary of 316.7 MCM/year indicate the coastal zone is at risk of seawater intrusion, particularly during the dry season when rainfall and river flows are very low. Outflows to the Indus River along the western model boundary are 610.7 MCM/year, and net flows are 109.7 MCM/year, indicating this section of the river is highly connected to the aquifer. The net annual gain in aquifer storage during this period is 87.6 MCM/year, indicating that it has contributed to high watertables in Sujawal over time. The major outflow from the aquifer is evapotranspiration at 2,199.8 MCM/year due to high summer temperatures and shallow watertables underlying 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 salinity onto the surface (Figure 4).

Crucially, the water balance also points to the fact that in zones where water levels are shallow, and groundwater salinities are high, SID will need to reduce seepage from the canal supply system to reduce waterlogging and associated salinity impacts. The water balance does not tell us what the impact on waterlogging and salinity will be in the next 50 years or the unintended consequences of global warming, which is resulting in climate

[6] Acharya, G. (2002). Life at the margins: The social, economic and ecological importance of mangroves. *Madera y Bosques, 8*, 53–60.

[7] Kanwal, S., Ding, X., Sajjad, M., & Abbas, S. (2020). Three decades of coastal changes in Sindh, Pakistan (1989–2018): A geospatial assessment. *Remote Sensing, 12*(1), 8.

change and already changing the functioning of natural ecosystems, including groundwater.[8] Pakistan is especially susceptible and ranks seventh in the Global Climate Risk Index of countries most affected by climate change.[9] To learn about possible future outcomes, we undertook a series of scenarios to quantify the state of the aquifer in response to pumping and climate stress.

Figure 4. Surface salinity from shallow groundwater in Jongo Jalbani village, Shah Bandar taluka, Sujawal, Sindh.
Photo courtesy Dr Abdul Latif Qureshi

Model scenarios: We undertook two sets of scenarios to understand the long-term effects of reduced flows in the Pinyari CCA and climate change on the aquifer. The Baseline (*BL*) and Reduced Flow scenarios (*RF*) were run from 2010 to 2060, while the climate change scenarios were simulated from 2010 to 2100.

The *BL* scenario simulates similar levels of rainfall and canal flows from 2010 to 2020, while the *RF* scenario simulates the response to the five years with the lowest stream flow and record drought, which occurred from 2008 to 2012. Reductions in surface water flows also impact the availability of canal water for irrigation. The canal flows were segregated into three zones corresponding to Main Pinyari, Daro Branch, and Pinyari Branch and the return flows were estimated based on reduced canal water availability. Comparisons of these two scenarios showed us the decline in surface water flows available for irrigation, which 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 to the *BL* scenario and a decrease in the drain outflow of 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.

Water security in Pakistan's future 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. The reduction in surface flows will be a key driver in transforming cropping patterns to less water-intensive crops. Due to high summer temperatures in Sujawal and a shallow groundwater table, a reduction in evapotranspiration rates, which allows salinity to manifest itself on the soil surface, can be reduced, which can improve agricultural production in areas prone to salinity and waterlogging. There are also additional benefits to reducing waterlogging, such as reduced flooding, as a small increase in the depth to water will allow greater infiltration of monsoon rains, which would normally result in inundation and the loss of cropping land.

For the reduced flow scenario, there are significant inflows of 273.3 MCM /year from the sea boundary into the top layer of the modelled groundwater system, indicating that areas adjacent to the sea and tidal rivers are at risk of waterlogging and salinity. To preserve Pakistan's coastline in the future, new strategies will be required to manage salinity and inundation as well as the loss of biodiversity in the coastal zone south of the Pinyari CCA. This will require a rethink of how coastal ecosystems can be protected and made productive.

Climate change impacts: The projected rainfall and evapotranspiration for the SSP2-4.5 and SSP5-8.5 scenarios[10], with reduced flows in Pinyari CCA were used to simulate groundwater conditions to 2100.

[8] Ahmed, W., Ahmed, S., Punthakey, J.F., Dars, G.H., Ejaz, M.S., Qureshi, A.L., & Mitchell, M. (2024). Statistical Analysis of Climate Trends and Impacts on Groundwater Sustainability in the Lower Indus Basin. *Sustainability, 16*, 441. https://doi.org/10.3390/su16010441

[9] Eckstein, D., Hutfils, M.-L., & Winges, M. (2018). *Global Climate Risk Index 2019. Who Suffers Most from Extreme Weather Events?* Bonn, Germany: Germanwatch Briefing Paper.

