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Assessing Groundwater Monitoring in Sujawal and Guidance for Strengthening Groundwater Monitoring across Sindh

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We also gratefully acknowledge the 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 (CSU) and key national partners the Mehran University of Engineering and Technology (MUET), the Muhammad Nawaz Sharif University of Agriculture Multan (MNSUAM), in collaboration with the University of Canberra and Murdoch University in Australia, the CSIRO, the International Union for the Conservation of Nature (IUCN, Pakistan), the Society of Facilitators and Trainers (SOFT, Pakistan), and the International Center 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 the simulation of feasible adaptation options. This report analyses the present groundwater monitoring data and provides guidance on developing monitoring and modelling strategies to support the directives in the Sindh Water Policy.

Executive Summary

Agricultural enterprises, including millions of smallholder farms, are strategically important for Pakistan's food security and economic development. The increasing dependence on groundwater for irrigation and drinking purposes makes it vitally important to assess the condition of the resource so that appropriate management strategies can be developed for the sustainable use of groundwater. Informed decisions based on monitoring data are necessary to support policies that encourage sustainable resource use, management, and conservation. Good spatial and temporal coverage of monitoring data is needed to manage Pakistan's vast groundwater resources. Both are lacking in Sindh and many other parts of Pakistan, which is experiencing declining groundwater quantity and quality.

Land and water systems are under pressure in Sindh, with the fragile freshwater lenses at risk from overexploitation and increasing salinity from upconing and lateral migration from surrounding areas with brackish groundwater. Additionally, shallow watertables combined with marginal to saline groundwater and high summer temperatures result in widespread waterlogging and salinity in Sindh. The lower reaches of the Southern Indus Basin are at greater risk due to the flat topography, shallow watertables, and reliance on surface water for irrigation, which prevents farmers from accessing groundwater due to high groundwater salinity levels. In the southernmost reaches of Sindh along its vast coastal lands, the threat is further compounded by rising sea levels, resulting in seawater intrusion and inundation of about 1.2 million hectares of coastal lands. In this context, monitoring systems must be designed to provide information on water and salt transport processes for shallow and deeper groundwater.

Throughout the region, the salinity of groundwater increases with depth. Studies have estimated that over 70% of the irrigated areas of Sindh are underlain by marginal to highly saline groundwater. Where watertables are relatively deeper (over 12 to 15 metres), salinity is less prevalent, and these areas are underlain by freshwater lenses. Basharat et al. (2014) estimated these fresh groundwater zones at depths greater than 15 metres covered 46% of the canal commands in Sindh. Farmers exploit the freshwater lenses that have accumulated from canal seepage and irrigation return flows in these areas for supplementary irrigation, allowing a significant boost in agricultural production from increased cropping intensity. As more and more farmers access the freshwater lenses, excessive exploitation of these freshwater zones increases the risk of depletion along with the consequent migration of groundwater from surrounding saline areas and upconing of the deeper saline groundwater, which can deteriorate the water quality of the freshwater source.

As the distance from the source of fresh seepage increases, the thickness of the layer of fresh water reduces, and management becomes more important. Canal delivery efficiency can directly impact the amount of freshwater available. The tail ends of canal command areas often do not receive their full allocation, forcing farmers to use groundwater, which is more costly and often of lower quality. In these tail areas, fresh groundwater is limited due to supply factors (less reliable delivery in the canals means less fresh seepage to groundwater) and demand factors (less canal delivery leads to greater groundwater use). Balancing the extraction volume and the fresh recharge that has accumulated due to seepage from the Indus Basin Irrigation System (IBIS) is an important part of managing groundwater and soil salinity.

In coastal regions, a further source of salinity in shallow groundwater and soils results from marine intrusion. This effect is exacerbated by the combination of waterlogging and salinity in the canal commands and rising sea levels as a response to global climate changes, as well as tidal surges during the monsoon season. Management in the coastal zone will require a fine balance as declines in outflows to the sea will accelerate seawater intrusion into coastal lands. Beyond water management, these coastal areas will require investments in biodiversity conservation to ensure healthy and productive ecosystems that can reduce some of the impacts of rising seas.

Groundwater monitoring is essential for understanding aquifer responses to stresses and developing strategies to improve land and water management for better water productivity outcomes. Sustainable management of the resource also requires strategies that are co-developed with stakeholders in the Sindh. To sustain the resource, resource managers in the Sindh Irrigation Department and other stakeholders need sufficient monitoring data to support the water policy objectives in Sindh. To achieve these policy objectives, it is essential to have best management practices for groundwater monitoring that support and lead towards the sustainable development of groundwater resources – for both agricultural and domestic use. In this report, we provide guidance for establishing a strategic monitoring network that can be adapted for future planning of a monitoring program for the sustainable management of groundwater resources in the Sindh. We further

elaborate on steps the Sindh Irrigation Department must take to develop best practices for monitoring the quantity and quality of groundwater in the irrigated canal commands and the coastal zone, which is at risk from seawater intrusion. These include developing an institutional framework for groundwater management, as well as a functional and strategic groundwater monitoring network. An essential part of this process is establishing groundwater management areas and groundwater extraction thresholds for each groundwater management area. Governing a common pool resource will require engagement with communities, the transfer of knowledge and capacity building, and developing an understanding of water sharing for a better future. To achieve this, the Sindh Irrigation Department must build significant capacity, including in-house skills for assessing groundwater resources, modelling, and strategies to manage resources sustainably. Finally, the success of groundwater monitoring will require reporting on monitoring plan outcomes to identify where and how improved resource management benefits local communities.

Contents

List of Figures

List of Tables

Abbreviations

ACIAR	Australian Centre for International Agricultural Research
ASSIB	Adapting to Salinity in the Southern Indus Basin
CSIRO	Commonwealth Scientific and Industrial Research Organisation
EC	Electrical conductivity (1 mS/cm= 1dS/m = 1,000 μS/cm)
IBIS	Indus Basin Irrigation System
IWRM	Integrated Water Resources Management
PCRWR	Pakistan Council of Research in Water Resources
ppm	Parts per million
SCARP	Salinity Control and Reclamation Project
SID	Sindh Irrigation Department
SIDA	Sindh Irrigation and Drainage Authority
SMO	SCARP Monitoring Organization

1. Introduction

The increasing population in Pakistan and changing climatic conditions have imposed stresses on natural resources such as land, water, and ecosystems. This has led to a change in water use for agriculture in the country. Historically, Pakistan has relied on its surface water supply. However, in recent decades, it has experienced a rapid growth in groundwater usage (Qureshi et al., 2010).

In Pakistan, where agricultural production is important for economic development, the increasing dependence on groundwater for irrigation and drinking purposes makes it vital to assess its present situation and develop policy recommendations to support its sustainable management. However, to manage Pakistan's vast groundwater resources, good spatial and temporal coverage of monitoring data is needed – both of which are lacking in Sindh and many other parts of Pakistan, which is experiencing declining groundwater quantity and quality. Waterlogging and groundwater salinity are widespread in Sindh. Both land and water systems are under pressure, with the fragile freshwater lenses at risk from overexploitation and salinity from upconing and lateral migration from surrounding areas with brackish groundwater.

In the 1960s, the Lower Indus Project (LIP) was initiated by the Water and Power Development Authority (WAPDA). This program consisted of a series of investigations, including the drilling of deep boreholes and pumping tests to improve understanding of the resource and the impact that the salinity of the shallow groundwater has on agricultural production. Bore holes, from 30 m to 90 m deep and a few much deeper bores were drilled in the Guddu, Sukkur, and Kotri Barrage commands to determine aquifer characteristics and the quality of groundwater in horizontal and vertical scales (van Steenbergen et al., 2015). The general pattern of groundwater distribution in the Lower Indus Plains is one of good-quality water immediately adjacent to the river, with increasing salinity as you move away from the river (Figure 1). However, over the past five decades, seepage from canals and irrigation return flows has also resulted in freshwater lenses near main canals such as the Rohri Canal and in significant areas covering Khairpur, Naushero Feroze, and parts of Shaheed Benazirabad districts. Less good quality water is available on the right bank of the river than on the left (van Steenbergen et al., 2015), which is due to the proximity of limestone hills on the right bank as well as the poor aquifers associated with the Piedmont plains. Another important feature is the lack of fresh groundwater in the Indus Delta area south of Hyderabad, except for some shallow pockets in the recently abandoned riverbeds of the Gaja Command (Government of Sindh, 2018). Some shallow bores (hand pumps) are used mainly for drinking – this is an important source as sometimes it may be the only source of potable water in the delta regions and areas where canals are non-perennial. However, there is virtually no monitoring data outside the canal commands, so, for example, pockets of fresh groundwater along the coastal belt are not mapped.

Throughout the region, the salinity of groundwater increases with depth and none of the boreholes have recorded areas where saline water overlies fresh water in Sindh. Based on the assessments of the LIP, it is estimated that 71% of Sindh's irrigated area has groundwater that is marginally to highly saline (>1500 ppm) for irrigation (van Steenbergen et al., 2015, citing a report from 1990). However, the picture improves at shallower depths (<15 metres), where watertables are relatively deeper and salinity is less widespread. According to Ahmad (1995), there are many sites where shallow useable groundwater exists. The total fresh groundwater zones at shallow depths (<15 metres) are estimated at 46% of the area (Basharat et al., 2014). However, improved monitoring and detailed groundwater investigations are needed to precisely assess groundwater quality change with depth.

