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project

Improving Groundwater Management to Enhance Agriculture and Farming Livelihoods in Pakistan

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1 Executive summary

Pakistan's population of over 220 million relies heavily on its agriculture-based economy, and especially on irrigated agriculture. The centrally managed surface water supply across the Indus River Basin is insufficient to support current agricultural practice, and dependence on groundwater has rapidly increased in the Indus Basin provinces of Punjab and Sindh. In Balochistan, irrigators rely almost entirely on groundwater, and the province has witnessed some of the most rapid rates of depletion. The governance and management of water in Pakistan is transitioning from a situation characterised by little interest in groundwater, towards a future where groundwater issues will be central to planning.

This project aimed to build the capacity of researchers, farmers, farming communities and relevant government and non-government agencies to improve groundwater management in ways that enhance farming family livelihoods in Pakistan. Enhancing farming livelihoods includes ensuring long-term sustainability of agriculture and fairness of consideration across the socio-political spectrum. The project objectives were to:

1. Develop and articulate a shared understanding of sustainable groundwater use for agriculture and the need for improved management in Balochistan, Punjab and Sindh provinces.
2. Develop, with collaborating stakeholders in each case study, groundwater management tools and options that have the potential to enhance livelihoods of farming families.
3. Enhance capacity and institutional arrangements for post project adoption of tools and options developed in Objective 2 by collaborating stakeholder organisations.

This project's theory of change acknowledges the challenges facing farmers by focusing efforts on building the capacities of the organisations, institutions and individuals in and around case study farming communities. The project posits that building the collaborative and adaptive capacity of water management agencies along with increasing their capacity to gather and use information, will enable stronger, better informed water using communities to emerge.

The overall approach was ongoing co-inquiry and co-design; that is, the Project Team took a collaborative, iterative and adaptive approach. To achieve the objectives and make real impacts knowledge creation and sharing activities focused on six case study sites: two each in Balochistan, Sindh and Punjab, between 2016 and 2021.

The Project Team, comprising personnel from fifteen organisations, gradually built a strong learning and support network. Capacity in groundwater monitoring was enhanced through improved equipment and software, and skills in groundwater modelling were developed within universities and provincial government Irrigation Departments. These skills enable consideration of the consequences of management actions by governments and individual farmers. Participatory social and economic studies supported development of the project's case study Stakeholder Forums, deliberative spaces where information and learning could be shared among agency staff, farmers, universities and non-government organisations, and where water efficient farming systems could be developed and trialled, supported by apps and equipment.

The story of groundwater in Pakistan that we tell in this report is one of hope and despair. In Punjab, Sindh and Balochistan a range of practices need to change, including greater adoption of low water use (low delta) crops and improved irrigation and land management. While specifics will vary, common to all is that these changes only take place when trust is well established, and quality data are available. Developing trust and creating data sets takes time, but the benefits of that investment are demonstrated by this project, which has had positive impacts on the capacity of the extended agriculture and irrigation community in Balochistan, Punjab and Sindh to act in ways that better manage groundwater.

This project has resulted in significant human and social capital, as well as some infrastructure, being built in some parts of the country. There is some changed awareness and practice in the six sites of the project. These are small steps, and continued investment is needed to turn the small steps into larger ones.

2 Background

2.1 The situation

The aim of this project, initiated in 2015, was to build the capacity of researchers, farmers, farming communities and relevant government and non-government agencies to improve groundwater management in ways that enhance farming family livelihoods in Pakistan.

Pakistan's population of over 220 million relies heavily on its agriculture-based economy. This sector contributes 23% of Gross Domestic Product (Usman 2016) and around 45% of employment (Mahmood & Munir, 2018). Agriculture also accounts for around 95% of the country's water consumption (Young et al. 2019). With growing demand for water, the stress on available resources is also increasing. The traditional source of water, centrally managed and supplied from rivers via surface infrastructure, is insufficient to support current agricultural practice. Surface water supply is highly variable, particularly for farmers at the tail (distant) end of supply canal systems in Sindh and Punjab. Because of this, and increased cropping intensities, dependence on groundwater, which is sourced using unregulated tubewells, has rapidly increased. Young et al. (2019) estimate groundwater usage in the Indus Basin as 62 billion cubic metres (BCM) and the net depletion of groundwater is about 1 BCM. The continuous decline of groundwater levels observed throughout the Indus Basin points to an imbalance between extraction and recharge (Ashfaq & Ashraf, 2006, Ashfaq et al., 2006). Groundwater as a source of water for irrigation also underpins the productivity of Balochistan, the so-called 'fruit basket' of Pakistan. Groundwater in Balochistan is available for irrigated agriculture there through tubewells, springs and community based Karezes, but agricultural production is threatened by rapidly depleting groundwater levels (Khair et al., 2011).

The governance and management of groundwater in Pakistan is in a state of transition from little or no attention being given to groundwater resource management, towards a future where groundwater will be required to be managed sustainably for all uses including environmental needs. The key drivers of this transition are:

- the increasing realisation among heads of government that Pakistan faces a bleak, water stressed future as clearly articulated in the National Water Policy (NWP) (Ministry of Water Resources, 2018);
- the passing of the 18th amendment to the Constitution which relegates the responsibility for water resources management to provincial governments;
- increasing awareness among irrigators that unsustainable use of groundwater is resulting in declining groundwater levels which in turn is driving up the cost of pumping, and resulting in water quality decline; and
- the increasing calls for reallocation of water from the agriculture sector to meet domestic demand from increasing urbanisation driven by rural to urban migration. Major cities like Lahore and Multan are entirely dependent on groundwater and an existing project funded by AIIB is planning to divert 10% of Lahore city's water supply from agriculture to meet domestic and industry demand.