[10] SSP2-4.5 (intermediate greenhouse gases emission) and SSP5-8.5 (very high greenhouse gases emission).

The modelled layer water balance for 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 that gradients will be reversed 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, resulting in upward mobilisation of salinity from the deeper layers where salinities are generally higher. The mobilisation of salts from the deeper layers to the top layer will likely exacerbate waterlogging and impact agricultural productivity in the region.

The SSP5-8.5 scenario indicates a marginal increase in rainfall recharge and a similar marginal increase in evapotranspiration compared to the SSP2-4.5 scenario. The significant difference occurs in boundary inflows from the sea due to the rising sea levels between 2010 and 2100, resulting in significantly greater net inflows of 188.4 MCM for the SSP5-8.5 scenario compared to 42.6 MCM for the Baseline scenario. The simulated increase in net inflows from the sea boundary are expected to continue to increase post-2100 as sea levels continue rising to 1.86 m 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.

Mapping freshwater lenses: Waterlogging and salinity are ubiquitous in the coastal areas of Sindh. The depth to water and EC maps in Figure 5 shows that within ten years there have been significant changes in the spatial distribution of salinity with expansion of EC in the marginal range. The EC maps also show there are isolated shallow lenses along the Indus River that are relatively fresh and may be suitable for livestock and some domestic uses and small-scale agricultural activities at the household level. These lenses are particularly prominent along the Indus River. 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 not available. 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. This relies on the transmissive nature of the aquifer and rainfall and seepage from irrigation return flows. This is likely unsustainable as salinity will increase over the long term.

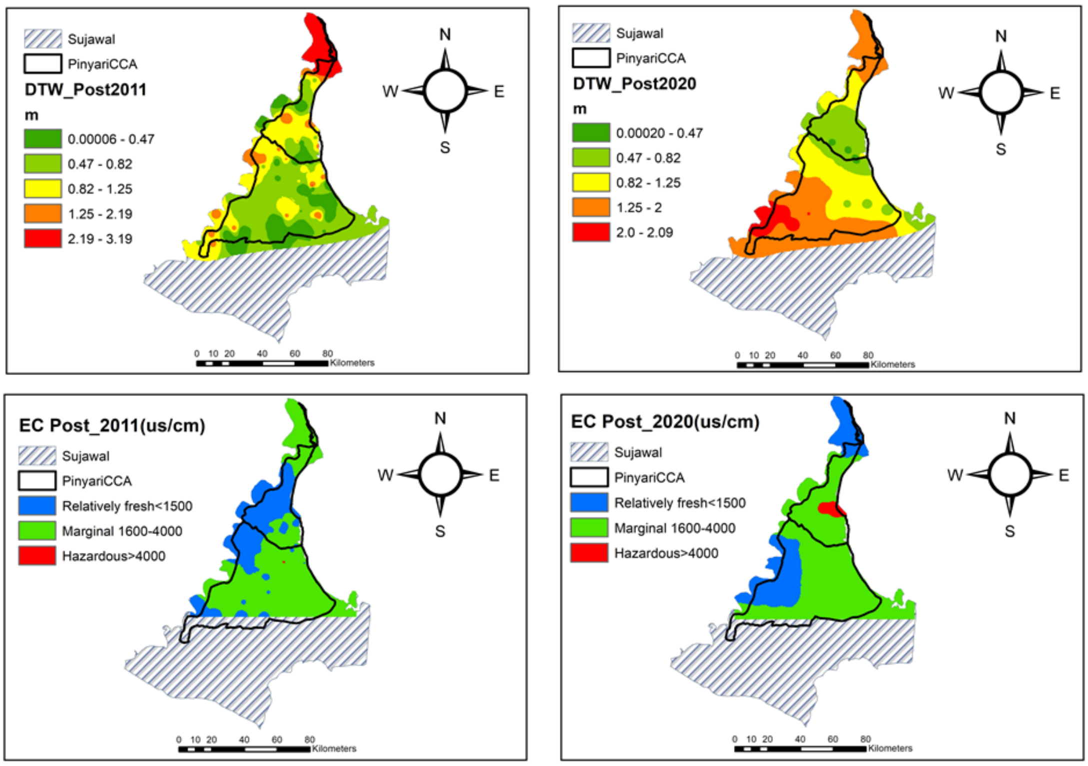

Figure 5. Spatiotemporal variation in depth to water and EC for Pre2011 and Pre2020