Groundwater in the Indus Basin is naturally saline, except adjacent to former courses of the rivers that cross the plain or modern-day freshwater bodies such as the Indus River or the canals and waterways of the Indus Basin Irrigation System. Seepage from these water bodies has led to the development of a layer of fresh water which, due to its lower density, sits atop the saline groundwater. This layer is thickest adjacent to these water bodies, particularly adjacent to the Indus River and main canals, and decreases rapidly with distance from the water bodies. The shallow fresh groundwater which has accumulated from rainfall, river and canal seepage, and the prevalence of flood irrigation in Sindh, is a significant resource, and access to this fresh groundwater allows farmers to increase cropping intensity from 67% to over 120% in the canal command areas in the northern and mid regions of Sindh. These areas cover large parts of Ghotki, Begari Sindh Feeder, Northwest, Rice Canal, Khairpur East, Khairpur West Feeders, Naushero Feroze, Shaheed Benazirabad, and the upstream and downstream command areas of Rohri Canal near the Indus River where the shallow groundwater lens was found to be suitable for irrigation (Ahmed et al., 2021; Salam et al., 2023).

In the Indus Basin, the topographic gradient becomes shallower, and the proportion of finer sediment increases as you move south. These two factors affect drainage capacity and water quality, contributing to the challenges of waterlogging and salinity commonly encountered in Sindh. In addition to its association with waterlogging, the salinisation of agricultural land is also caused by the long-term use of marginal-quality groundwater. In both cases, evaporation from the ground surface leaves salt in the soil profile, and this repeated mechanism leads to secondary salinisation of the land and, in the long term, causes the complete loss of agricultural land to salinisation. Examples of this can be seen in the districts of Shaheed Benazirabad and around Mirpurkhas, Sanghar, and the delta regions. An example of salinity manifestation on a property in the Malwah distributary command in Shaheed Benazirabad district is shown in Figure 2.

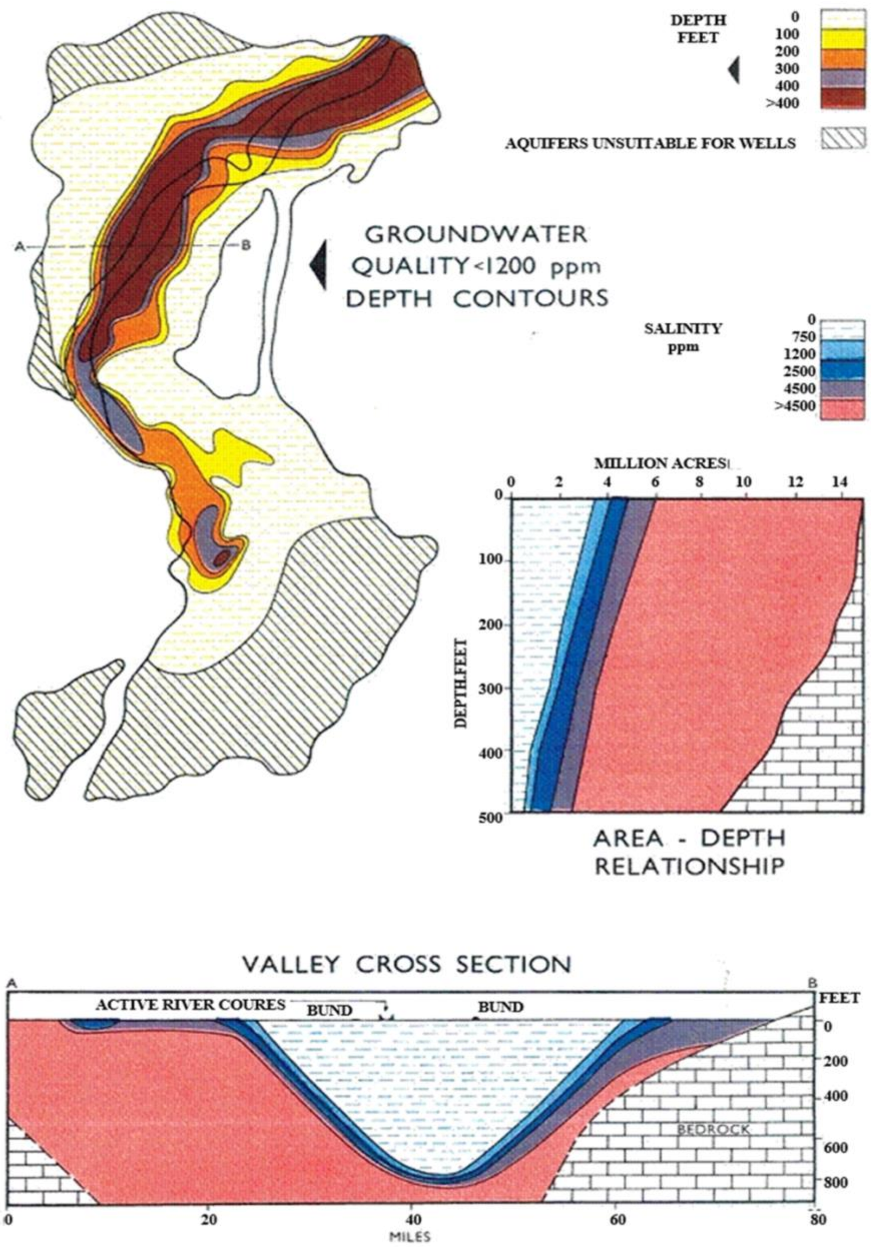

Figure 1: Vertical and horizontal extent of groundwater salinity in Lower Indus.

Source: van Steenbergen et al. (2015).

Figure 2: Salinity manifestation on the surface soil in Malwah command, Shaheed Benazirabad.

Balancing the extraction volume and the fresh recharge that has accumulated due to seepage from the Indus Basin Irrigation System (IBIS) is an important part of managing groundwater and soil salinity. As the distance from the source of fresh seepage increases, the thickness of the layer of fresh water reduces, and management becomes more important. Canal delivery efficiency can directly impact the amount of freshwater available. The tail ends of canal command areas often do not receive their full allocation, forcing farmers to use groundwater, which is more costly and often of lower quality. In these tail areas, fresh groundwater is limited due to supply factors *(less reliable delivery in the canals means less fresh seepage to groundwater)* and demand factors *(less canal delivery leads to greater groundwater use)*. Outside the area served by the IBIS, groundwater recharge is solely from rainfall, runoff, and flooding and in these areas, groundwater is deeper and more saline.

In coastal regions, a further source of salinity in shallow groundwater and soils occurs from marine intrusion. This effect is exacerbated by the combination of waterlogging and salinity in the canal commands, rising sea levels as a response to changes in the global climate, and tidal surges during the monsoon season. Management in the coastal zone will require a fine balance as declines in outflows to the sea will accelerate seawater intrusion into coastal lands. Beyond water management, these coastal areas will require investments in biodiversity conservation to ensure healthy and productive ecosystems that can reduce some of the impacts of rising seas.

The occurrence of salinity in the soil and the shallow groundwater is influenced by how groundwater and the land are used. In an environment like Sindh, where fresh groundwater exists in thin lenses, management of land and water is critical. Salinity and waterlogging are not new for Sindh. They were anticipated when the Sukkur Barrage was commissioned in 1932 and were taken more seriously in the 1970s, when it was reported that 70% of the watertable in Sindh had increased to a depth of less than 1.5 metres and 20% to within 2 metres (Rehman et al., 1998). To remediate the rising watertable in Sindh, the Government of Pakistan initiated a comprehensive program to lower the watertable by installing deep tubewells under the Salinity Control and Reclamation Project (SCARP). These tubewells helped lower the watertable and control waterlogging and salinity in large areas, allowing farmers to improve crop production. Despite the benefits of this intervention, the operation of the SCARP tubewells diminished because of poor maintenance and high operational and maintenance (O&M) costs. In some cases, where the tubewells are used to supplement the irrigation water, they remain functional.

Later, in 2002–2003, the Government of Sindh commissioned a pilot project on transitioning SCARP tubewells to farmer-owned and operated tubewells due to the huge O&M costs. The SCARP transition of handing over tubewells to the community was partially completed in only the Rohri freshwater zone.

Recently, in Sindh, a major shift has been taking place towards converting groundwater pumping systems from grid-supplied or diesel power to decentralised on-site solar-powered pumping systems. For example, the scheme of *250 No. Solar Tubewells in Sindh*, which is in addition to the existing SCARP tubewells. The major drivers for this shift include unreliable grid supplied electricity (frequent breakdowns and interruptions) and high energy costs. Solar-powered pumping is seen as a solution to these problems. However, it may be noted that until now, the lack of electricity supply has also been a limiting factor in how much groundwater was pumped. With that constraint gone (at least during daylight hours) and the seeming ‘free’ supply of energy, groundwater pumping will increase. Since water metering is absent and water billing is based on crops grown, the (mis)use of water is expected to grow significantly.