Overlaying these drivers is the prospect of a changing climate and its likely impact on both surface and groundwater resources in the long term. Pakistan is now considered a water scarce country (1000 m^3/capita/year) and is likely to reach absolute water scarcity conditions (<500 m^3/capita/year) by 2035 (Muzammil et al., 2020). Diversion of surface water to meet rising urban demand will impact on availability of agricultural water. Pakistan is facing choices; transform its agriculture to use water better or reduce its reliance on agriculture. The latter alternative is disruptive, and not an immediately viable proposition given the country's weak industrial base.

Individual farmers and their communities are vulnerable to loss of livelihood in this uncertain, and rapidly changing situation. The situation is compounded by the scarcity of data on the groundwater that farmers are increasingly accessing, and what data exist are poorly understood by the organisations who collect and manage the data. While assisting farmers and farming communities is an ultimate aim of ACIAR projects, the institutional, social and biophysical complexities by which farmers' choices are constrained mean that focusing only on direct assistance is likely to have little impact.

The complexity and size of the challenge requires an integrated approach towards sustainable management of groundwater to enhance productivity and thereby farming family livelihoods. Integrated management also requires more participatory governance arrangements to enable groundwater users and other relevant stakeholder communities to more effectively engage in the knowledge gathering and decision-making processes determining sustainable and fair use of groundwater (Mitchell et al., 2012).

2.2 Theory of change

This project's theory of change acknowledges the challenges facing farmers by focusing efforts on building the capacities of the organisations, institutions and individuals in and around case study farming communities. The project posits that building the collaborative and adaptive capacity of water management agencies along with increasing their capacity to gather and use information, will enable stronger, better informed water using communities to emerge.

Thus, while this is a project aimed at improving both the livelihoods of farmers and their impact on groundwater management, we consider these ends will be achieved through a variety of enhanced community capacities. This increased capacity should allow all project participants to continue to learn with and support each other, and ultimately support ongoing improvement in community use of groundwater.

2.3 Report structure

The following report summarises the objectives, methods, achievements, results, and impacts, and discusses the implications of this work. Part A provides the overall story of the project, focusing on results, impacts and conclusions. Part B includes additional information on methods as well as detailed results and outputs. Separate detailed reports on individual research and implementation activities have also been produced, and links to these are included (see Section 8.2).

3 Objectives

The aim of this project was to build the capacity of researchers, farmers, farming communities and relevant government and non-government agencies to improve groundwater management in ways that enhance farming family livelihoods in Pakistan.

'Capacity' describes the ability to act. Much of the current and future impact of this project is through increasing the ability of a wide range of people to act in response to increasing groundwater scarcity. Capacity can be understood using a capitals framework; increases or improvements in aspects of human, infrastructure and social capital indicate that capacity has been built. This project focused on building human capital (knowledge and skills) and infrastructure (improved monitoring and modelling), and two aspects of social capital: networks and norms.

The project adopted a case study approach to enable in-depth understanding of particular groundwater systems and associated socio-political contexts and engaged and built capacity of groundwater managers and users in each case study context through collaboration. Three provinces, Balochistan, Punjab and Sindh, were selected for the case study investigations. These three provinces represent a diversity of groundwater use and conditions due to their different hydrogeological settings but similar opportunities to enhance agriculture and livelihood outcomes through improved groundwater management.

The specific **project objectives** were to:

1. Develop and articulate a shared understanding of sustainable groundwater use for agriculture and the need for improved management in Balochistan, Punjab and Sindh provinces.
2. Develop, with collaborating stakeholders in each case study, groundwater management tools and options that have the potential to enhance livelihoods of farming families.
3. Enhance capacity and institutional arrangements for post project adoption of tools and options developed in Objective 2 by collaborating stakeholder organisations.

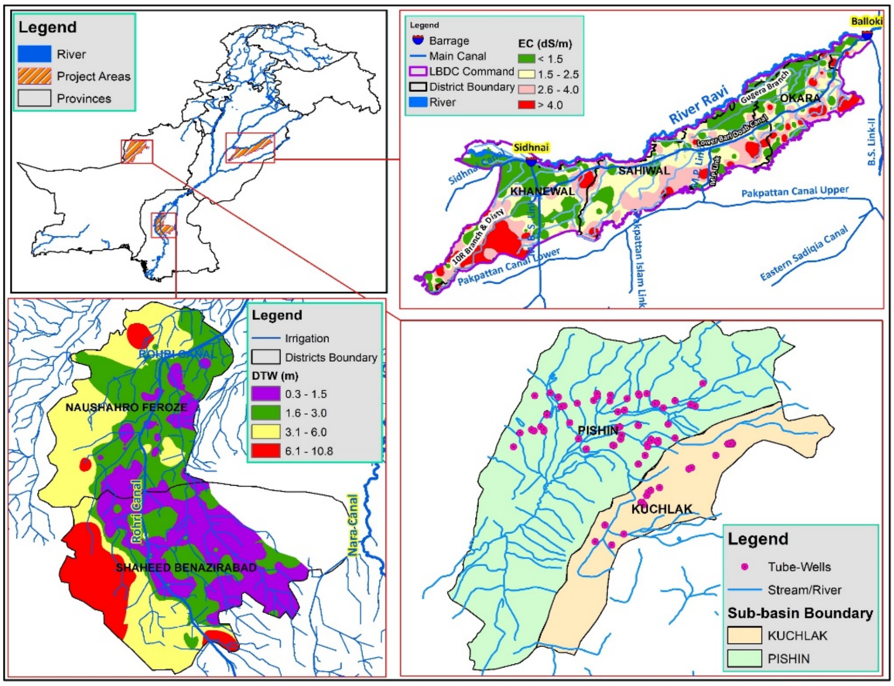
Given the project's aim involved longer term capacity building outcomes, and the uptake of groundwater management tools and processes, a clear delineation between what could be achieved by project's end was critical, as was a clearly defined strategy for complete hand over of project outputs to research users by project's end. Using a collaborative Impact Pathways analysis, we determined our **end of project outcomes** to be:

1. Farmers, farming organisations and partner non-government organisations have started introducing improved groundwater management practices.
2. Government agencies in Pakistan have started developing/ demonstrating improved groundwater-related planning, monitoring, management strategies/ options and policies.
3. Relevant provincial-level government agencies, non-government organisations and farming organisations have developed effective partnerships for ongoing discussion on groundwater management issues and solutions.

