Groundwater Policy Brief for Southern Punjab

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Increasing reliance on groundwater to supplement crop water requirements is leading to steady declines in watertables in many parts of the world, but more so in China, India, and Pakistan. To try to achieve sustainable groundwater use, resource managers and water policy experts have long advocated the need to improve irrigation efficiency. However, the perceived water savings is often used to expand irrigation or increase cropping intensities. The recent trend in Punjab is towards regulating the use of groundwater. However, this is politically unpalatable as there is a strong link between groundwater use and improved food security and livelihood outcomes.[1] As a common pool resource, groundwater and its use is dispersed widely among many thousands of smallholder farmers. This makes regulation a daunting task and implementation of a regulatory framework near impossible. And the issue is not just about depletion, The emergence of groundwater pollution and increased salinity from overexploitation are now significant concerns for policymakers.

A key barrier to improved groundwater management is the need to first build the technical capacity of relevant institutions to improve (1) monitoring systems, (2) archiving and accessibility to groundwater data, (3) modelling groundwater systems to understand the water budget and likely impacts of climate change, and (4) 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.

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[1] Imran, M., Ali, A., Ashfaq, M., Hassan, S., Culas, R., & Ma, C. (2018). Impact of Climate Smart Agriculture (CSA) Practices on Cotton Production and Livelihood of Farmers in Punjab, Pakistan. *Sustainability, 10*(6). https://doi.org/10.3390/su10062101

What has changed: Irrigated agriculture has played an important role in enhancing Pakistan's food security and economic sustainability. The role of surface water irrigation remains pivotal in agricultural production. However, in recent decades, the share of irrigation from groundwater has increased exponentially. An estimated 1.2 million tubewells in Punjab extract over 55 billion cubic metres of groundwater annually from the Indus Basin aquifer. This results in continuously declining groundwater levels in the eastern doabs[2] of Punjab and increasingly deteriorating water quality. Of particular conern to farmers are declining groundwater levels and associated salinity impacts on soils and cropping systems. Nowhere are the impacts of salinity felt more than in large parts of Southern Punjab, where the use of groundwater in some cases exceeds the surface water supplied for irrigation. This will have far-reaching consequences for farming communities and will increase the vulnerability of smallholder farmers.

With the exponential increase in groundwater use in Punjab since the 1990s, the decline of groundwater levels has been of increasing concern among policymakers. Much focus has been on improving on-farm water use efficiency, but there have been no tangible results in decreasing groundwater usage. What is needed then is not a simple *one-size-fits-all solution or policy*. What is needed is a paradigm shift on how we monitor and manage groundwater levels and quality, where management approaches are varied to suit specific situations, demand, and 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 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 multi-disciplinary, combining remote sensing and groundwater modeeling with a strong social research component to work closely with affected communities. The two study areas used for remote sensing and groundwater modelling are the Southern Bari doab in Southern 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 salinity, and seawater intrusion in the Indus delta regions are significant issues affecting coastal communities.

This study developed a groundwater model of the Southern Bari doab (Figure 1) to simulate scenarios that help understand impacts of climate change and increased groundwater pumping on the aquifer system.

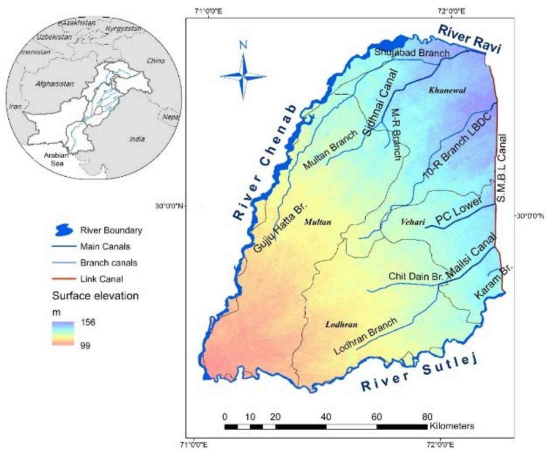

Figure 1 Location of the Southern Bari doab

Pumping in the Southern Bari doab has increased continuously over the past four decades. Figure 2 shows the increase in the number of tubewells from 2010 to 2020.