In Section 2, we review salient features of the National Water Policy and Sindh Water Policy, focusing on the expectations for groundwater monitoring to be undertaken by the Sindh Irrigation Department and possibly the Sindh Irrigation and Drainage Authority. Section 3 provides an overview of groundwater challenges in Sindh, followed by the benefits groundwater monitoring can provide for sustainable resource management and Section 4 provides a brief summary of the benefits of improved groundwater monitoring. In Section 5, we summarise the organisations engaged in groundwater studies and outline the fragmented nature of the work undertaken on groundwater, followed by a brief status of the existing groundwater monitoring data. Lastly, in Section 6, we provide specific guidance for improving the existing monitoring in Sindh and the need for a strategic monitoring framework to provide the basis for informed decisions on resource management for Sindh.

2. Groundwater Monitoring Policy and Guidance

2.1 National Water Policy

National Water Policy: Pakistan's National Water Policy 2018 provides a broad policy focus for groundwater resource management and a set of principles on which provincial governments can implement water conservation, water development, and water management efforts. It advocates the adoption of integrated water resource management (IWRM) and explicitly notes the need to strengthen institutional and management capacity for water management at all levels of governance.

The NWP acknowledges the variability in water availability in various regions of the country, particularly variability in precipitation, surface water, and groundwater, which increases stress on the sharing of water resources. The policy focus on groundwater is as follows:

- Aquifers, particularly the Indus Basin aquifer, are an important national resource that merit protection from pollution and unsustainable abstractions. The NWP recognises that this is a challenge and will require extensive knowledge transfer to groundwater users.
- The NWP stresses strengthening monitoring systems to determine sustainable groundwater potential and prepare groundwater budgets for sub-basins and canal commands. It emphasises measures to prevent lateral/vertical movement of saline waters into freshwater zones and advises the provincial governments to enforce legislation and take regulatory measures.
- The policy advises the adoption of technologies for sustainable extraction of groundwater from shallow freshwater lenses overlying saline water using skimming wells.
- The policy recommends the transition of remaining SCARP tubewells in the public sector to the private sector, leaving the development of fresh groundwater entirely to the private sector as a local resource. However, the local level groundwater management policy is not clear other than urging enforcement and regulatory measures to limit extractions.
- A significant thrust of the NWP is on enhancing artificial recharge schemes where technically and economically feasible, along with priority investment for groundwater recharge schemes.
- The policy states abstractions from the aquifer shall be managed sustainably to balance recharge and boundary flows but it lacks guidance on how this is to be achieved, leaving it to provincial departments to effect change.
- The NWP advises that secondary salinisation due to indiscriminate groundwater abstraction should be avoided by controlling or restricting pumping through enforcement of a strict regulatory framework. However, it does not provide a framework for how 1.4 million tubewells can be regulated or how regulatory measures can be implemented.
- Protecting water resources, lakes, rivers, canals and groundwater from pollution is considered a national priority.

Groundwater directives include the creation of groundwater management planning and regulatory zones. The NWP advocates a range of groundwater foci, the first two relating to education (recognition of groundwater as a resource) and monitoring. Points 3, 4, and 5 are focused on supply options. The NWP recommends managing the watertable to avoid adversely affecting crop growth or increasing the risk of soil salinity and saltwater intrusion. The last two points will be difficult to implement where groundwater use is high, and aquifers are showing signs of stress without significant investment in adaptation options. Implementing a regulatory framework will be challenging, with over 1.2 million tubewells in Punjab and over 100,000 tubewells in Sindh. We foresee the need for a dedicated stakeholder engagement process to improve knowledge of groundwater irrigators and allow irrigators to have a voice in managing the resource.

The policy objectives broadly call for improving groundwater management in Pakistan by strengthening and capacity building of water sector institutions, upgrading water sector information systems for evidence-based decision-making, improving asset management, and restoring and maintaining the health of the environment and water-related ecosystems. The NWP divests significant responsibilities to the provinces. How provincial investment will be ensured is unclear. However, the NWP has identified the need to establish a new

‘Groundwater Water Authority’ in each province to oversee groundwater regulation. The Groundwater Authority would facilitate regulations to ensure the efficient and sustainable use of groundwater, industrial uses, and wastewater management.

2.2 Groundwater guidance provided in the Sindh Water Policy

The Sindh Water Policy outlines the need to adopt an integrated water resource management approach emphasising sustainable exploitation and management of groundwater aquifers in Sindh. The policy recognises the importance of the freshwater lenses, which are contributing to increased cropping intensities in Sindh and highlights the need to regulate groundwater resources. This objective is also stated in the Sindh Agriculture Policy (2018–2030) and Sindh SDG (2030) agenda for conserving agricultural productivity in Sindh. Groundwater supplements surface water in the canal command areas and is considered an important resource for dryland agriculture in Sindh. Policy directions for groundwater in Sindh are as follows:

- Groundwater management is the second priority of the new water policy in Sindh. The policy recognises that there is no regulation to control groundwater exploitation, indicating the need for local regulations to impose restrictions on the overuse of groundwater. In support of this, a licensing committee has been designated to regulate and monitor the commercial use of groundwater.
- The Sindh Water Policy directs the establishment of a Sindh Water Resources Management Department to integrate the responsibility of the Sindh Irrigation Department (SID) and Sindh Irrigation Drainage Authority (SIDA). Within the Water Resources Department, a Groundwater Directorate will be established and will be responsible for planning, managing, and regulating projects like SCARP, LBOD and RBOD for mitigating waterlogging issues and draining the saline water into the sea. However, groundwater planning and management must extend beyond the remit of these projects as there is substantial use of fresh groundwater in significant areas of the Left Bank of Sukkur Barrage covering the districts of Khairpur, Sukkur, Naushero Feroze, and Shaheed Benazirabad.
- The policy calls for the establishment of a Hydro-Agro Informatics Centre to strengthen the monitoring network of groundwater aquifers that can assist the decision-making body towards the sustainable management of groundwater.
- The policy emphasises the enforcement of regulations for the safe extraction of groundwater in accordance with the site-specific aquifer conditions in various ecosystems. This important objective will require a significant investment in capacity building and up-skilling of SID and SIDA within the new Groundwater Directorate.
- Conjunctive use of groundwater and surface water in freshwater zones is recommended to reduce waterlogging and salinity and enhance agricultural productivity. At the same time, the policy calls for limits on extraction rates to avoid upconing of the underlying saline groundwater. Limits on extractions will only be possible through significant investment in knowledge transfer to groundwater users and building a consensus approach.
- The canal management strategy indicates freshwater recharge to aquifers must be preserved and sustainably used.
- In the dryland areas, the Sindh Water Policy advocates constructing small dams to improve groundwater storage. Local planning and licensing of groundwater abstractions at some locations will be necessary to avoid agricultural users overexploiting groundwater reserves in these areas.
- The protection of freshwater lenses in rural areas is proposed by constructing unlined canals and selective lining in areas vulnerable to waterlogging and salinity. The policy advises implementing a selective drainage strategy to avoid waterlogging and allow freshwater recharge into groundwater.
- A groundwater licence will be issued to relevant stakeholders based on its intended use and an analysis of the impacts of excessive groundwater abstraction on the environment.
- The involvement of private companies outside the canal command area provides a licence to stakeholders based on the above point.
- Enhancing monitoring networks for groundwater is necessary to improve understanding of the resource, develop groundwater models for accurately assessing the water budget and scenario modelling to improve resource management.
- Educating communities and stakeholders about the importance of surface and groundwater and improved strategies for conjunctive use and management in Sindh.

3. Groundwater Challenges

3.1 Waterlogging and salinity

Much of the groundwater underlying Sindh province has elevated salinity levels from marginal to saline and shallow watertables underlying much of the canal command areas in Sindh make it susceptible to waterlogging. Shallow watertables and high evapotranspiration rates prevalent during the summer months in Sindh result in expressions of salinity on the soil surface. Over the years, seepage from canals and irrigation return flows have resulted in the accumulation of freshwater lenses in many of the canal command areas in Sindh. The prominent areas of Sindh with freshwater lenses, which farmers are exploiting for supplementing shortfalls in canal water supplies and for increasing cropping intensities, are found in the districts of Khairpur, Sukkur, Naushero Feroze, and Shaheed Benazirabad, which cover about 29% of Sindh. These freshwater lenses are of limited thickness, and generally overlie saline groundwater. A recent study by Young et al. (2019) indicated that groundwater supplies about 20% of the irrigation water requirements for agriculture, which is extracted from over 100,000 tubewells, most of these are farmer-owned assets. The public sector tubewells are largely electric tubewells, whereas most of the farmer-owned tubewells are diesel operated with a small number of solar-powered tubewells. Farmers generally prefer diesel-operated tubewells to ensure water availability during periods of frequent electricity blackouts or load shedding or a lack of access to electricity infrastructure.

Fresh groundwater in Sindh along the left bank of the Indus River in the areas of Ghotki, Khairpur, and Rohri are exploited by farmers. Here, farmers have installed shallow groundwater tubewells to exploit the accumulated freshwater lens and supplement canal water irrigation. Access to groundwater has increased the cropping intensity from about 70% to about 100% in Sindh. A survey of randomly selected farmers across four districts (Badin, Matiari, Mīrpurkhās, and Tando Allahyar) indicated that 23% of farmers were fully dependent on groundwater and 77% used both surface and groundwater for irrigation (Mangan et al., 2016). In the riverine areas that lie outside the canal command areas, there is uncontrolled use of groundwater for irrigation. The source of this water is seepage from the Indus River, which accumulates fresh groundwater that can be exploited with relative ease and supports agricultural production in the non-command areas.