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 concentration of seawater. 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 coastal areas.[11]

Understanding the salt balance: Waterlogging and salinity are major concerns for farming communities in Pinyari CCA and for coastal communities that depend on the coastal zone for eking out subsistence livelihoods, including small-scale aquaculture. The SSP5-8.5 indicates a reversal of gradients will occur under these climatic conditions with net upward flows of 22.2 MCM from Layer 2 to Layer 1 of the aquifer, with a similar net upward flow from Layer 3 to Layer 2 of 8.7 MCM. The average groundwater salinity in the deeper aquifers in the coastal district of Sujawal was estimated to be 28,000 µS/cm (about half of the salinity of seawater), which would result in upward mobilisation of 0.56 million tons of salinity to the upper layers from the deeper layers where salinities are generally higher. Under the medium emission SSP2-4.5 scenario, the upward mobilisation of saline groundwater from the deeper layers would transport about 0.07 million tons of salt.

Net inflows from constant head boundaries will be an additional source of salt influx into the coastal zone. For the climate change scenarios, the net influx of salts along the coast will be 5.7 million tons for the SSP2-4.5 and 6.8 million tons for the SPP5-8.5 scenarios. This will require the SID to undertake adaptation strategies, including potential consideration of physical barriers, such as dikes or polders for additional protection of coastal lands as the relentless rise in sea levels continues.

There are additional options for controlling waterlogging in Sujawal. 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 via a tidal link to the sea. This will decrease water levels and allow freshwater lenses to develop. A word of caution though: this option may work only for a few decades until rising sea levels will impact the drainage system.

Agriculture in Sujawal comprises smallholder farmers and impacts on agricultural productivity will significantly impact livelihoods, which will likely result in out-migration to cities in search of employment opportunities. In many of the coastal areas of Sindh, educational opportunities are limited, suggesting youth are most at risk from declining opportunities due to a low skills base. Policy experts in agriculture, irrigation and rural development will be required to develop an integrated solution for coastal agricultural communities. *These climate scenarios tell us that under climate change, agricultural systems in coastal Sindh may not be sustainable, resulting in significant mobilisation of salinity from the deeper aquifer layers and from the influx of seawater intrusion along the coast.* These changes will be particularly concerning for smallholder farmers with restricted access to groundwater for irrigation.

Can adaptation options help communities achieve a sustainable future? We designed a scenario to investigate which combination of adaptation options could help farming communities move towards a sustainable future. To manage widespread shallow watertables and reduce salinity impacts on agricultural land, we designed a mix of adaptation options, including 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.

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[11] Lytton, L., Ali, A., Garthwaite, B., Punthakey, J.F., & Basharat, S. (2021). *Groundwater in Pakistan's Indus Basin: Present and future prospects.* Washington DC: World Bank.

Change to water-efficient cropping systems: The adaptation strategies adopted for simulating outcomes for the high emission climate change scenario SSP5-8.5 included replacing 25% of the rice crop with sunflower and 25% of the sugarcane crop with mustard as water-efficient crops. To determine suitable areas for replacing rice and sugarcane, we mapped the rice and sugar crops for Pinyari CCA and the depth to water and EC for Pinyari CCA to delineate areas where the depth to watertable was less than 1.5 m (high risk of waterlogging) and where the EC was in the marginal to brackish range. 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 6). The average depth to water in post-monsoon 2020 was 0.82, 1.14, and 0.84 m in zones 5, 6 and 7, respectively.

Green barriers as a nature-based solution: Seawater intrusion from rising sea levels and high tides typically experienced during the monsoon season and storm surges result in land loss 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 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. 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, which would be suitable for planting native trees, including fruit trees and medicinal trees which could provide economic returns for coastal communities (Figure 7). Examples of native salt-tolerant species include Babbur (*Acacia nilotica*), which occurs in thick forests along the Indus banks. Nim (*Azadirachta inidica*), Ber (*Ziziphus vulagaris*) or Jujuba, Lai (*Tamarix orientalis*), Kirrir (*Capparis aphyla*) and Kandi (*Prosopis cineraria*) are the more common trees. The establishment of trees 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.

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 (see Figure 7). River Saltbush (*Atriplex Amnicola*) and Old Man Saltbush (*Atriplex nummularia*) are suitable in the coastal zone in Sindh.