4 Methodology

This section provides an overview of the approach and methods used to meet the project objectives in ways that create lasting impacts. A summary of the methods is included in Part B (Section 10). Details of methods, including participants, analyses and references, are provided in the individual technical reports associated with the project (see Section 8.2).

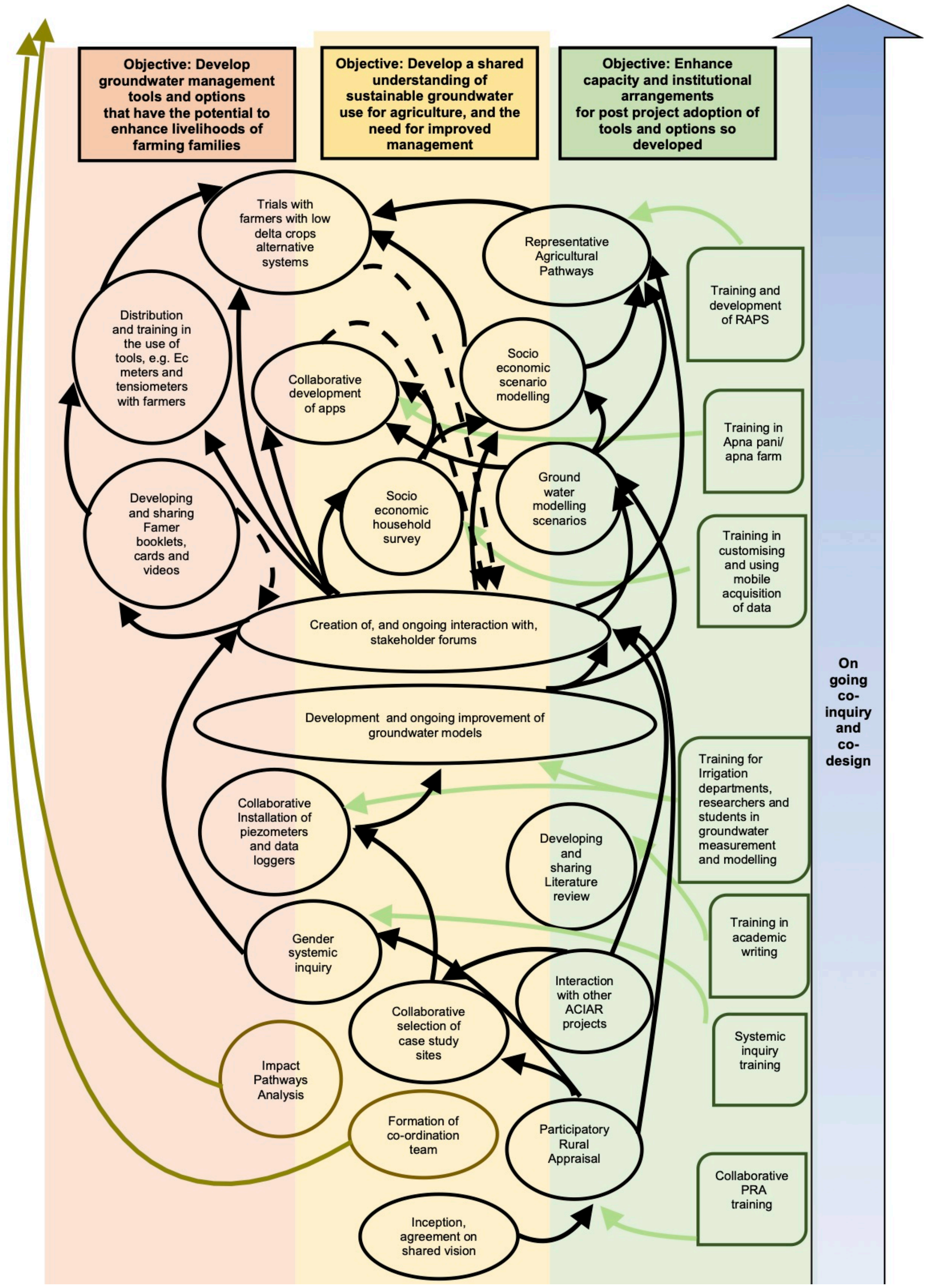
The project focused on six Pakistan case study sites; two each in Balochistan, Punjab and Sindh (Figure 4.1). The details and selection of these is discussed below.



The project was undertaken between 2016 and June 2021 by the following partner organisations

- Charles Sturt University (CSU)
- Pakistan Council of Research in Water Resources (PCRWR)
- University of Agriculture, Faisalabad (UAF)
- International Center for Agricultural Research in the Dry Areas (ICARDA)
- Balochistan University of Information, Technology, Engineering & Management Sciences (BUITEMS)
- Mehran University of Engineering & Technology (MUET)
- NED University of Engineering & Technology (NED)
- Sindh Agricultural University (SAU)
- PMAS Arid Agriculture University (UAAR)
- Balochistan Irrigation Department (BID)
- Punjab Irrigation Department (PID)
- Sindh Irrigation Department (SID)
- International Waterlogging & Salinity Research Institute, Water & Power Development Authority (IWASRI, WAPDA)

The overall approach of this research is to build capacity through **ongoing co-inquiry and co-design**, that is, it is collaborative, iterative and adaptive action research. To achieve the objectives and to make real impacts involved undertaking integrated knowledge creation and sharing activities, as summarised in Figure 4.2. Each of the key methods presented in Figure 4.2 are discussed in Part B, Section 10.