3.2 Groundwater use is under pressure

Sindh is expected to experience drier and hotter climates, increasing evaporative demand and requiring more irrigation water. Farmers in parts of Sindh are aware of the changes being experienced due to climate change. They are seeking technologies to modify the crop microclimate during the long, hot summer months from April to June. Another concern facing irrigators is the priority assigned to water reallocation from agriculture to the domestic sector to meet human needs for potable water and hygiene. The Sindh Irrigation Department (SID) has reallocated 37 m3/s (1200 cusecs) of irrigation water for diversion from Keenjhar Lake for Karachi, and it is likely that in future, this amount will be doubled, resulting in a shortage of irrigation water supplies in the command area in Thatta district. Access to additional freshwater sources is a critical constraint. In the current situation, we can expect water availability and distribution problems in agriculture to intensify, and under this scenario, irrigators will likely have no option but to exploit additional groundwater and shift to more efficient cropping systems. What seems to be concerning is a lack of attention to understanding what will happen if farmers cannot adapt at the required pace of change and the lack of research on the respite that adaptation options are likely to provide farmers. As conditions change, adaptation options may need to be modified or may fail as climate change, energy, water, and food security demands converge.

3.3 Coastal Regions of Sindh

Shallow saline watertables are widespread in the coastal regions of Sindh. In the districts of Thatta, Sujawal and Badin, canal water supplies are preferred for irrigation due to elevated salinity levels of the underlying groundwater. Mapping salinity in these districts has limitations due to the paucity of monitoring bores. To begin with, neither SID nor SIDA have established a monitoring network in the coastal districts. The only available spatial and temporal data is from the SCARP Monitoring Organization (SMO) bores dating from 2010 to 2014. Recent data from 2018 and 2019 have also been collected from a few monitoring bores, largely due to the lack of funding for SMO operations and the absence of a designated institution responsible for groundwater monitoring. The lack of capacity for groundwater resource monitoring and mapping, modelling and management within the institutional setup in Sindh is also a contributing factor.

Much is unknown about the coastal districts in Sindh. For example, a cross-section of the surficial aquifer through the Thatta, Sujawal and Badin coastal districts shows sand sequences ranging from a few metres to about 50 metres, which are generally interlayered with clays (Figure 3). 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). An additional constraint is the absence of deep boreholes – the deepest boreholes drilled in this region range from about 90 to 135 metres; however, the alluvium is expected to be much deeper as the thickness increases towards the coast.

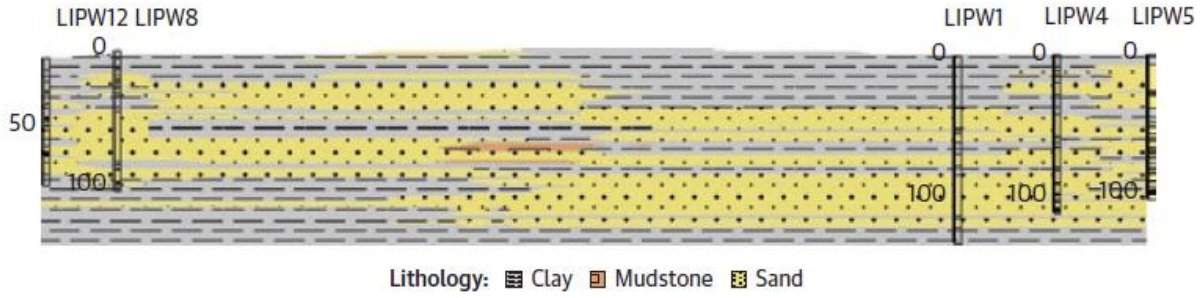

Figure 3: Cross-section of alluvium through the coastal districts of Thatta, Sujawal and Badin.

Source: Lytton et al. (2021).

3.4 Unmanaged groundwater extraction from thin freshwater layer

The exploitation of groundwater resources in Sindh is not managed. Farmers with the resources readily invest in tubewells for groundwater irrigation to supplement shortfalls in canal water supplies. This is even more evident in the tail end of canals, where water levels are relatively deeper and the groundwater quality is marginal at best. Inequity in surface water distribution and increasing irrigation intensities have led to an increase in dependence on these fresh groundwater lenses, which also provide a reliable source of drinking water for rural communities. Government subsidies for installing high-capacity solar tubewells for irrigation are exacerbating this trend and undermining farmer incentives to avoid the unsustainable use of groundwater. Groundwater level declines will become a critical issue for farmers, as overexploitation of the freshwater layers will accelerate the lateral intrusion of groundwater and upconing of deeper saline water into the freshwater zone. There is a crucial need to monitor groundwater levels and maintain pumping at sustainable rates that preserve the integrity of fresh groundwater layers. A balance between recharge to the freshwater lenses and the level of acceptable groundwater pumping while ensuring the freshwater lenses have an acceptable level of salinity will be needed to maintain a higher level of cropping intensity, which is essential for food security in Sindh. This will require some farmers to transition cropping systems to more favourable crops that are less water intensive yet provide similar or better returns, improved land management practices, and a gradual conversion from flood to furrow irrigation. One promising way to develop broad support towards adopting such new on-farm practices involves a form of integrated scenario modelling known as Representative Agricultural Pathways, which has been used in our prior ACIAR project – see Nasir et al. (2021).

3.5 Deteriorating drainage infrastructure

The SCARP and LBOD projects were initiated in the early 1960s and 1990s to address waterlogging and drain the excess water, respectively. These projects involved pumping saline groundwater (through tubewells) and its disposal in drains. The projects brought benefits for controlling the watertable and improving agriculture productivity, but over time, the efficacy of the drainage network was reduced. The main reasons include the high operating cost of tubewells, the lack of operation of the SCARP tubewells due to poor maintenance, and the lack of maintenance of the drainage network. Additionally, there is no monitoring in place of the drainage system, which can provide information on the efficacy of the system and crucial data for modelling and water budgeting. The rehabilitation of the existing drainage system will require significant investment by the Government of Sindh, as it is seen as a vital component for extending the viability of agriculture in Southern Sindh.

3.6 Seawater Intrusion

The canal command areas in the coastal districts of Thatta, Sujawal and Badin face significant challenges with waterlogging and salinity due to relatively high watertables and the underlying marginal to brackish groundwater. To the south of these canal command areas lies the coastal zone, which is subject to seawater intrusion, rising sea levels and coastal inundation. Seawater intrusion is a significant threat to the agricultural lands in the coastal regions of Sindh, which also has a devastating impact on the fragile ecosystem of the Indus Delta in Sindh and on coastal communities that derive their livelihoods in the coastal zone.

Managing groundwater and maintaining the fresh and saline interface is pivotal. The information regarding the seawater interface and its response to freshwater recharge in the Sindh delta region is poorly understood. About 1.2 million hectares have been affected by seawater intrusion and inundation (Khaskheli et al., 2018), and Siyal (2018) indicated that approximately 32 hectares of delta land is being lost daily due to seawater intrusion. This huge land loss could have provided livelihood opportunities for coastal communities struggling to find alternate livelihood opportunities. Recent modelling studies of Sujawal and the coastal zone undertaken as a component of this project indicate that significant areas of coastal land are likely to be affected by seawater intrusion. The climate change scenarios indicated 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 about 6.7 and 7.5 times greater than the baseline scenario. Additionally, the simulated increase in net inflows from the sea boundary are expected to continue to increase post-2100 as sea levels continue rising, with resulting net inflows and coastal inundation expected to be even greater (Jamali et al., 2024).

3.7 Lack of institutional and regulatory groundwater policy framework

Increasing groundwater pumping is resulting in the transport of salinity to the crop root zone, posing ongoing risks to irrigated cropping systems and land salinisation. Water levels, salinity of groundwater, and groundwater extractions are neither monitored nor managed. The lack of a structured approach to managing groundwater resources is due to the absence of institutional structures for managing groundwater resources in Sindh. SID has a unique opportunity to design a groundwater monitoring and management system from the ground up and incorporate the experience of groundwater monitoring and management from countries where groundwater management has advanced greatly. Moreover, the lack of groundwater management in Sindh is putting resource condition at risk, as not only is there a lack of data and knowledge of the state of the resource, but it also means environmental costs are undocumented, as are the impacts on agricultural productivity improvements.

Groundwater extractions in Sindh’s freshwater areas are resulting in changes to the condition of the resource. Farmers in Malwah command have raised serious concerns about declines in groundwater quality and its consequent impact on land salinisation and understand that climate change is impacting their enterprises. They have strongly advocated the need for improved and equitable surface water management. Policy mechanisms that enable community-based aquifer management and co-ownership of aquifer shares (e.g., in a system of correlative rights), which forms a basis for water sharing, could help the transition to sustainable groundwater management. As part of the reformation for instituting a framework for managing Sindh groundwater resources, the Sindh Irrigation Department will need to have a mechanism dedicated to knowledge sharing activities with communities to support the nascent water policy initiative being undertaken by the Government of Sindh.