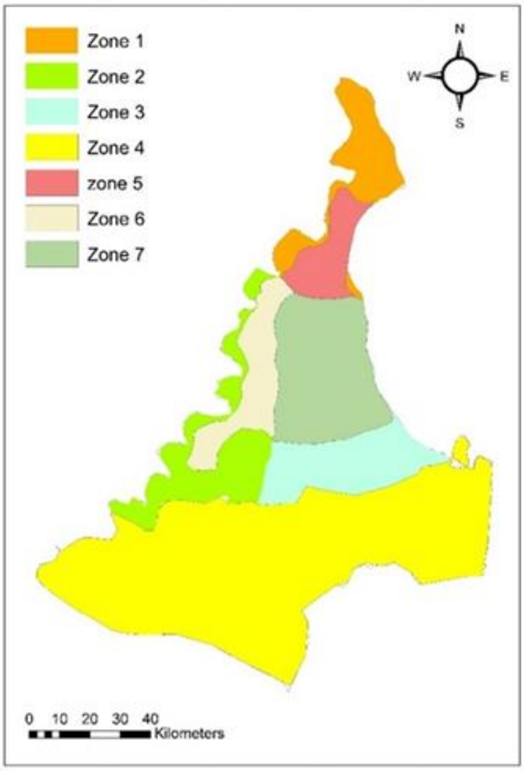

Figure 6. Zones delineation based on variation in depth to watertable

The establishment of seagrasses 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 help improve the ecosystem in the delta areas and 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. Seagrasses act as carbon sponges that trap and store carbon while providing crucial support to various marine life forms and sustaining ecosystem balance. The establishment of 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.

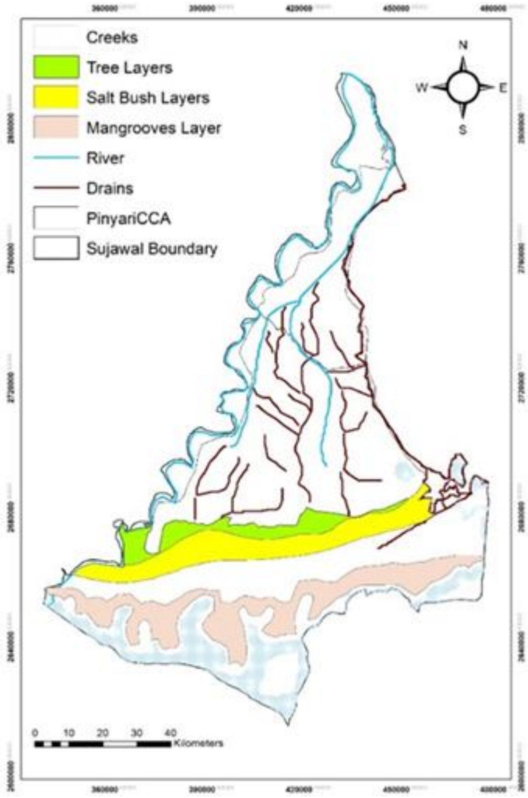

Figure 7. Proposed green barriers in the coastal zone of Sujawal

The mangroves zone was demarcated along the southern creeks to act as a green barrier for coastal erosion and seawater intrusion (Figure 7).

Implementing adaptation options for the SSP5-8.5 climate change scenario: The water balance for the SSP5-8.5 scenario with adaptation options for Pinyari CCA shows a significant decrease in recharge from 1927.3 MCM/year (without adaptation) to 1787.4 MCM/year (with adaptation), thus reducing the risk of waterlogging and salinity in zones 5, 6, and 7 within Pinyari CCA. The increase in river inflows from 495.1 without adaptation to 569.1 MCM/year 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 will result in increased river inflows, which will be beneficial for creating a freshwater lens along the banks of the Indus. Analysis of evapotranspiration for the tertiary barrier (tree zone) was 166 MCM/year, for the secondary barrier (saltbush zone) 89 MCM/year, and for the primary barrier (mangroves zone) 71 MCM/year. Increased evapotranspiration from these zones will decrease water levels in the secondary and tertiary barrier zones. The establishment of mangroves provides a primary barrier to coastal erosion. The secondary and tertiary barriers provide added protection to the southern areas of Pinyari CCA.