Objective: Develop groundwater management tools and options that have the potential to enhance livelihoods of farming families
Objective: Develop a shared understanding of sustainable groundwater use for agriculture, and the need for improved management
Objective: Enhance capacity and institutional arrangements for post project adoption of tools and options so developed
Trials with farmers with low delta crops alternative systems
Representative Agricultural Pathways
Training and development of RAPS
Distribution and training in the use of tools, e.g. Ec meters and tensiometers with farmers
Collaborative development of apps
Socio economic scenario modelling
Training in Apna pani/ apna farm
Developing and sharing Famer booklets, cards and videos
Socio economic household survey
Ground water modelling scenarios
Training in customising and using mobile acquisition of data
Creation of, and ongoing interaction with, stakeholder forums
On going co-inquiry and co-design
Development and ongoing improvement of groundwater models
Training for Irrigation departments, researchers and students in groundwater measurement and modelling
Collaborative Installation of piezometers and data loggers
Developing and sharing Literature review
Training in academic writing
Gender systemic inquiry
Interaction with other ACIAR projects
Collaborative selection of case study sites
Systemic inquiry training
Impact Pathways Analysis
Formation of co-ordination team
Participatory Rural Appraisal
Collaborative PRA training
Inception, agreement on shared vision

5 Key Results

This section summarises just the key results from four years of collaborative inquiry. More details about these and all other results from the project are provided in Part B of the report, and even greater detail in the individual technical reports associate with this project (see Section 8.2).

5.1 Capacity building in collaborative research

Collaborative research built social capital in the form of networks and norms. In this project we demonstrated that:

5.1.1 Universities and government agencies in Pakistan can work collaboratively, and across provinces, for enhanced impact

A feature of this project is the development of professional networks that involve Irrigation Departments, universities, the Pakistan Council for Research in Water Resources (PCRWR) and agricultural agencies. While these networks were mainly within provinces, growing professional relationships were also apparent across provinces in the form of, for example, the ‘socioeconomic team’, and the ‘groundwater team’; groups of academics and agency staff that were focused on specific aspects of the project. The growing professional networks contributed to new norms of working with and supporting each other. At different times different team members ‘carried’ parts of the project, to overall mutual benefit. This increase of social capital is a real and important result.

5.1.2 Stakeholder forums are a useful platform for discussion and engagement

Stakeholder forums can be considered as ‘spaces’ where people with a shared interest can meet, learn and design new futures together. For this project, stakeholder is a broad term, and may include farmers, villagers, staff from agencies and NGOs, and university academics and students. Women and men, young and old, have been encouraged to be part of Stakeholder Forums. Initial workshops to build the Stakeholder Forums were based on collaborative problem solving, and combined information sharing with co-design of future activities. These workshops drove the design of the on trials that occurred towards the end of the project, ensuring that there was already wide ‘buy-in’ for the interventions being trialled. The concept of this type of co-design platform is comparatively new in Pakistan, but this project showed that it is possible and feasible to create them, and that there are ongoing benefits in doing so.

5.1.3 Improved institutional capacity in monitoring and modelling groundwater

The capacity to undertake groundwater modelling has increased in Pakistan, particularly in Mehran University of Engineering and Technology (MUET) but to some extent also in the Punjab Irrigation Department (PID) and PCRWR. Enhanced professional networking encourages use of these clusters of people with modelling capacity within Pakistan.

In addition to the improved monitoring network, including use of auto-loggers with greater monitoring accuracy, and modelling capacity, the project has developed Apna Pani and Apna Farm, mobile tools for the use of agencies and farmers respectively. A framework has been established for a system tool that can be further developed by agencies in Pakistan.

5.1.4 Women are an underused resource

This project showed that women in all the case study areas are concerned about water availability and quality challenges, especially but not limited to drinking water. Women currently have limited involvement in irrigation water management generally, as well as in relation to groundwater. Some women in Sindh and Punjab indicated that they would welcome future opportunities to be involved.

5.2 Understanding the groundwater situation

Better understanding by individuals and agencies of groundwater resources and the impacts of management actions is key to better management. Regional groundwater flow models using MODFLOW were developed for the Lower Bari Doab Canal (LBDC) Command Area in Punjab, the left bank of Sukkur Barrage Command in Sindh, and Kuchlak sub basin of the Pishin Lora Basin in Balochistan to capture the spatial and temporal variations of the factors affecting groundwater levels in these areas.

Modelling enabled water balances to be determined for the case study areas, and also to understand the impact of future system stresses. More detail is provided in Part B (Section 11.1) of this report, and full reports for each area are also available (see Section 8.2).

Groundwater use is generally not monitored in Pakistan, so primary and secondary sources were used to obtain estimates of groundwater usage. To estimate groundwater extractions a survey of tubewells were conducted to map and quantify groundwater use at head, middle and tail-end reaches of LBDC which was used to estimate groundwater extractions based on average pumping hours. Secondary data for the groundwater models was obtained from respective irrigation departments. In Sindh a survey was undertaken of the number of tubewells in the areas where pumping is occurring and these estimates were extrapolated based on average pumping hours per tubewell and the average discharge. In Kuchlak estimates of tubewell usage were based on average discharge and times of operation provided by BID.

5.2.1 Punjab

The water balance for two distributaries in the LBDC Command Area, 1R (Okara) and 11L (Sahiwal) was extracted from the regional Lower Bari Doab model to understand groundwater usage in our case study sites. The water balance for 1-R in the Okara district shows that pumping removes about 45% of inflows from recharge and canal seepage, however the net balance for 1-R is negative because of significant outflows to the surrounding areas of Okara.