3.8 Lack of sufficient data to establish groundwater budgets

Groundwater monitoring in Sindh has been given little attention compared to surface water. No single department has had the responsibility to collect groundwater information. Much of the data sources can be traced to the SMO program, which was operational until 2014–2015. Data collected on research projects largely remain within educational institutions and are not digitised or are aimed solely at individual agencies. WAPDA-SMO has been collecting groundwater data since the 1970s to assess drainage needs in the province but not for groundwater management. However, over the last several years, the data collection by the SMO has been limited due to financial constraints. A review of groundwater resources in the Indus Basin by Lytton et al. (2021) and a comprehensive modelling study of the Rohri Canal command area (Ahmed et al., 2021) have strongly advocated for dedicated monitoring bores installed with loggers to monitor water levels and salinity to provide high-frequency data that can provide information on intra-seasonal trends and can form the basis for informed decision-making and for establishing groundwater management areas.

4. Purpose and Benefits of Groundwater Monitoring

The purpose of monitoring groundwater is to measure its behaviour and response to system stresses and management interventions, and to develop adaptation strategies. Data spanning several years and decades enable long-term predictions and guide water management and land planning decisions. Monitoring data on water levels and water quality coupled with detailed hydrogeological characterisation of the aquifer and the application of modelling tools allows resource managers to map zones at risk from water level declines and declining water quality. Modelling provides opportunities for improving the monitoring programs and for optimising monitoring networks. In the ASSIB project, we have modelled the response to management scenarios, such as reduced surface water flows and increased pumping scenarios, and climate change impacts to improve our understanding of groundwater resources in Southern Punjab and the coastal district of Sujawal. Monitoring networks also play a vital role in understanding the impact of changes in water quality and mapping water quality hotspots, such as elevated levels of arsenic and other trace metals that impact potable water sources and community health, and monitoring compliance, such as discharges to streams and lakes.

Remote sensing and GIS are powerful tools for mapping crops and mapping spatial and temporal changes in rainfall and precipitation, soil salinity and coastal inundation. Remote sensing is particularly useful for mapping land use changes and the impact that changes in land use have on groundwater recharge, such as the spread of peri-urban areas. An important outcome is to use this information to assist farmers in transitioning to crops suited for particular agroclimatic zones and adopting water-efficient crops. Analysis of temporal changes in a management area can improve understanding of spatial and temporal changes in the management area, such as planning changes in conjunctive management.

Agriculture use: Agriculture provides the main livelihood of rural communities in Sindh and various estimates suggest that groundwater contributes about 20% of irrigation water, with the rest coming from surface water. Most groundwater extraction for irrigation is from farmer-owned tubewells and a few publicly owned tubewells in the province. A recent report by the PCRWR (2020), indicates that the volume of groundwater extraction in Sindh has increased to 19 BCM, which is a cause for concern as extractions in Sindh are unmanaged. Groundwater extractions from the freshwater lenses need to find the right balance between recharge and extraction, and the extraction rates should be managed to avoid upconing of saline water from deeper layers.

Potable and domestic use: Access to fresh groundwater sources using handpumps is vital for providing reasonably good quality water for potable and domestic uses for rural communities in Sindh. In Sindh, more than 70% of the drinking water and water for domestic uses is obtained from groundwater. Some communities, for example, in Thar desert areas, depend solely on groundwater to meet their potable and domestic needs.

Dryland agriculture: The Barani areas of Sindh depend on groundwater for livestock rearing and smallholder agricultural enterprises. In the dryland areas, significant amounts of groundwater are accessed to support agriculture in the province of Sindh.

Industrial use: Almost all industries, including sugar mills, cotton factories and other industrial enterprises in rural Sindh, extract groundwater and dispose of effluents in canals or drains. Monitoring groundwater use by industry and disposal of treated effluents needs to be a priority action for the Sindh Irrigation Department due to the high risk of contaminating the shallow freshwater lenses in Sindh.

Watertable management: The flat terrain and shallow watertables require regular monitoring to sustain agriculture and for improved management of waterlogging and salinity, which are widespread in Sindh.

Seawater intrusion: Regular monitoring in the Indus Delta region is essential to understand the impacts of seawater intrusion along Sindh's coastal areas and to co-design appropriate adaptation strategies for coastal communities.

Monitoring the environment: The design of a strategic monitoring program with a well-designed network of monitoring bores and sentinel bores, together with the application of remote sensing, is essential for improving environmental management and designing programs to improve the health of ecosystems. The Sindh government will require improved performance on environmental management of the many freshwater lakes, creeks and wetlands in Sindh, and in particular, the rehabilitation of the coastal ecosystem, which supports fisheries and other food sources in coastal Sindh.

5. Organisations Engaged in Groundwater Studies and Present Status of Groundwater Monitoring

The government of Sindh is responsible for monitoring groundwater in the province, but until recently, no government agency in the province had been assigned to this role. The Sindh Water Policy has indicated that this responsibility lies with the Sindh Irrigation Department.

Several departments carry out development work. However, none of them has developed strategies to manage groundwater. The focal department is the Sindh Irrigation Department (SID), which largely manages the irrigation supply network and has recently tried to build skills and capacity in groundwater monitoring and modelling. The Agriculture Department provides basic extension services such as advising farmers on crop water requirements and managing waterlogging and salinity. Public Health provides drinking water to rural and remote communities by drilling tubewells and small water supply works. More recently, the Sindh Irrigation and Drainage Authority (SIDA) has undertaken water balances for some canal command areas to estimate the quantity of water available for irrigation. The Environmental Protection Agency is charged with assessing and protecting the quality of water and water quality standards for different uses; however, it does not possess the legal and regulatory structures to enforce environmental protection laws. Each of these departments has interlinked roles that can affect groundwater management in the province of Sindh; however, each department works in isolation without a good grasp of the community needs to manage groundwater sustainably.

Over the past decade, there has been a greater emphasis on understanding groundwater resources and their importance for Pakistan's economy and food security. Research institutes and organisations such as the IWASRI and PCRWR have carried out groundwater research and have been active in monitoring groundwater. There has also been support for groundwater studies from national universities and international organisations, including the World Bank, ACIAR, ADB, IUCN, IWMI, and FAO. A brief overview of the role of various national and provincial government organisations in groundwater management is given in Appendix A.

Under the recent Sindh Water Policy (2023), much of the responsibility for monitoring groundwater quantity and quality and for groundwater planning, management and equitable resource sharing in Sindh will lie with the SID. To fulfil its mandate, the SID plans to develop a dedicated division to monitor and manage groundwater resources in Sindh and invest in capacity building in groundwater monitoring, planning and management.

5.1 Existing status of aquifer data, groundwater monitoring and management

5.1.1 Static data

Detailed hydrogeological investigations were carried out in the Lower Indus Project by WAPDA. The geological information has recently been compiled under an SDIP-funded CSIRO project titled "Regional groundwater model of the Indus Basin, Pakistan: hydrogeological analysis of bore logs" (Schmid et al., 2017). A detailed dataset of lithology at different depths is available in digital format. Recently, the PCRWR conducted groundwater investigations and mapping in the Lower Indus Plain (Iqbal et al., 2020).

Time series data: As discussed earlier, the SMO formerly had a systematic monitoring program of depth to watertable and groundwater water quality in canal command areas of Sindh. The data collection was started in the 1970s to assess waterlogging and propose drainage systems accordingly. The observations were mostly taken biannually (pre- and post-monsoon). Data is not available in digital form except for the years 2009, 2013, 2014, and 2015, but it is in paper records. Moreover, the available data showed several missing periods (years) and locations due to the non-functioning of several observation points. In recent years, the SMO has faced funding and mobility constraints because of old vehicles, and data collection is now intermittent and incomplete.

During the 1980s and 1990s, the SCARP project (including fresh and saline pumping tubewells) was handed over to the Sindh Irrigation Department. However, the observation points in the SCARP project areas were still monitored by the SMO. The maintenance and operation of SCARP tubewells, including fresh and saline pumping tubewells is the responsibility of the Sindh Irrigation Department, while the maintenance of observation wells remains the responsibility of SMO.

5.1.2 Summary of groundwater datasets and monitoring infrastructure

Static datasets required for characterising the aquifer are available in different reports. Table 1 lists datasets available for the irrigated area of Sindh (the Lower Indus Basin). There is a huge gap in data availability for non-irrigated areas. There are also gaps in data and knowledge to allow a detailed hydrogeological characterisation of the Indus Delta region and its complex ecosystem.

Dynamic datasets available do not have continuous time series data, specifically, for groundwater level and quality. The frequency of measurement is also low, only twice annually at best. Weather parameters have continuous temporal measurements, but these datasets are spatially sparse. The Sindh Irrigation Department has continuous series of temporal datasets of flows at barrages and major canals, but the data becomes sparse as the scale reduces to the farm level and there are no measurements of groundwater pumping. Demand side data is not officially recorded but research studies have reported this data using approximate measurements and remote sensing. Data on tubewells reported by Sindh agriculture statistics (Jica 2022) show tubewell numbers have increased; however, there is a dire need to update the statistics on tubewells and the pumping capacity of tubewells in Sindh. Besides total installed pumping capacity, other information regarding pumping, such as tubewell depth, pipe size, discharge of each tubewell, energy source, and pump type are not available, although there are datasets for SCARP wells, but these have not been updated. It is important that groundwater pumping datasets be collected both for private and government tubewells. Table 1 divides the datasets in terms of whether they are static or dynamic.