[2] Doab is the interfluvial land between two rivers.

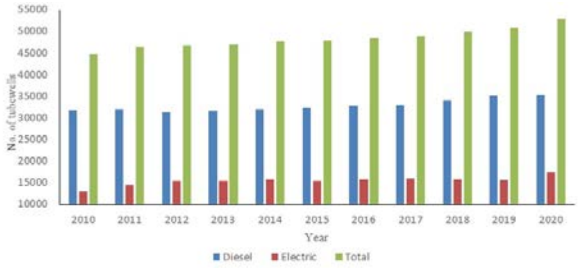

Figure 2. Tubewells in the study area (2010–2020)

We also simulated adaptation strategies that will be useful for policymakers. Understanding aquifer behaviour in response to system stresses will improve how institutional actors manage and govern groundwater use.

Groundwater modelling outcomes: A groundwater model was developed in collaboration with the Punjab Irrigation Department (PID) for the Southern Bari doab in Southern Punjab. The study area of 11,348 km^2 traverses four major districts: Multan, Khanewal, Vehari, and Lodhran. The area forms a large triangle with the Chenab River on the western boundary, the Sutlej River on the eastern end, and the southernmost point forming the confluence of the Sutlej and Chenab Rivers. The irrigation network in the area involves three major irrigation canals, Sidhnai, Pakpattan Lower, and Mailsi, as well as the Sidhnai-Mailsi Link Canal, and several branch canals. A conceptual model of the Southern Bari doab is shown in Figure 3.

Figure 3. Conceptual model of the Southern Bari doab

An analysis of the water balance from the groundwater model indicated that the average annual river and canal seepage over the 10 years from 2010 to 2020 was 1,647.9 MCM/year, while the recharge from field application losses of surface supplies and pumping return flow was 1,484.7 MCM/year. The annual average groundwater extraction was modelled at 3,355.5 MCM/year, representing 92% of the total outflows from the aquifer and resulting in a decline in net storage of -533.4 MCM/year. The water balance shows an imbalance between the aquifer's inflows and outflows, resulting in an annual loss in groundwater storage, which is evidence of high pumping in the Southern Bari doab. Crucially, the water balance also indicates that attempts to limit seepage from the canal supply system will accelerate the decline in groundwater levels since about 53% of groundwater is replenished by canal seepage. Analysis of the different layers in the model further indicates that groundwater outflows of 3,355.5 MCM/year occur from the top layer of the aquifer to Layer 2, which indicates that Layer 1 is being depleted gradually in response to pumping.

What the water balance does not tell us is how long the aquifer can cope with this level of stress, what the impacts on groundwater levels will be in the next 50 years, nor the unintended consequences of global warming, which is resulting in climate change and already altering the functioning of natural ecosystems, including groundwater.[3] Pakistan is especially susceptible to climate change and is ranked the seventh most affected country in the Global Climate Risk Index.[4] To learn about possible future outcomes, we undertook a series of modelling scenarios to quantify the state of the aquifer in response to pumping and climate stress.

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[3] 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*(1), 441. https://doi.org/10.3390/su16010441

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

Model scenarios: We undertook two sets of scenarios to understand the long-term effects of pumping and climate change on the aquifer. The Baseline (*BL*) and Pumping scenario (*PS*) were run from 2010 to 2060, while the climate change scenarios were simulated from 2010 to 2100.