The water balance for the top three layers for the Lower Bari Doab Canal model shows the potential for salt transport upwards from the deeper, more saline aquifer with excessive pumping. Therefore, there is a need to manage both pumping from shallow areas in both fresh water and saline groundwater areas as well as pumping from deeper parts of the aquifer, as the latter has the potential for mobilising salt transport. In the Indus Basin salinity generally increases with depth, therefore keeping the third layer in equilibrium is important in minimising the risk of higher salinity groundwater flowing upwards from the deeper layers. The water balance for layer three shows that the deepest layer is in balance with a net flow into the layer of 1.2 MCM/yr. However, continued increases in tubewell irrigation from the second layer will likely result in a reversal of gradients which will increase salinity of irrigation water ultimately impacting crop yields and soil structure.

Seven future groundwater scenarios were undertaken to evaluate aquifer response in the future, and to assess the availability of groundwater for irrigation. The results of the Business as Usual (no change) scenario indicates that if conditions remained similar to the September 2015 to October 2035 period, maintaining the current rate of pumping of 4316 MCM per year will not result in significant drawdowns. However, a 20% increase in pumping due to increases in population and/or cropping intensity while keeping surface water supply constant, will reduce net groundwater storage by 146 MCM per year and accelerate declines in groundwater levels.

5.2.2 Sindh

The water balance for the left Bank Sukkur Barrage model estimated a net decline in groundwater storage of 1.039 BCM in response to current annual groundwater extractions of 3.249 BCM. The recommended sustainable yield is estimated at 3±0.3 BCM to allow for adaptive management during times of drought and to cater for inadequate surface supplies. The recommended sustainable yield takes into consideration the fact that extraction rates cannot be curtailed abruptly or by a significant amount as there is increased livelihood dependence on groundwater in this area. The freshwater lenses in Sindh are an important source of supplementary groundwater for irrigation and are instrumental in allowing farmers in Sindh to increase cropping intensity and improve livelihoods. Thus, to ensure sustainability of the system, extraction regimes will need to be adjusted to minimise upward flows from the lower parts of the aquifer to prevent accelerated salinisation.

The water balance for the irrigation divisions shows that the inflows from recharge and river/canal seepage, and outflows from pumping are significant in Moro and Khairpur East. Much of this recharge is a result of irrigation return flows[1], seepage from distributaries, minors and water courses at the farm level. All divisions show a net decline in storage which, over time, will result in declining water levels, and increased salinity from lateral intrusion into freshwater lenses. The exception is the Nasrat Division which shows relatively less decline in the net storage due to shallow water tables and high salinity of the underlying groundwater that limits farmers from using groundwater. SCARP tubewells and drains will need to be maintained in Nasrat Division to manage waterlogging and salinity.

Scenario modelling predicted that for all seven future groundwater scenarios, there will be reduction in groundwater storage levels for the five irrigation divisions for the Left Bank Sukkur Barrage. Consequently, our results suggest that there is value in establishing groundwater management areas and setting allocation limits for the irrigation divisions of Khairpur East, Khairpur West, Moro, Dad and Nasrat to ensure that groundwater depletion is managed within acceptable limits and to develop management plans that are suitable for localised management. The overall guidance for recommended sustainable extraction limits is given for the entire model and improving irrigation efficiency and replacing a percentage of high water use crops with low water use (low delta) crops will allow for adjustments in groundwater abstractions without the need for over-regulation. To adopt this approach successfully requires building of knowledge and awareness around groundwater and salinity issues among Sindh farmers. This project has taken that crucial first step in building trust through the stakeholder forums.

5.2.3 Balochistan

In the Kuchlak sub-basin a selection of observation bores have shown that a decline in water levels of between 80 to over 100 m has occurred in a span of 8 years. This is a clear indication that unconstrained pumping is resulting in a race to the bottom. The water balance for Kuchlak estimates a net loss in storage over the simulation period of -451 MCM/yr which equates to an average decline in water levels of 5.4 m/yr. Of the three watersheds in the Kuchlak sub-basin, the worst affected is the Rokhi Lora watershed where groundwater depletion is a staggering -158 MCM/yr equivalent to an average decline of 6.2 m/yr.

In the Kuchlak sub-basin, groundwater is heavily overexploited leading to unprecedented declines in the water table - unlike anywhere in Pakistan. Improving management of groundwater will require a rethink of cropping practices, choice of crops, and improved land and water management practices aimed at conserving surface and groundwater resources. This rethink is vital for sustaining agricultural livelihoods in Kuchlak. Groundwater management will require a process of involving communities of groundwater users who are empowered to co-design with government stakeholders a better and more sustainable future for Kuchlak.

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[1] *Some portion of applied water is not consumed in fields and flows to groundwater table. Irrigation return flow is the fraction of irrigation that reaches the groundwater table (the term used by agricultural engineers and scientists for 'irrigation in excess of plant needs' that will drain from the soil and 'return' to groundwater (or surface water) bodies according to the physical properties of the sub-soil profile). The reason why irrigation return flows should not be ignored is because the use of groundwater irrigation adds salts to the soil surface. The effect is compounded if the groundwater used for irrigation itself has significant salinity as is the case in the mid regions of doabs and tail ends of canals. In these cases canal water used for irrigation can provide helpful dilution as it is of low salinity.*

Our study recommends the introduction of a phased reduction in the long-term extraction thresholds for the Kuchlak sub-basin and following that to co-design with the Kuchlak community a gradual reduction in the extraction limits over three decadal planning periods to allow for a phased reduction in pumping, and simultaneously introducing gradual uptake of low-delta high value crops, improved irrigation and land management practices, improved management of surface water sources, and the introduction of a network of injection bores to enhance recharge of the aquifer. The three decadal planning periods will require the various agencies of the Government of Balochistan to work with the groundwater users in Kuchlak to plan for a sustainable future.

5.3 Managing groundwater while improving farming community livelihoods

Socioeconomic modelling and the application of Representative Agricultural Pathways (RAPs) provided an understanding of the current situation for farmers in the case study areas and indicated the potential for improving groundwater management through improved on-farm awareness of groundwater and the options for improved water use efficiency.