The water balance for the coastal zone showed river inflows were 333 MCM/year for the Pinyari CCA, while river inflows for the coastal zone had reduced to 211 MCM/year. Mitigating seawater intrusion into the Indus Delta will require increased flow releases below the Kotri Barrage. The adaptation options also result in reduced salinity transport from the deeper layers as the reversal of gradients indicates that salt transport will decrease to 0.34 million tons under the SSP5-8.5 scenario with adaptation compared to 0.56 million tons under the SSP8.5 scenario without adaptation. 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, including addressing 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. In the end, what we do to preserve the ecosystem of the Indus Delta will depend on the value society places on the productive functioning of biodiversity of the unique ecosystems of the Indus Delta.

Water policy: Partly in recognition of Pakistan's accelerating water crises, the Ministry for Water Resources (MoWR) published the National Water Policy (NWP) document in April 2018. The Council of Common Interests also endorsed the policy. It provides a broad policy focus for groundwater resource management. The policy focus on groundwater recognises that the vast Indus Basin aquifer is an important national resource that merits protection from pollution and unsustainable abstractions. The NWP emphasises strengthening monitoring systems to determine sustainable groundwater potential, prepare groundwater budgets for sub-basins and canal commands, and prevent the lateral/vertical movement of the saline water interface into freshwater zones. The policy specifies that *groundwater abstraction is to be managed sustainably to balance recharge and boundary flows and the need to regulate pumping*. The policy also prioritises investment in groundwater recharge schemes. The policy objectives broadly call for improving groundwater management in Pakistan by the strengthening and capacity building of water sector institutions; upgrading water sector information systems for evidence-based decision-making; improved asset management; and restoring and maintaining the health of the environment and water-related ecosystems.

In 2023, the Government of Sindh promulgated the Sindh Water Policy (SWP), 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. The Sindh Water Policy guides sustainable groundwater management, highlighting the importance of groundwater resources in Sindh and stressing the need to manage groundwater abstraction from freshwater lenses for agricultural production to reduce soil salinisation.

From a policy perspective, there is a renewed focus on protecting aquifers from overexploitation and consequent pollution. The objective of the NWP is to provide a framework and set of principles on which provincial governments can prepare and implement water conservation, development, and management efforts. Both the NWP and the SWP emphasise establishing monitoring networks, setting sustainable groundwater yields, and avoiding the vertical movement of saline water. The SWP also has a renewed focus on groundwater pollution and water quality impacts on human health.

Policy guidance: The key areas for improving resource management include monitoring, mapping, modelling, and management. This needs a supportive institutional structure with adequate capacity in groundwater resource management.

Monitoring strategy: Given the backdrop of the NWP and PWP from a policy perspective, resource monitoring is a crucial function of the irrigation department. The design of monitoring systems and their instrumentation with loggers to measure water levels, temperature, and EC, will provide reliable data for resource managers to allow informed decisions on managing the resource. Monitoring also needs to be strategic, targeting areas where groundwater levels are declining. It is also important to understand the risks posed by increasing salinity and declining water quality. The network of bores with biannual monitoring of depth to groundwater and EC measurements in Sindh, which is used in this study, was developed by the SMO. There are, however, significant data gaps, and many monitoring bores have been abandoned or are not monitored due to funding constraints. The 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.[12] 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.

Monitoring of freshwater zones and marginal quality zones is required to understand the impacts of pumping. Monitoring bores drilled to different depths will offer improved insights into future salinity impacts as pumping will likely increase in future years. Adequate spatial and temporal monitoring data are key elements for improving the understanding of groundwater resources and for governments to make informed decisions.

[12] Salam, H.A., Ashraf, M., Iqbal, N., Gul, N., Farooque, M., & Memon, S. (2023). *Exploring groundwater dynamics: A comprehensive investigation and spatial mapping in canal command areas of Sindh.* Islamabad, Pakistan: Pakistan Council of Research in Water Resources.

The investment in establishing the monitoring infrastructure will also require institutional arrangements for regular monitoring and maintenance of assets, including data sources.

Monitoring and managing data: Groundwater data and the monitoring and mapping of water resources in sub-basins need to be based on a well-designed and accessible Water Resources Information System (WRIS). Data structures need to be simple and easy to understand, monitoring bores need a unique identification number linked to each sub-basin, and each production bore or tubewell must have a unique identifier. The integrity of data and quality control are required to ensure duplication and errors in the data are removed. All data needs clear, self-explanatory metadata. Temporal data (canal flows, groundwater level and water quality measurements, etc.) need a separate and accessible database. In other words, the spatial data should be separate from temporal data; and groundwater and other relevant datasets from various organisations should be integrated in the WRIS. It will be critical to have an institutional home in Sindh, such as the Water Resources Directorate, where data can be stored, updated and managed and made available and which will engender ownership of the resource. Managing data sources is a key aspect to ensure that government agencies, researchers and academics have access for providing timely advice to government and improving sustainable use of groundwater.