The *BL* scenario simulates pumping based on the pumping level from 2010 to 2020, while the *PS* scenario simulates the response to pumping, which increases based on past trends. Comparisons of these two scenarios showed that the top Layer 1 would continue to be depleted in response to pumping concentrated in the deeper Layer 2, similar to the finding for the calibrated model. The important difference is that net inflows to Layer 2 from the top layer are 3,079.7 and 3,252.7 MCM/year for the *BL* and *PS* scenarios, respectively, confirming the ongoing depletion of the top layer. This means that declining groundwater levels will impact pumping costs as the pumping lift will increase. Some farmers with shallow tubewells will lose access to groundwater for irrigation, forcing them to increase tubewell depth with the possible need for submersible pumps – expensive alternatives for smallholder farmers.

The dynamic interaction of Layer 2 with the deeper Layer 3 is also equally concerning. Pumping in Layer 2 results in enhancing upward flows from Layer 3. The net flows from Layer 3 to the middle Layer 2 are 234.6 and 748.5 MCM/year for the *BL* and *PS* scenarios, respectively. This finding shows that increased pumping will increase inflows from Layer 3, which will consequently impact salt transport from the underlying deeper strata of the aquifer. We did not have EC measurements in Layer 3 as the existing network of monitoring bores does not monitor this data. Taking EC values for Layer 2 and a conservative estimated average salinity of 1,400 µS/cm provides an estimate of 0.21 and 0.67 million tons of salt transported annually from Layer 3 to Layer 2 for the *BL* and *PS* scenarios, respectively.

The groundwater pumped for irrigation from the large number of tubewells in the Southern Bari doab will transport these dissolved salts onto the soil surface, adding to the salinity loading of the crop root zone. To manage this increasing salinity, irrigation and on-farm water management departments must undertake knowledge transfer programs on conjunctive use practices to ensure that salt accumulation can be managed. To understand why this is important, we refer to studies[5,6] that indicate increasing salinity with depth in the Indus Basin aquifer. This means that these upward flows will enhance salinity mobilisation, deteriorate water quality in Layer 2 over the long-term, and result in groundwater pumping for irrigation of higher salinity.

The change in EC from 2010 to 2020 in Figure 4 shows that within 10 years, the EC over a large area in Layer 2 has transformed from relatively fresh areas to marginal quality, indicating the impact of high pumping rates on salinity mobilisation. Over the long-term, the sustainability of the current system will be at risk from declining water quality, and declining water levels in Layer 1 will increase pumping costs for farmers and costs for deepening wells for smallholder farmers. The costs associated with drilling deeper wells may exclude some farmers from using groundwater for irrigation.

[5] 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.

[6] 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*(1), 441. https://doi.org/10.3390/su16010441

Climate change impacts: For climate change scenarios, rainfall recharge and evapo-transpiration were estimated based on rainfall and temperature projections, pumping was increased using historical trends during 2010–2020, and canal supplies were similar to those from 2010 to 2020. The simulated scenarios for SSP2-4.5[7] and SSP5-8.5 showed significantly alarming trends. The net loss in groundwater storage is projected at -2,192.2 and -2,204.6 MCM/year under the SSP2-4.5 and SSP5-8.5 scenarios, respectively. This represents a significant decline in net storage compared to -517 MCM/year for the calibrated model, which will accelerate depletion in the top layer along with water quality decline. Moreover, the rate of decline accelerates over time. The increased Pumping scenario (PS), which simulates pumping increasing based on the historical trend from 2010 to 2020, indicates the net loss in groundwater storage has declined to -939.6 MCM/year. The hydrographs presented in Figure 5 demonstrate an inflection point around 2040, indicating that a sustained increase in pumping beyond 2040 will result in significant declines in water levels and increased salinity mobilisation from deeper layers resulting from the stresses imposed on the aquifer.

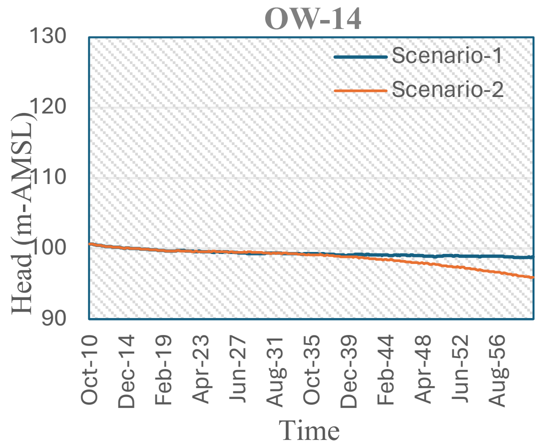

Figure 5. Simulated heads for the baseline (1) and increased pumping (2) scenarios.