The Pakistan Bureau of Statistics' Agricultural Statistics of Pakistan 2010–2011 reported the number of tubewells and lift pumps in Sindh was 38,330 and 7,809, respectively. The number of private farms reported to own tubewells in Sindh is 30,644, according to the Agriculture Census of 2010. The cost of fuel and maintenance of the wells is borne by the farmer. With the best intentions, the Government of Sindh and its Agriculture Department are promoting solar panels for tubewell with 80% of the cost borne by the government and 20% from beneficiary contributions to the construction cost. However, there is a lack of studies on the cumulative impacts of solar-powered tubewells on Sindh's freshwater lenses. Additionally, the Sindh Irrigation and Drainage Authority (SIDA) is also considering constructing communal wells for irrigation, which it mandates per SWMO 2002 (Japan International Cooperation Agency, 2022).

Table 1: Summary of datasets

	Static Datasets	
	Datasets	Status
1	Lithological bore logs	Information available from (HTS/MMP 1965). A digital dataset is provided by CSIRO at https://data.csiro.au/collections/collection/CIcsiro:28053v1
2	Electric resistivity logs	Information available from a recent report by PCRWR (Iqbal et al., 2020).
3	Hydraulic characteristics of the aquifer	Information available from LIP report 1961.
4	Groundwater salinity profile	Information available from a recent report by PCRWR (Iqbal et al., 2020).
5	Upper soil characteristics	Information available from WAPDA and maps from the Geological Survey of Pakistan.
6	Hydraulic characteristics of canals	Information available with Sindh Irrigation Department.
7	Hydraulic characteristics of drainage network	Information available with Sindh Irrigation Department.
8	Cropping patterns	Information available at the district level scale; irrigation division also collects crop area for each distributary.

	Dynamic Datasets	
9	Evapotranspiration	This information is available in the form of proxy estimates by using satellite data. A recent report by CSIRO.
10	Rainfall and other weather datasets	The Pakistan Metrological Department records this information on stations in Sindh.
11	River/canal flows	River and main canal flows are available at the SID. At a smaller scale (Distributaries/Minors and watercourses) this information is available in gauge recording.
12	Pumping rate	This information is not available.
13	Irrigation water use	Water supply as per rotation plan is available but actual use not estimated except for a few research projects.
14	Tubewell numbers	Agriculture statistics report these numbers, but it is not clear about the survey method.
15	Groundwater levels	SMO has information regarding water level (pre- and post-monsoon). This is available with data gaps since the inception of SMO until 2015.
16	Groundwater salinity	SMO has information regarding salinity (pre- and post-monsoon). This is available with data gaps since the inception of SMO until 2015. Other research organisations also compiled this information in different projects but only for the specific research project.
18	Groundwater seawater interface	Information not available.
19	Return flows from and to groundwater	Information not available.
20	Soil salinity	Information available from WAPDA and the Geological Survey of Pakistan in the form of maps.
21	Environmental requirements for groundwater	Information not available.

6. Guidance for Groundwater Monitoring

Groundwater monitoring is essential for understanding aquifer responses to stresses and developing strategies to improve land and water management for improved water productivity outcomes. Sustainable management of the resource also requires strategies that are co-developed with stakeholders in the Sindh. To sustain the resource, resource managers in the Sindh Irrigation Department and other stakeholders need sufficient monitoring data to support the water policy objectives in Sindh. To achieve policy objectives, it is essential to have best management practices for groundwater monitoring that support and lead towards the sustainable development of groundwater resources and address associated impacts on agriculture and domestic use. Figure 4 shows the pivotal role of monitoring to achieve resource sustainability.

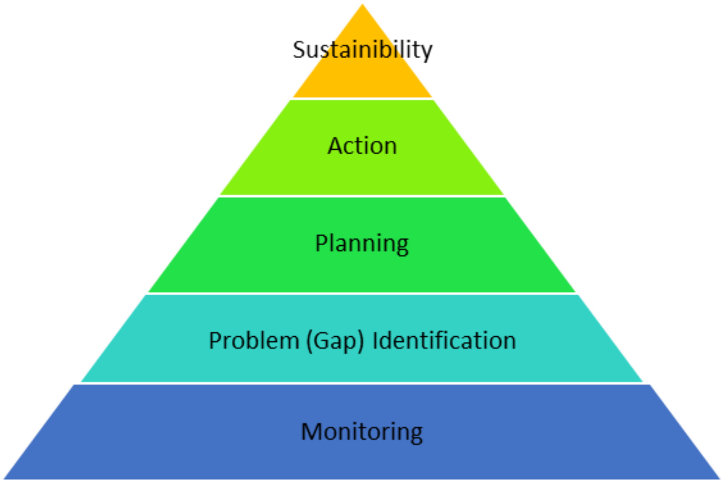

Figure 4: Process of achieving resource sustainability.

In this section, we provide guidance on best management practices that can be adapted for future planning of a monitoring program for the sustainable management of groundwater resources in the Sindh. Below are the steps, which are further elaborated in the next sections.

- Develop an institutional framework for groundwater management.
- Develop a groundwater management planning framework.
- Establish a functional monitoring network.
- Delineate groundwater management areas and establish groundwater extraction thresholds in the management areas.
- Engage communities for knowledge sharing, capacity building, security of monitoring equipment, and developing an understanding of water sharing.
- Establish technical assistance for assessing groundwater resources, modelling, and strategies to manage resources sustainably.
- Monitor plan outcomes.

6.1 Develop an institutional framework for groundwater management

The Indus Basin aquifer system is one large connected system that requires integrated management. To manage it in an integrated manner, an institutional system that connects local scale to sub-regional and basin scale monitoring is required. Historically, the SCARP monitoring organisations were established in the SCARP areas responsible for monitoring the groundwater system for the SCARP divisions and reporting to IWASRI for wider reporting. The main purpose of this institutional setup was to monitor and manage the implementation and execution of the drainage projects. However, after the devolution of power and handing over of the SCARP projects to the irrigation department, this system is not fully functional (although it still exists) due to the lack of financial resources, low capacity in groundwater within the irrigation department, and no clear lines of responsibility. It is now recognised that groundwater monitoring has to be extended to a broader vision of integrated water resources management. An institutional arrangement is required that contains dedicated units for groundwater management. A way forward would be to use the existing surface water management structure and establish new groundwater management areas that entirely focus on groundwater management. Similar to canal command areas, groundwater management areas can be identified and further divided into sub-divisions headed by a provincial body, which reports to a central body at the national level. Figure 5 below shows an example of such a hierarchical setup.

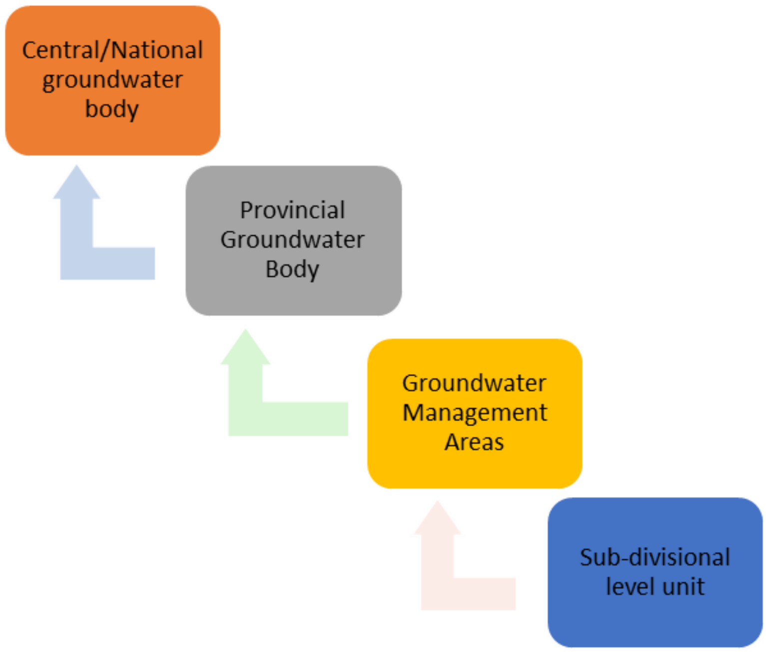

Figure 5: Groundwater governance hierarchy.

6.2 Develop a groundwater management planning framework

Key Steps

- Conceptualise the groundwater management program and institutional arrangement.
- Develop a governance plan, establish roles and responsibilities, and staffing requirements.
- Establish legal and technical support for the development of groundwater units.
- Define detailed tasks, cost estimates, and implementation strategies.
- Equip the institutes with essential hardware and software and establish data collection, management, and reporting protocols.

6.3 Establish a functional monitoring network

Accessing good-quality data to evaluate aquifer responses is a key constraint in Sindh. The existing data on depth to water and EC are fragmented with data discontinuities and errors. Moreover, the same monitoring bores are not monitored consistently, consequently, management decisions are based on data that provide a partial understanding of the system, resulting in a low predictive value. The flow complexity in aquifers requires extensive data and detailed modelling to answer development questions related to aquifer performance and groundwater management. Comprehensive spatial and temporal monitoring data are key elements for improving understanding of groundwater resources and providing governments with technical advice to make informed decisions.

We recommend that the Groundwater Directorate begin a program of instrumenting monitoring bores with CTD loggers to monitor conductivity, water levels, and temperature. It is particularly useful to monitor drawdown and water quality hotspots in command of the branch canals and distributaries in the middle and tail reaches. Systematic monitoring of these parameters will allow the Sindh Irrigation Department to improve its understanding of aquifer responses and develop a groundwater management strategy. The frequency of monitoring needs to be increased, particularly in non-perennial commands such as the Pinyari canal command, where depletion zones, waterlogging and water quality issues have been identified. At present, where monitoring data is available pre-2015, piezometers were monitored twice annually during the pre- and post-monsoon seasons. A cost-effective way to increase the frequency and accuracy of monitoring is by instrumenting piezometers with loggers, which can be programmed to monitor at more frequent intervals, e.g., 12 hourly or daily. This will need a dedicated budget, including for transport for field activities.