5.3.1 Punjab

There is potential to improve water use efficiency (WUE) in both case study areas. Farmers at the head of both distributaries have improved resource use efficiency, including technical, economic and water-use efficiency than middle and tail farmers. This study has shown that, by adopting water-smart practices, farmers can save inputs, increase their production and profit. Because the farmland is already nearing its maximum cropping intensity across both growing seasons, there is little scope to use ‘saved’ water by expanding irrigation, so increasing WUE relates directly to reduced groundwater use.

There are strong indications that farmers, especially in the middle and tail of the command areas, are willing to reduce water consumption by changing crops and practices. However, adoption of water-smart practices is constrained by poor access to farm services such as the availability of resources, access to credit, market and agricultural extension services.

5.3.2 Sindh

The farmers in the tail areas of in both case study districts are highly dependent on groundwater compared to canal water while the majority of farmers at head areas use canal water for irrigation. Farms in both case study districts could save a significant amount of water and improve water use efficiency with the help of sustainable groundwater management practices and technologies. Consequently, if water use efficiency improves, it should be possible to reallocate a proportion of the irrigation to the other water demands, without compromising the production of major crops. However, most farmers had not had the opportunity to access training in water management options and better ways to use the available limited resources of water.

5.3.3 Balochistan

WUE can be improved in both study areas in Balochistan Province. Among the crops grown, wheat crop production was more water use efficient while tomato, apple and apricot were less efficient with significant scope for improvement. Under the current irrigation system (mainly flooding) farmers are using 50% more water than the actual crop water requirement. There is limited general awareness about the water resources and their availability and an extensive campaign is needed to educate farmers about improved water management practices. There is some scope for increases in irrigated agriculture if High Efficiency Irrigation Systems and low water use crops are used, but only if aquifer recharge can be managed. A return to closer management, such as allocation limits, is needed. Some self-regulation is possible because agriculture will not be viable if aquifer recharge does not occur.

The RAPs work undertaken in Kuchlak is resulting in adoption of high value, low delta crops such as pistachios, and adoption of high efficiency irrigation for pomegranates. Adoption of new crops and sustainable farming practices, with improved irrigation management will be a slow process as it takes time to scale out these activities, but it also requires a multi-skilled team consisting of social researchers, groundwater managers, hydrogeologists, irrigation and agricultural specialists is required to work with community groups to develop a sustainable future for Kuchlak.

5.3.4 WUE and improved groundwater management

It is possible that increasing WUE will lead to more water use by expanding the cultivated area but when farmers have to pay for water, or have limited area of land (through already high cropping intensities, or salinity), water saving will be an attractive option. Compared with canal water, groundwater is expensive, and may be of poor quality, and is not attractive to farmers, who use it because they feel they have no choice. Improving choice through WUE in Pakistan can therefore be part of better management of groundwater. For example, in the Punjab trial farmers are applying four irrigations for Sunflower instead of the six to eight that are needed for maize. Since groundwater irrigation is expensive compared to canal irrigation, which is virtually free, then it is reasonable to assume that farmers will use less groundwater if they make equal or more profit.

Improving WUE on its own will not necessarily lead to reduced groundwater pumping, but if it is introduced as part of a package of capacity building it is a feasible option that requires comparatively little investment in awareness raising, and concurrent investment for value chains for low delta crops.

6 Impacts

6.1 Progress towards end of project outcomes identified through Impact Pathway Analysis

The evidence of progress towards the three end of project outcomes identified through Impact Pathways Analysis is summarised in Table 6.1.

Table 6.1. Evidence for progress towards outcomes

Intended End of Project Outcomes	Progress Achieved	Evidence
Farmers, farming organisations and partner non-government organisations have started introducing improved groundwater management practices.	Some achievement in the project's case study areas: • Some leading farmers in these areas are observing groundwater levels and quality and have an improved understanding of the threats to groundwater resources and how these impacts on their livelihoods. Some are beginning to trial low delta crops and more efficient irrigation methods as a means to slow groundwater decline. • Other farmers beyond the project's leading farmers are observing these developments, with some in the Punjab case studies expressing a desire to plant Moong Bean and sunflower. • The Punjab socioeconomic team is in close contact with those teaching/research organisations in the area to continue to monitor and evaluate. • In Balochistan, on the piezometer sites, farmers are observing water levels and fluctuations in water tables due to increased awareness, training and equipment provided by this project. • Tensiometers are being installed on 12 to 15 farms on all the four piezometer sites to help farmers judge the crops stress level on their farms and plan irrigation when needed. This will help avoid over irrigation which is usually a practice in the area. • In Balochistan a complete package of technology was given to farmers that includes information regarding judicious water use; HEIS; low delta crops; design and layout of farmers plots; and installation of HEIS along with fruit plants. • Some farmers in all three provinces are using EC meters to measure their	The area under low water use (low delta) crops such as moong beans has greatly increased in the study area. Relatives of farmers from Shakarghar area visited the study area in 11-L and showed desire to also grow low delta crops like moong beans. Their main crops are rice and wheat and they are only using GW because there is no surface water is available. At their request, the Punjab team visited them to investigate the potential of low delta crops such as lentils, millet, sunflower and garlic. A Balochistan farmer mentioned that due to the use of a drip irrigation system, he can now irrigate all his farm (15 to 20 acres) with one three-inch tubewell. To do this with traditional flood irrigation would require two such tubewells. In this way HEIS and low delta crops are helping reduce groundwater pumping. For example, in Balochistan, farmers in the project areas use EC meters to test water quality on farm, rather than the expense of taking samples to Quetta. They can take rapid remedial measures to control salinity. PMAS-Arid Agriculture University has adopted the applications and has started using it under its National project on Pilot Project For Data-Driven Smart Decision Platform (DDSDP). https://ddsdp.uaar.edu.pk The application is hosted at here