The water balance shows enhanced depletion in all layers. In Figure 6, the depth to watertable for the pre-monsoon period shows that by 2020, hotspots designated by the dark red areas have started to develop along the southern parts of the study area between Jehanian and Lodhran. These areas are likely to increase in the future as pumping and climate stresses increase.

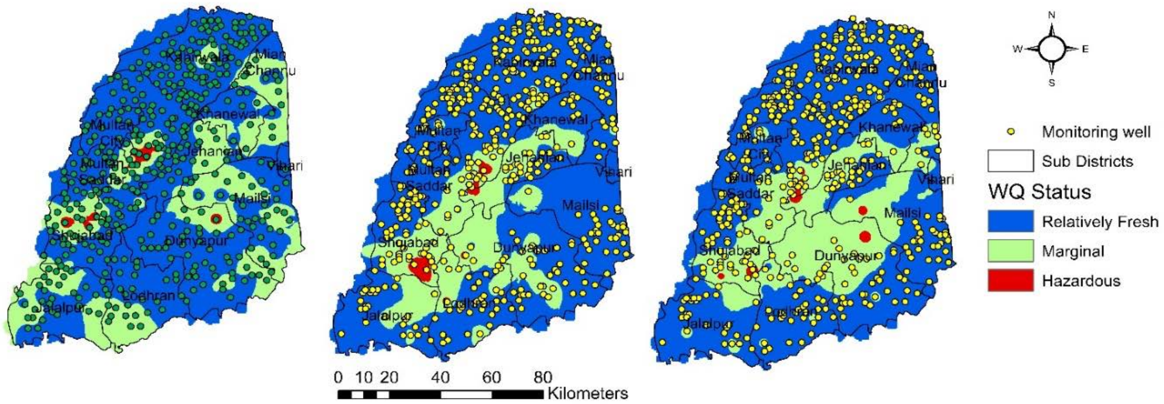

Figure 4. Spatiotemporal variation in EC for Pre- 2010, 2015 and 2019

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

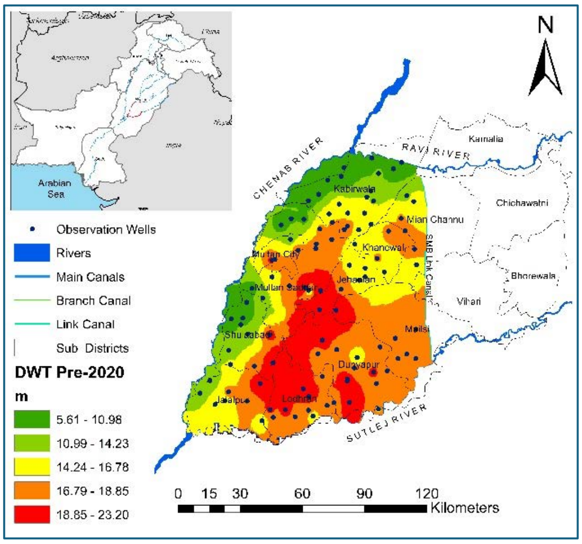

Figure 6. Simulated depth to water in pre-monsoon 2020 (m).

The simulated heads in 2100 for the SSP5-8.5 climate scenario in Figure 7 indicate the extent of depletion in the top layer. The maroon colour indicates the drying out of a large area by 2100, which will harm smallholder farmers relying on shallow tubewells for irrigation. It will also mean households relying on handpumps for potable water supply will be denied access to groundwater, with far-reaching impacts on health and livelihoods.