Construction details of each new piezometer need to be logged, and detailed bore logs during drilling new piezometers or tubewells need to be documented by a competent professional. This will yield a valuable dataset for understanding the hydraulic properties of the aquifer, which will also support other activities, such as groundwater modelling and managing depletion or waterlogging issues.

Where water quality issues have been identified, additional monitoring points will be needed to understand the risks from heavy metals and microbial contaminants that may adversely impact human or animal health to enable managers to modify usage patterns or impose restrictions on usage.

In Sindh, five domains need immediate monitoring for sustainable management of land and groundwater resources: (i) Monitoring of freshwater lenses; (ii) Monitoring of shallow groundwater levels; (iii) Monitoring of the saline water and freshwater interface; (iv) Monitoring of groundwater depletion in non-irrigated areas; and (v) Monitoring contaminants of concern (COC) such as arsenic, fluoride and cadmium, and for agricultural areas nitrates and other contaminants from fertilisers. At a later stage, this can be expanded to include pesticide residues in groundwater. A functional monitoring network must provide at least the minimum data for informed decision-making. Archiving and accessibility of monitoring data and quality checks are vital investments for managing groundwater resources. As improved understanding develops, an automated monitoring network with high frequency of monitoring coupled with advanced data management and analysis system should be established for these domains.

6.3.1 Rehabilitation and revival of the SCARP monitoring network

The most cost-effective way for the Sindh Irrigation Department to establish a strategic and robust groundwater monitoring network is to revive and rehabilitate the existing SCARP monitoring network, which has largely been abandoned. The SCARP Monitoring Organisation (SMO), as part of WAPDA’s efforts to evaluate the success of drainage projects, was the most systematic groundwater monitoring conducted in Sindh from 1970 to about 2015. The parameters monitored were depth to water, EC, TDS, pH, and total anions and cations, which were measured biannually during the pre- and post-monsoon seasons. Of the 2758 monitoring bores, 1482 are being monitored, which includes 840 shallow monitoring wells, 440 open wells, and 202 deep tubewells, while the remaining 1276 bores are non-functional. A list of these bores is given in Appendix A. Each functional monitoring bore should be digitised with accurate coordinates using a differential GPS, the size and depth of the monitoring bore recorded, and the condition of the bore recorded with an asset number and a program for rehabilitation planned as required. These functional bores should be instrumented with CTD loggers to measure depth to water, temperature, and conductivity. An assessment needs to be carried out to see if it is feasible to rehabilitate non-functional bores, and these bores also need to be digitised. Downhole cameras can be used to assess the condition of the bore. If the bore is deemed unsuitable for rehabilitation, it needs to be removed, if possible, and sealed off to prevent surface pollution from entering the aquifer.

Key Steps

- Establish protocols for the design, implementation, and maintenance of a robust monitoring network.
- Revive and rehabilitate the SCARP monitoring network in Sindh and install loggers in functional piezometers.
- Install multilevel piezometers for monitoring salinity stratification.
- Develop a sustainability plan for the monitoring network.
- Establish training and capacity building in logger installation and data retrieval.
- Establish a reporting and advising mechanism based on monitoring data.
- Deploy an intelligent monitoring system coupled with a database, remote sensing, and modelling framework.

6.4 Delineate groundwater management areas and establish groundwater extraction thresholds in the management areas

To streamline the implementation strategy, it is essential to assess the existing situation and identify critical management areas. In these areas, thresholds and targets need to be established. To achieve this, a detailed water balance assessment will be required with the help of modelling and remote sensing techniques. Water balance for each groundwater management area should be established, and a critical threshold for water level, water quality, and groundwater storage targets would need to be established. The irrigation and agriculture departments would need to co-develop critical thresholds with stakeholders to develop a consensus based on the water balance assessment. An implementation plan would also be required to ensure strategies to achieve the set targets over a planning period together with stakeholders in the management areas.

Key Steps

- Build on the existing spatial and temporal database developed at MUET or through World Bank funding.
- Develop analytical tools and knowledge products for institutional actors and communities.
- Demarcate and establish groundwater management areas (GMAs).
- Establish targets and co-develop implementation strategies for groundwater management.
- Legalise the GMAs, targets and implementation strategies over a specified planning period in agreement with stakeholders.
- Co-develop a mechanism for governing groundwater as a shared resource.

6.5 Community engagement – knowledge sharing, capacity building, security of monitoring equipment, and developing an understanding of water sharing

Groundwater is a common pool resource, and achieving sustainability will only be possible by adopting a consensus approach and engaging all stakeholders. The following steps can be taken to ensure community engagement:

Key Steps

- Establish an awareness program regarding sustainable management of groundwater resources.
- Establish community stakeholder groups.
- Engage the community in monitoring and sharing groundwater information.

6.6 Establish technical assistance for assessing groundwater resources, modelling and strategies to manage resources sustainably

Data is only useful when it is transformed into knowledge that can be used for decision-making. That is only possible if sufficient institutional capacity is built for managing groundwater resources. To achieve this, it is essential to build the capacity of existing staff and partnerships with research and development organisations to enhance institutional capacity, build knowledge networks, and develop a decision support system for groundwater management.

Key Steps

- Conduct a comprehensive training needs assessment.
- Assess the capacity of the departments.
- Develop a comprehensive training implementation plan.
- Training of trainers.

6.7 Monitoring plan outcomes

Resource condition: A well-planned monitoring network will also provide crucial data on water levels, water quality, and the impact of climate on the resource.

Resource use: A well-planned monitoring network will provide useful data on the groundwater system and help minimise uncertainty in current and future groundwater resource availability and use.

Data infrastructure: A well-designed data information system will allow systematic archiving of data, quality checking data, and allow data to be shared between agencies, researchers, communities, and civil society.

Sustainable yield: A well-planned monitoring network will provide crucial data for developing groundwater models to estimate sustainable yields at the sub-basin and canal command area levels.

Manage pollution: Monitoring to identify pollution hotspots and sources and minimising pollution from various sources is essential to improve the condition of the groundwater source.

Water sources: Identify the availability and reliability of alternative water source options.

Management decisions: Data from the monitoring network will allow for evidence-based management decisions and influence data collection efforts to streamline and improve data collection.

Groundwater management strategies: Analysis of monitoring data can provide advice on improved groundwater management strategies to manage and minimise groundwater depletion and water quality decline in agricultural areas where groundwater is depleted as well as monitoring and controlling extractions by industries relying on groundwater.

Institutional capacity: Improving institutional capacity for efficient management and delivery of services is essential for achieving equitable outcomes.

Cost savings for the Government of Sindh: Currently, there are over several hundred non-functional bores. There is a significant cost involved in drilling bores and if these are non-functional, they do not serve any purpose. A well-designed groundwater monitoring system that is maintained regularly, with proper design of monitoring bores, is essential for the judicious use of investment funds in monitoring systems.

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8. Appendix A

This Appendix summarises the roles of key national and provincial organisations involved in groundwater monitoring, including details about the monitoring infrastructure used.

8.1 SCARP Monitoring Organization (SMO)

The most systematic groundwater monitoring in Sindh was carried out by the SCARP Monitoring Organization (SMO) as part of WAPDA's efforts to evaluate the success of drainage projects. The parameters monitored were depth to water, EC, TDS, pH, and total anions and cations, which were measured biannually during the pre- and post-monsoon seasons. Of the 2758 monitoring bores, 1482 are being monitored, which includes 840 shallow monitoring wells, 440 open wells, and 202 deep tubewells while the remaining 1276 bores are non-functional. Data consistency is a serious concern as many monitoring wells do not have correct coordinates or have partial data. Monitoring of this network ceased in 2015 due to funding constraints. It was partially restarted in 2018–2019. The locations of groundwater observation points across Sindh are given in Figure 6 (which includes a small area where the IBIS extends into Balochistan).

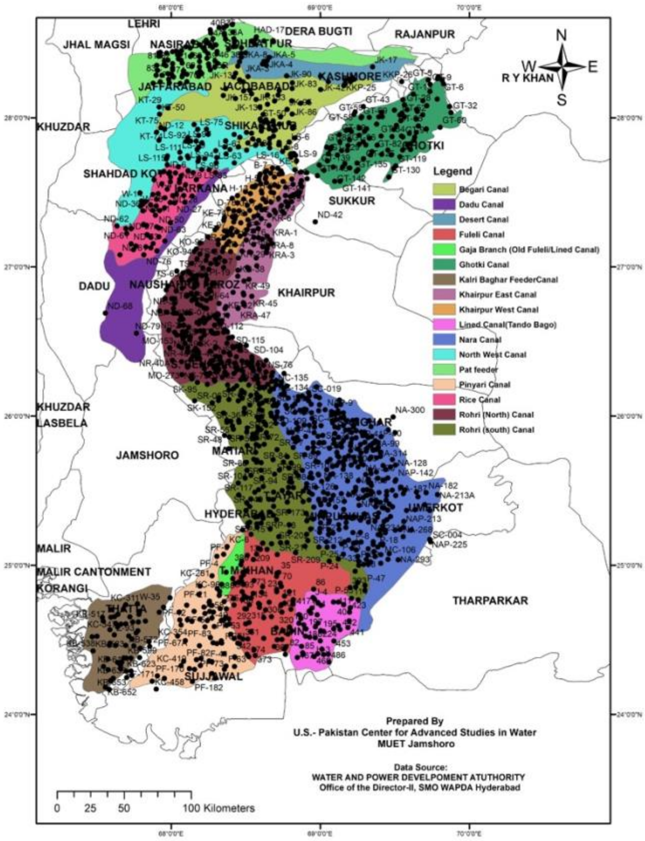

Figure 6: SMO functional observation points in Sindh and Balochistan.