	irrigation water quality to improve conjunctive use decision-making. • Some agency staff are using Apna Pani to observe groundwater levels, and some farmers are using Apna Farm to help inform their decisions about suitability and feasibility of low water use crops • The project's approach to groundwater management is attracting interest widely	Currently, the researchers at PMAS-AAUR and CSU are collaborating on further development of these applications. Various institutions from Turkey have requested to help them by using the same methodologies developed and used in the groundwater project in Pakistan.
Government agencies in Pakistan have started developing/ demonstrating improved groundwater-related planning, monitoring, management strategies/ options and policies.	• Irrigation Departments in Punjab, Sindh and Balochistan are beginning to improve their groundwater related activities. • Insufficient data, especially in Sindh and Balochistan, mean that much of the improvement in GW planning manifests as efforts to improve data collection and management. • In **Punjab**, PID is undertaking a project on institutional transformation to a Water Resources Department in which groundwater management and development of groundwater management plans are being developed. • PID engineers, beyond those engaged with in the project, have become involved in improved groundwater monitoring, and modelling. • In **Sindh**, more than 20 SID personnel, 2 female engineers from SMO, and several graduate students have been trained in groundwater monitoring and modelling. • SID is now relying on Mehran University staff (Waqas Ahmed) to provide further training in groundwater modelling • In **Balochistan**, BID has sought funding for installation of another 150 piezometers.	PCRWR will implement a groundwater recharge project in Islamabad Capital Territory wherein 100 inverted wells are being constructed. In order to monitor these, 20 piezometers with CTD drivers will also be installed. The Punjab Government has established a new process specifically to deal with groundwater management in the province including monitoring, registration of tubewells, and licensing. Following this project PID has installed 10 groundwater sensors/loggers on an experimental basis at the Eastern Sadiqia Command Area. These are providing real time data once in week. This is improving the reliability, accuracy, and frequency of data that is collected. PID has started groundwater modelling in Old Mailsi Canal Command Area in South Punjab MUET have secured a 180 million PKR project in collaboration with BUITEMS under LCF HEC-World Bank umbrella for smart groundwater monitoring in Quetta Valley".
Relevant provincial-level government agencies, non-government organisations and farming organisations have developed effective partnerships for ongoing discussion on groundwater management issues and solutions.	This is the area of greatest impact, with the achievement deliberately pursued early in the project to enable sufficient time for partnerships to develop. Numerous effective partnerships are evidenced from this project. For example: • Irrigation Departments in all three provinces have stronger groundwater related relationships with each other, and with PCRWR, academia in Pakistan and Australia. • In Sindh and Balochistan in particular, Agriculture Department staff are collaborating with Irrigation Department staff with regards to planning on farm management of groundwater.	MUET (Sindh) is working with BUITEMS (Balochistan) on a Local Challenge Fund. This has been shortlisted for Rs 100 million project. A funding proposal is being developed by Salman Sarwar (trained by this project) from CERBM, a joint initiative of the Government of Balochistan and the University of Balochistan, for a Public Private Partnership. The proposal responds to the Secretary Environment's interest in ways to control groundwater depletion in the Quetta valley.

	• Stakeholder Forums (SFs) have been established in six areas. These SFs provide a space to bring together leading farmers, agency staff, NGOs and others from the community for ongoing sharing of information and ideas. Action plans established by the SFs were beginning to be implemented when Covid-19 disrupted social activities, and it remains to be seen if they continue after the pandemic is controlled in Pakistan.	

In addition to some key impacts presented in Table 6.1, the sections below provide qualitative (rich, deep) data, much of which was distilled from interviews held with key project personnel via Zoom, in March 2021. All co-ordinating team personnel were invited to add their comments to the draft of this section. Where appropriate below, CT member's reflections are quoted verbatim, shown in italics and credited with initials. These are organised as Scientific, Capacity and Community Impacts in line with ACIAR guidelines.

6.2 Scientific impacts – now and in 5 years

The increased scientific understanding of groundwater in each Province is discussed under capacity impacts. The other scientific impacts of this project are evidenced mainly through post graduate research, and technical publications.

6.2.1 Post graduate studies

Ten Masters and 4 PhD students have worked with this project.

The impact of these studies goes beyond the substantive contribution to knowledge made through their published theses. Many of the students will continue to make positive impacts in Pakistan, in areas related to groundwater:

Two students have completed their MS in economics [at BUITEMS]. One student studied the impact of solar on groundwater exploitation. The other student worked on the efficiency in groundwater use. Both used the theoretical frameworks and models of the socioeconomic frameworks developed by the project...One student is teaching at [BUITEMS University College] Zhob university as a lecturer and is trying to obtain a PhD scholarship based on his research work. The second student… will likely get a job in the area of water management. SK

My PhD is not personal to me, but it will be a great benefit to our research institute, our Punjab Irrigation Department. This is a major contribution of this project, towards the human resource once I am qualified with a PhD from Charles Sturt University, I think it will an asset for the PID and IRI and this is all due to this ACIAR project. ZS

6.2.2 Technical publications

At the time of publication of this report, five academic journal papers, two peer reviewed books, seven book chapters and 30 conference presentations have resulted from this project (see section 8.2 for details). Of special note were the many co-authored project-focused papers presented at the Australasian Groundwater Conference in Brisbane, 2019.

6.3 Capacity impacts – now and in 5 years

'Capacity' describes the ability to act. Much of the impact of this project has been through increasing the ability of a wide range of people to act in response to increasing groundwater scarcity. The major capacity impacts can be described as capitals – infrastructure, human and social.