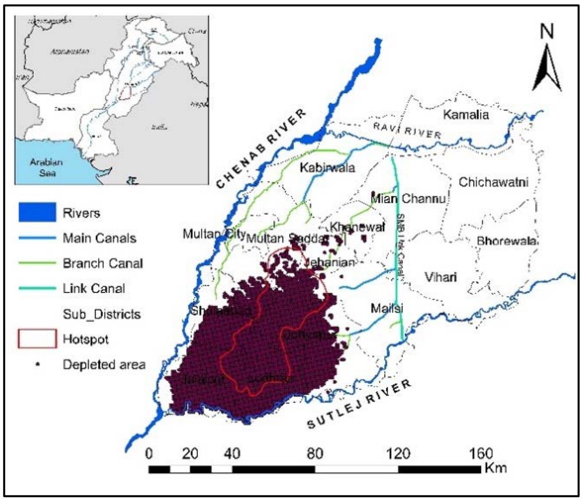

Figure 7. Water levels (m MSL) in the top layer for SPP5-8.5 scenario.

Understanding the salt balance: In the Southern Bari doab, groundwater pumping from 2010–2020 averaged 3,355 MCM/year. The average groundwater salinity was estimated to be 1,000 µS/cm from 2010 to 2020, with 20% return flows resulting in 1.7 million tons of salt deposited in the root zone. The estimated salt load for the Indus Basin is about 1 ton/ha; however, our estimate for Southern Punjab is conservatively 1.48 tons/ha, which increases the risk of salinisation for agricultural lands in Southern Punjab.

Pumping trends continue to increase until 2100 for the climate change scenarios. To compensate for the increased pumping in Layer 2, the net outflows from the deeper Layer 3 to Layer 2 will also increase to 1,779.1 and 1,789.5 MCM/year for the SSP2-4.5 and SSP5-8.5 scenarios, respectively. These net inflows will result in significant transport of dissolved salts, which will be pumped from Layer-2 for irrigation. Using conservative estimates of groundwater salinity (1400 µS/cm), about 1.59 million tons of salt will be transported annually from Layer-3 to Layer-2 under the climate change scenarios. Since most of the irrigation pumping occurs from Layer-2, groundwater salinities will inevitably increase over time. An analysis of the pumping from 2010–2100 and 2090–2100 indicates that pumping will increase under the SSP2-4.5 climate regime from 5,574 to 8,723 MCM/year, respectively. This has huge implications for salt transport – salt deposition in the root zone will increase to 5.37 tons/ha between 2090 and 2100. This level of salt transport will result in an existential threat to farming livelihoods in Southern Punjab.

These climate scenarios tell us that the increasing pumping trends under climate change scenarios will not be sustainable, resulting in significant declines in net storage, water levels, and water quality. Water levels for both climate scenarios will rapidly decline, particularly beyond 2040, after which the declines accelerate. The drying out of a large part of Layer 1 will significantly impact farmers, who will be forced to deepen wells to access groundwater and increasingly use groundwater with higher salinity levels. In the worst-case scenario, farmers will be forced to abandon groundwater irrigation, which will impact food security in Southern Punjab. The dewatering of Layer 1 in response to pumping in Layer 2 is of particular concern for smallholder farmers who may have restricted access to groundwater. Equally concerning is the increased inflow into Layer 2 from the deeper Layer 3, which amplifies the risk of salt mobilisation. This, in turn, will result in the extraction of groundwater of higher salinity, adding to the buildup of salts in the crop rooting zone.

Adaptation options can help communities achieve a sustainable future: We also developed a scenario to investigate which combination of adaptation options could help communities achieve a sustainable future. The simulated adaptation options for the Southern Bari doab included replacing between 20% and 30% of the existing high-water use crops, such as cotton, rice, and sugarcane, with low delta crops, mainly mung beans and onions; simulating flood flows in the River Chenab and Ravi; and environmental amelioration of the riverine corridors. Despite including these adaptation options, the result would be a significant loss in net storage in the underlying aquifer of 681 MCM/year compared to -939.6 MCM/year for the PS scenario. A simulation without the recharge option indicated a loss in groundwater storage of -773 MCM/year, which indicates that the inclusion of the recharge options by simulating flood flows adds 92 MCM/year to groundwater storage.