Modelling the resource: There is often a misconception that once a model has been developed there is no need for additional modelling or upgrading the models. This erroneous thinking leaves the management of the resources in limbo. Models are useful tools, and in most countries where groundwater management has advanced considerably, models are developed and updated every 5 to 7 years to understand how the behaviour of the aquifer has changed with increasing system stresses. Models also allow an estimate of the sustainable yield, giving resource managers insights into sustainable limits for pumping and the consequences of long-term exceedance of sustainable limits.

We recommend that groundwater management strategies be developed at regional scales, drawing on strategies adopted in Australia. Long-term sustainable yields can also be determined for specific groundwater management areas through agreements with water users, which can be revised after 5 to 10 years of application based on a water sharing plan developed with stakeholder agreement. The sustainable yields can also be revised in response to droughts or increased development of groundwater use in the management area, to minimise impacts on smallholder farmers, and allow access to groundwater for potable use and environmental management. Such a process could be developed for designated groundwater management areas in Sindh, which would rely on having revised and improved groundwater models in place. Crucially, SID as the resource manager would need significant capacity enhancement in groundwater planning and management to develop a sound understanding of risks to groundwater from overexploitation and salinity intrusion, climate change impacts on groundwater, and to co-develop strategies to improve groundwater management with affected communities for a sustainable future.

Understanding the water balance: This study has shown that increasing exploitation of groundwater resulting in continuous declining groundwater levels, is also accompanied by increased salt loading in the crop root zone. Thus, both declining groundwater levels and increasing salinity and sodicity are of concern.

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. In Figure 8 below, a sunflower crop is shown in the Pinyari CCA, indicating the potential for productive farming in the coastal districts of Sindh.

Figure 8. Sunflower crop in the Pinyari CCA in Sujawal district.
Photo courtesy Mr Shahryar Jamali

The Water Resources Directorate would need to integrate the management of water in such a way that it provides benefits for irrigation, domestic needs, industries, the environment and coastal protection.

In future years, some regulation of pumping will be required to control pumping from the freshwater lenses in Sindh and to licence and regulate large water users. Individual hotspots in these areas will require enhanced monitoring and enhanced recharge or limits on groundwater exploitation, ongoing review and adaptive management, and steps for safeguarding and improving water quality management. However, a word of caution is warranted. Groundwater management in Sindh faces significant challenges as many smallholder farmers rely on over 100,000 tubewells in Sindh. The estimate of 100,000 tubewells needs updating as recent estimates indicate groundwater extractions in Sindh have increased from 1.6 BCM to 19 BCM.[13] These smallholder farmers underpin the future of water productivity improvements and economic development of the agriculture sector in Sindh, as access to limited fresh groundwater resources has enabled farmers to increase cropping intensities with significant contributions towards food security and livelihood improvements. To develop effective groundwater management plans, the SID must undertake extensive community consultation and have community support to implement management changes. This can only happen through consultation and mutual consent supported by effective knowledge transfer and access to information for groundwater users. Implementing groundwater management plans without a participatory and consensus approach involving groundwater users will not be possible. The SID must avoid going down the path of permission and punishment, which, for all practical purposes, is unlikely to produce desirable outcomes for the sustainability of the aquifer.

The development of models at the sub-regional scale is useful for the SID to improve the planning and management of surface and groundwater resources. These models can be used for conjunctive management planning. The sub-regional models can also form the basis for models at the canal command scale once improvements are made to groundwater monitoring. As the share of surface water decreases and groundwater levels continue to decline, there will be increased pressure on government agencies to find socially and technically acceptable solutions as well as to give due consideration to the environment. Robust models at sub-regional and canal command scales will allow improved management of Sindh's fragile freshwater lenses and, crucially, to evolve strategies for equitable water-sharing plans.