8.2 Sindh Irrigation Department (SID)

Between 1970 and 2000, there has been a gradual handover of SCARP tubewells to the Sindh Irrigation Department. At present, the Sindh Irrigation Department and Sindh Irrigation and Drainage Authority are responsible for operations, maintenance, and rehabilitation of SCARP tubewells; however, many tubewells are not functional due to a lack of maintenance. Table 2 lists the SCARP and LBOD tubewells that are now the responsibility of the Sindh Irrigation Department. These tubewells are managed under different drainage divisions. As of 2020, 36% of all tubewells are non-functional due to various faults (based on data proved by the SID) (Table 2).

The Sindh Irrigation Department also works on schemes in the Annual Development Plans (ADP), which include the rehabilitation of drainage schemes, old tubewells, and pumping stations, the installation of new tubewells (including solar tubewells), and the remodelling and lining of drains. Under the 250 No. Solar Tubewell in the Sindh project, the Sindh Irrigation Department has subsidised the installation of 106 solar tubewells in fresh and saline zones. Unfortunately, these tubewells have been installed without undertaking site investigations, monitoring and water balance studies to understand the recharge and discharge from the aquifer, which makes it difficult to devise an appropriate operational strategy for these tubewells to allow the freshwater aquifer to be used sustainably.

Table 2: Status of pumping tubewells in SCARP and LBOD divisions (based on 2018 data provided by SID).

Project	Division	Sub Division	Total Tubewells	Tubewells under Defects/ Faults						Non Operational Tubewells	Operational Tubewells	Non-operation Tube wells
				Transformers theft/ Burnt	11 KVA Line	Bore failure	Motor Burnt/ Defect	Pump Defect	Control Panel Defect			
Ghotki Fresh Ground Water Project	Tubewell Division Ghotki	Tubewell Sub-Division Ubauro	217	12	1	7	7	7	-	34	183	15.66
		Tubewell Sub-Division Ghotki - I	205	10	3	6	20	10	-	49	156	23.9
		Tubewell Sub-Division Ghotki - II	207	33	7	2	5	5	-	52	155	25.12
		Tubewell Sub-Division Pano Akil -I	273	13	7	3	10	8	-	41	232	15
		Tubewell Sub-Division Pano Akil -II	190	20	13	-	5	3	-	41	149	21.57
		Sub Total	**1092**	**88**	**31**	**18**	**47**	**33**	**-**	**217**	**875**	**19.87%**
Khairpur SCARP Project	Tube well Division Khairpur	Tube Well Sub Division Khairpur	179	60	16	19	5	-	5	105	74	58.6
		Tube Well Sub Division Kotdiji	146	41	15	13	5	3	4	81	65	55.4
		Tube Well Sub Division Gambat	177	61	3	1	17	6	4	98	79	44.6
		Tube Well Sub Division Ranipur	143	20	5	28	14	3	2	72	71	49.6
		Sub Total	**645**	**182**	**39**	**61**	**41**	**12**	**15**	**356**	**289**	**55.1**
North Rohri Fresh Ground Water Project	Tube well Division Nowshero feroz	Tubewells Mech. Sub Division N.Feroz	234	51	1	48	12	2	-	114	120	48.7
		Tubewells Civil Sub Division N.Feroz	226	55	-	32	15	2	2	106	120	46.9
		Tubewells Sub Division Kandyaro	121	8	-	30	-	1	-	39	82	32.23
		Sub Total	**581**	**114**	**1**	**110**	**27**	**5**	**2**	**259**	**322**	**44.50%**
South Rohri Fresh	Tube well Division No. 1 Hala	Tubewell Sub-Division Hala	161	28	1	7	3	16	1	56	105	34.7
		Tubewell Sub-Division Saeedabad	119	27	1	5	5	10	-	48	71	40.3
		Tubewell Sub-Division Shadadpur	200	45	1	2	9	13	3	73	127	36.5
		Tubewell Sub-Division Hala & Matyari	110	17	-	-	5	-	2	24	86	21.8
	Tube well Division No.2 Hala	Tubewell Sub-Division Tandojam	216	27	-	11	13	11	-	62	154	28.7
		Tubewell Sub-Division TandoAdam	213	35	-	8	-	9	-	52	161	24.4
		Tubewell Sub-Division Tando Allhyar	203	26	-	1	9	10	1	47	156	23.15
		Sub Total	**1222**	**205**	**3**	**34**	**44**	**69**	**7**	**362**	**860**	**29.62%**
Nawabshah Component	Drainage Division LBOD Nawabshah	Drainage Sub-Division Daur	277	43	55	13	6	21	-	138	139	49.8
		Drainage Sub Division-I Nawabshah	203	39	45	3	11	9	-	107	96	52.7
		Drainage Sub Division-II Nawabshah	162	18	33	17	9	3	-	80	82	49.3
		Sub Total	**642**	**100**	**133**	**33**	**26**	**33**	**-**	**325**	**317**	**50.60%**
Sanghar Component LBOD	Drainage Division LBOD Sanghar	Drainage Sub Division - I North Sanghar	258	24	7	1	25	3	3	63	195	24.4
		Drainage Sub Division - II South Sanghar	151	10	53	1	5	4	2	75	76	49.6
		Drainage Sub Division -III Central Sanghar	216	27	10	1	8	4	-	50	166	23.1
		Scavenger Sub Division Sanghar	171	23	-	2	10	-	1	36	135	21
		Sub Total	**796**	**75**	**70**	**5**	**48**	**11**	**6**	**224**	**572**	**28.10%**
Mirpurkhas Component LBOD	Drainage Division Mirpurkhas	Drainage Sub Division Mirpurkhas	169	26	25	-	5	4	6	66	103	39
	Drainage Division Badin	Sub Division Kot Ghulam Muhammad	191	10	75	-	22	5	10	122	69	63.87
		Sub Total	**360**	**36**	**100**	**-**	**27**	**9**	**16**	**188**	**172**	**52%**
Grand Total			**5338**	**800**	**377**	**261**	**260**	**172**	**46**	**1931**	**3407**	**36%**

8.3 Sindh Irrigation and Drainage Authority (SIDA)

The SCARP Ghotki Fresh Water Tubewell project was handed over to the Sindh Irrigation Department in three phases – 410 tubewells in 1984, 273 tubewells in 1990, and 397 tubewells in 1992, and the Government of Sindh installed 12 tubewells. A total of 1092 tubewells were installed during this period. Later, in 2001–2002, the Ghotki freshwater project was transferred from the Irrigation Department to Ghotki Feeder Area Water Board of SIDA. A report by the Ghotki Feeder Area Water Board in 2021 has indicated that 506 (46%) tubewells are non-functional. The high number of non-functional tubewells seems to be a common issue across the Indus Basin. Recent studies of the Indus Basin (Lytton et al., 2021) have indicated the need to address this issue by establishing drilling standards for monitoring bores.

8.4 Pakistan Council of Research in Water Resources (PCRWR)

The Pakistan Council of Research in Water Resources (PCRWR), part of the Pakistan Government's Ministry of Science and Technology, has launched several studies related to water management and quality monitoring. Recent projects cover the mapping of groundwater quality zones in the Lower Indus Plains (Salam et al., 2023), managing aquifer recharge (Arshad et al., 2023), and reviewing arsenic levels in groundwater (Hifza et al., 2023).

8.5 US Pakistan Center for Advanced Studies in Water-Mehran UET, Jamshoro

The US Pakistan Center for Advanced Studies in Water at Mehran University of Engineering and Technology Jamshoro, in collaboration with the SID funded by the Australian Centre for International Agriculture Research (ACIAR) and Charles Sturt University (CSU) Australia, undertook monitoring in the Malwah distributary command and extensive groundwater modelling of the Northern Rohri command, Sindh as part of the *Improving Groundwater Management to Enhance Agriculture and Farming Livelihoods in Pakistan*. The modelling studies provided water balance for the modelled area covering the districts of Khairpur, Sukkur, Naushero Feroze, and Shaheed Benazirabad and provided a sustainable extraction limit for the area. Additionally, climate change scenarios were simulated to understand the possible impacts of climate change until 2040.

As part of this project on *Adapting to Salinity in the Southern Indus Basin*, funded by ACIAR and Charles Sturt University, a database for the study area was compiled from data used for modelling and field studies data. Datasets from remote sensing of rainfall and evapotranspiration as well as river and canal data are available in this database. A detailed groundwater model for the coastal district of Sujawal was also developed, which simulated the impacts of reduced flows and climate change on waterlogging and salinity in the Pinyari command and the risk of seawater intrusion in the coastal zone of Sindh.

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