Moderating the impacts of overexploitation of groundwater and insufficient surface water supply under projected climate change conditions will require additional options for managing groundwater sustainably. A vital component for designing additional adaptation options will require a groundwater management plan for the area and the co-development of a water-sharing plan with strong community buy-in. As knowledge of the area increases and there is greater trust between institutional actors and groundwater users of the Southern Bari doab, the regulation of pumping may also be required in hotspots to allow equitable access to groundwater for smallholder farmers. This will be vital to develop strategies for a sustainable future for all farmers in Southern Punjab.

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 policy was endorsed by the Council of Common Interests, which 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 deserves 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 lateral/vertical movements 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 that pumping must be regulated*. The policy also prioritises investment in groundwater recharge schemes. Its objectives broadly call for improving groundwater management in Pakistan by strengthening water sector institutions and associated capacity building, upgrading of information systems for evidence-based decision-making, improving asset management, and restoring and maintaining the health of the environment and water-related ecosystems.

The Government of Punjab also developed the Punjab Water Policy (2018) to guide sustainable groundwater management. The PWP highlights the importance of groundwater resources in Punjab and provides directives for managing groundwater abstraction for agricultural production, minimising the impact of soil salinisation, and preventing water quality deterioration to minimise health impacts. The central theme is balancing recharge and groundwater abstractions through monitoring and regulation, reallocating canal allowances, and promoting artificial recharge in communities. The policy focuses on enhancing water availability and improving water quality to ensure improved potable water supplies for communities, the use of groundwater as a buffer during droughts, water conservation, and managing waterlogging and salinity.

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, water development, and water management efforts.

Both the NWP and the PWP emphasise the establishment of monitoring networks, setting sustainable groundwater yields, and avoiding the vertical movement of saline water.

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

Monitoring Strategy: Given the backdrop of the NWP and the 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, allowing informed decisions on managing the resource. Monitoring also needs to be strategic, targeting areas where groundwater levels are declining to help understand the risks posed by increasing salinity and declining water quality.

Significant reliability issues exist with the existing network, which has many non-functioning monitoring bores (see Figure 8). Moreover, the locations of these bores are not ideal; they are often situated in secure sites in government schools and villages rather than in the field where groundwater pumping occurs. In Punjab, where groundwater use for irrigation is equal to that of surface water, accurate and reliable groundwater information is essential. Areas of relatively high groundwater exploitation require a robust monitoring system on a priority basis.

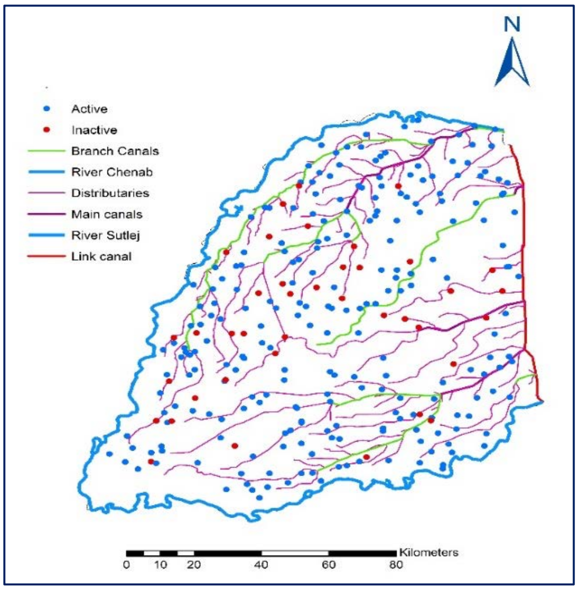

Figure 8 Location of active and inactive monitoring bores in the study area

The 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. For instance, some handpumps in the Southern Bari doab access shallow groundwater near canals; however, there are more bores at deeper depths between 30m and 60m. So, monitoring only the top 30m will not fully capture the changes occurring in the aquifer in response to pumping stresses. Adequate spatial and temporal monitoring data are key elements for improving the understanding of groundwater resources and for governments to make informed decisions. Investment to establish monitoring infrastructure will also require institutional arrangements for regularly monitoring and maintaining assets, including data sources.