Climate change will impact groundwater: Climate change impacts in Sindh will be particularly detrimental to cropping systems, as high summer temperatures drive up demand for irrigation, and reduced availability of canal water for irrigation, and limited access to groundwater exacerbate uncertainties for future access and use. For coastal Sindh, sea level rise driven by climate change poses an existential threat to coastal communities. In Sindh's coastal districts of Sujawal and Badin, 2.95 million acres (1.194 hectares) have already been lost due to seawater intrusion and inundation.[14]

The need to adapt to preserve our water future: Changes in the groundwater regime take time, and no one solution can manage all aspects of groundwater in Sindh. We took the approach of partially changing the cropping patterns towards less water-intensive crops suitable for the agroclimatic zone of Southern Sindh as a more acceptable option for farmers. However, effecting this change will require establishing trust with communities and knowledge transfer. The simulated adaptation options for the Sujawal included: (i) changing a portion of the high-water using crops such as rice and sugarcane with low delta crops, e.g., sunflower and mustard; and (ii) nature-based solutions using green barriers. Our simulations indicated that despite the inclusion of adaptation options, the risk of waterlogging and salinity will be reduced marginally in the Pinyari CCA, and in the coastal zone, the risk from rising sea levels will pose an existential threat to coastal communities. The green barriers will help in the

[13] Salam, H.A., Ashraf, M., Iqbal, N., Gul, N., Farooque, M., & Memon, S. (2023). *Exploring groundwater dynamics: A comprehensive investigation and spatial mapping in canal command areas of Sindh.* Islamabad, Pakistan: Pakistan Council of Research in Water Resources.

[14] Khaskheli, N., Kalhoro, N.A., Wang, J., He, Z., Xu, D., Tunio, G.R., & Hussain, F.S. (2018). Impacts of tidal link drain, along the coastal areas of districts Badin and Sujawal in Indus deltaic region, Sindh Pakistan. *MAUSAM, 69*(4), 535–542.

medium term, but as sea levels continue to rise new strategies, including engineering options such as barrier dikes, vertical drainage, and the politically difficult task of increasing flows in the Indus River to reduce the impacts of sea level rise will be required. The SID will need to develop a coastal management strategy to mitigate these risks and enable a sustainable future for coastal communities.

Introducing water-saving technologies among progressive farmers needs to be encouraged and for this the SID needs dedicated staff with up-to-date knowledge of modern water-saving technologies. Adaptation options suited to 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 projects, which integrate remote sensing of crops, soils and crop water requirements with a land capability framework.[15]

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 MAR schemes, particularly in areas with relatively deep watertables. Mapping groundwater resources is essential to manage freshwater zones and devise strategies for the conjunctive use of canals and marginal groundwater to benefit farmers in Sindh.

Gender and diversity: The policy to increase women's participation in the workforce is strongly advocated in Pakistan's Vision 2030 document. Allowing entry points for women to a wider range of disciplines, including specialists in remote sensing, hydrogeology, geology, groundwater modelling, groundwater quality, environmental and socio-ecological specialists, and policy experts with improved gender balance will be crucial to the success of groundwater planning and management in Sindh.

Systemic co-inquiry: The Sindh level groundwater management planning process, where the institution is the main focus, involves over 5.8 million ha of irrigated agricultural land and over 100,000 tubewells. It would not be possible to implement groundwater management plans focusing solely on regulating groundwater extractions without a participatory and consensus approach with groundwater users, principally farming communities, to co-design improved cropping, land, and water management practices. A systemic co-inquiry is a facilitated process (*in this case, it should be facilitated by social researchers within or for the SID*) allowing people with differing experiences, backgrounds and perspectives to have their voices heard for a given situation of concern (*in this case it may be waterlogging and increased salinity mobilisation in the cropping zone, or depletion of freshwater lenses and groundwater quality deterioration*). The co-inquiry process is designed to enable the emergence of ideas and opportunities to improve the situation and to co-develop an inclusive (*though still partial*) view of the current situation, and what can be done to change the situation to a better or more sustainable state. An additional, often integral component for groundwater management and achieving consensus is the selection of a suitable planning period during which changed practices can be implemented. To improve the sustainability of the aquifer, the SID will need significant capacity development in groundwater planning, monitoring, modelling, and management and to adopt new approaches that incorporate social aspects and inclusivity and a consensus approach that considers socioeconomic factors rather than relying solely on a regulatory approach.

[15] Khan, M.R., Barrett-Lennard, E.G., & Punthakey, J.F. (2024). *Mobile and Web Applications for Land and Water Evaluation*. Albury NSW: Gulbali Institute, Charles Sturt University.