Monitoring and managing data: Groundwater data and monitoring and mapping water resources in sub-basins must 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 require a unique identification number linked to each sub-basin. Similarly, each production bore or tubewell must have a unique identifier. The integrity of the data and quality control are required to ensure that duplication and errors in the data are removed.

All data need clear, self-explanatory metadata; the temporal data (canal flows, groundwater levels, and water quality measurements, etc.) need a separate and accessible database. In other words, the spatial data should be separated from temporal data; and groundwater and other relevant data sets from various organisations should be integrated into the WRIS.

It will be critical to have an institutional home in Punjab. For example, the Water Resources Zone in the PID, where data can be stored, updated and managed and made available and which will engender resource ownership. Managing data sources is a key aspect of ensuring that government agencies, researchers and academics have access to data to provide timely advice to the government and improve the sustainable use of groundwater resources.

Modelling the resource: There is often a misconception that once a model has been developed there is no need for any additional modelling or upgrading of the models. This erroneous thinking leaves the management of resources in limbo. Models are useful tools, and in most countries where groundwater management has advanced models are developed and updated every 5–10 years to understand how aquifer behaviour is changing with increasing system stresses. Models also allow an estimate of the sustainable yield, giving resource managers insights into sustainable limits to 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 5–10 years of application based on a water sharing plan developed with stakeholder agreement. The extraction limits can also be revised in response to droughts or increased development of groundwater use in the management area to minimise the 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 the Southern Bari doab in Punjab. This would rely on having revised and improved groundwater models in place. Crucially, the PID as the resource manager would need significant capacity enhancement in groundwater planning and management to develop a sound understanding of the risks to groundwater from overexploitation and salinity intrusion and to codevelop strategies to improve the management of groundwater resources with affected communities for a sustainable future

Understanding the water balance: This study has shown that increasing groundwater use results in continuously declining levels and increased salt loading in the crop root zone. It is common to observe tubewells being operated for long periods (see Figure 9) in Jalalpur Peerwala, where declining groundwater levels and increasing salinity and sodicity are of concern.

Figure 9. Pumping groundwater for supplementary irrigation in Jalalpur Peerwala, Punjab. *Photo courtesy of M. Faisal Riaz.*

Groundwater is also abstracted by numerous privately owned tubewells in new housing communities, which are sometimes adjacent to agricultural areas. Growth in groundwater demand for domestic purposes is projected to increase by 4.85 BCM by 2050[8]. Hence, there is an imperative to monitor usage by large users and users of high-security water.

In the not-too-distant future, some regulation of pumping will be required to control pumping in hotspots and to licence and regulate large water users. Individual hotspots in these areas will require enhanced monitoring and recharge or limits on groundwater exploitation, ongoing review and adaptive management, and steps to safeguard and improve water quality management. However, a word of caution is warranted. Groundwater management in Punjab is fraught with difficulties as many smallholder farmers rely on over 1.2 million tubewells. These smallholder farmers underpin the future of water productivity improvements and economic development of the agricultural sector in Punjab. To develop effective groundwater management plans, the PID will need to 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. It will be impossible to implement groundwater management plans without a participatory and consensus approach involving groundwater users, especially farming communities. The PID 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.

Depletion in the Southern Bari doab gradually increases in response to the intensification of tubewells. However, individual hotspots in these areas require monitoring and improved groundwater management. The change in EC from 2010 to 2020, as shown in Figure 4, indicates that significant areas of the deeper aquifer from 30 m to 100 m have transformed from relatively fresh groundwater to marginal quality groundwater. These areas will require close monitoring of water levels, EC, SAR and RSC so farmers can receive appropriate advice.

Ongoing monitoring is also needed in other areas as there is little or no data in areas along the right bank of the Sutlej River. Strategic monitoring points in areas showing high EC and SAR need reporting mechanisms which are available to provide practical advice for the farming communities in those areas.

Developing models at the sub-regional scale will be useful for the Punjab Irrigation Department in improving the planning and management of surface and groundwater resources. These models can be used for conjunctive management planning and provide the basis for models at the canal command scale with spatiotemporal improvements for groundwater monitoring. As the share of surface water decreases, reliance on groundwater pumping will increase, resulting in continued declines in groundwater levels in the lower regions of the doabs. Consequently, there will be increased pressure on government agencies to find socially and technically acceptable solutions and give due consideration to the environment. Robust models at the sub-regional and canal command scales will allow for the improved management of hotspots and, crucially, the evolution of strategies for equitable water-sharing plans.

Climate change will impact groundwater: Climate change impacts groundwater recharge and exacerbates uncertainties for future access and use, especially for large aquifers across alluvial plains, such as the Indus Basin of Pakistan. Under the impact of climate change and escalating groundwater usage, our study demonstrates that large areas of the upper aquifer will be depleted up to and possibly beyond 30 m. Managing both depletion and water quality will require a rethink of groundwater management in Punjab. This will involve management of hotspots, licensing and regulation of high security and large water users, equitable sharing of groundwater, and improved knowledge transfer on water quantity and quality for farming communities.

[8] 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.

The need to adapt to preserve our water future: Changes in the groundwater regime take time, and no one solution can manage the overexploitation of groundwater in Southern Punjab. Our approach did not include any direct regulatory mechanisms for reducing the rate of groundwater extraction, due in part to the lack of regulation for groundwater use and the absence of controls on tubewell installation. Rather, we took the approach that partially changing the cropping patterns towards less water-intensive crops suitable for the agroclimatic zone of Southern Punjab would be 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 Southern Bari doab included: (i) changing a portion of the high water use crops such as cotton, rice, and sugarcane with low delta crops, e.g., mung beans and onions; (ii) simulating flood flows; and (iii) environmental amelioration of the riverine corridors along the Chenab River. The results of this scenario indicate that despite the adaptation options the resulting loss in net storage in the underlying aquifer would be -681.3 MCM/year. We also found that capturing monsoon flood flows in the Chenab and Sutlej Rivers offers opportunities for enhancing recharge to the aquifer, which enhances storage in the aquifer.

Our simulations indicated that despite the inclusion of adaptation options, there will still be a significant loss in net storage in the underlying aquifer. Thus, additional options for managing groundwater sustainably will be required, including resource planning and management and the co-development of a water sharing plan with strong community buy-in. As knowledge of the area increases and trust is built within the community of groundwater users of the Southern Bari doab, difficult discussions on the regulation of pumping may also be required in hotspots to allow equitable access to groundwater for smallholder farmers. We expect that a range of new adaptation options will be required to assist in developing strategies for a sustainable future.

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 socioecological specialists, and policy experts with improved gender balance will be crucial to the success of groundwater planning and management in Punjab.

Systemic Co-inquiry: The Punjab level groundwater management planning process, where the institution is the main focus, involves over 8 million ha of irrigated agriculture land and 1.2 million tubewells (a scale larger than the size of many countries). 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 PID*) which allows people with differing experience, backgrounds and perspectives to have their voices heard for a given situation of concern (*in this case it is groundwater depletion and groundwater quality deterioration*). The co-inquiry process is designed to enable the emergence of ideas and opportunities for improving the situation and to co-develop an inclusive (*though still partial*) view of what the current situation is, 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 over which changed practices can be implemented. To improve the sustainability of the aquifer with 1.2 million tubewell users will require the PID 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.