Enhancing capacity and institutional arrangements was one of the three major objectives of this project. As noted in the methodology, this involved ongoing interplay of training, developing shared understandings, and co-development of tools and knowledge. The separation of the impacts of these activities in the following section should therefore be understood as necessary for reporting, but not representative of the multi-layered nature of our project impacts. The difficulty of compartmentalising the project impacts is exemplified by this comment about on-going capacity, economic and environmental impacts:

[Prior to this project the view in Punjab was] that you can just monitor groundwater levels pre and post monsoon and that's good enough … just the introduction of the few loggers that we purchased for the project and put in our case study sites… When people started seeing the groundwater responses, both in terms of what levels and salinity, I think it really made [PID] understand that monitoring is a lot more useful …So it's now also impacting on the farmers through the RAPs... [For example] Sharaz, the farmer who is very concerned that his groundwater levels are falling by half a metre every year, and he's seen that because the log of data is being shared with him. And he's also got an EC meter and he's now getting other farmers coming to him and telling him to … test my water also, so I think this monitoring is just the first step towards raising awareness about what's happening with the groundwater. JP

6.3.1 Infrastructure capital

Up to date equipment and software

There is increased, and increasing, capacity for accurate groundwater monitoring and modelling in the three provinces because of the new piezometers, data loggers, modelling software and mobile apps provided through the project. The improvement in monitoring and modelling tools is likely to continue in the future. For example, encouraged by the experience of this project, a proposal has been submitted by BID staff for 150 new piezometers in Balochistan.

Tablets were purchased for the project to assist with Mobile Acquired Data, and these are now available in country for further research projects.

One new piece of infrastructure, Apna Pani/ Apna Farm was developed within the project

…three of our [PID] officers, one of the senior research officers, the junior research officers, they have got training in this and are using Apna Pani. … a GIS specialist got training on how to compile the information directly for the website and how to access it for our different purposes. ZS

The statement above exemplifies the need to support increased infrastructure capital, with increased human capital by providing knowledge, training and skill development.

6.3.2 Human capital

Groundwater monitoring and modelling

Training and ongoing mentoring has increased the capacity within Pakistan to make good use of the new piezometers, data loggers and modelling software. For example, groundwater monitoring practice has improved in Punjab, with improved data sets being the main impact.

The irrigation departments always look for big things, which are more development oriented, but this project has enhanced their capacity as well, in terms of the software, the models, and the data loggers. Now we are seeing them using the models on their own computer by themselves. FH

An important impact in this area, now and into the future, is the skills in modelling being built in Punjab, particularly at UAF, and also in Sindh. The team at MUET are now able to undertake modelling, and curate meta data to support it. Importantly, MUET team members are sharing their growing knowledge of groundwater modelling with staff from the Sindh Irrigation Department, and also providing some training in Balochistan.

Socioeconomic analyses

Another impact on human capital is increased understanding of the tools available for socioeconomic research, especially those that involve future scenarios. Scenarios based on a range of biophysical and socioeconomic data have been, and will be, catalysts for participatory and collaborative planning.

While there may be resistance to adopting this new RAPs approach compared to the more familiar household surveys and economic surveys currently used, there are some partners seeing the value in using this scientific way of creating some scenarios. When a technique is seen to have efficiency and impact by the stakeholders and policymakers there is likely to be more adoption. IB

Multi-stakeholder approaches

Through this project capacity is being built in using approaches and tools for working together across agencies and provinces and disciplines. For example:

People can now see that it is possible to have these quite complex projects if they are arranged in particular ways and we have shown one particular way. IB

It is the teamwork, it was our learning of the team of how to work together. We worked as a team and the result is very much obvious. MA

The multi-stakeholder approaches are likely to be used in future projects in Pakistan

Yes, whenever we are writing some new projects we always look at social and economic aspects as well. Otherwise, we were looking into the project from technical aspects only. FH

6.3.3 Social capital

A major impact of this project is the increase in social capital among the project team and their organisations, and their wider reach. Social capital is both networks and norms. An increase in social capital is shown by more, larger and stronger networks, and the increased depth of positive social norms. Both these aspects of social capital have been enhanced for the wider project community; many people are working with a wider range of other people, and in new ways that may be becoming standard. Some of this is exemplified below.

Networks

Multi-disciplinary, integrated projects are needed to address issues involving complex, uncertain futures. This project has not only shown that it is possible, but that it is also likely to become more common in future projects in Pakistan.

One important set of relationships is formal and informal networks forming around the Stakeholder Forum concept. As the following ‘Story of change’ from UAF recorded in

September 2018 shows, encouraging multi-player networks is not easy, but has great benefit.

LWR-036 Punjab 11L case study: Impact of establishing a stakeholder forum

Our project sought to establish a stakeholder forum for each of our case study sites and sought to include relevant local government staff. In the case of Punjab, our UAF researcher Asghar Ali sought to convince local Department of Agriculture staff to be involved in the forums – both staff in the extension department and in the on-farm water division. Our stakeholder analysis suggested that we needed both – extension officers have skills in working with farmers and have strong linkages into the farming communities; on-farm water management have the technical skills to improve the way water is managed on farm. The first few calls there was a consistently cold reception: "No we don't have time, it will be difficult for us to be involved." Asghar kept calling up to 4 times to each of the deputy director (district level), assistant director (local level) and even the Director at a more senior level for both divisions – kept trying to convince them that this was a good opportunity. Eventually they agreed to come to the meeting.

The meeting went much longer than intended because, for many of them, this was the first time all these people working in the local area were in the same room: farmer organisation president, government staff, private sector, local NGO reps and so on. The FO President was a big champion and facilitated getting a lot of the key people in the room, including a key local champion from PIDA.

What was most significant for the four Department of Ag staff was that this turned out be a rare opportunity where they were in the same room together, communicating with others, finding ways to collaborate with each other, sharing their experiences and methods for how to contribute to in field changes. On-farm water management staff were also able to improve their connections with farmer organisations; it was also a good opportunity for government department people to connect with those from the private sector. Asghar's assessment is that they all became very good friends; the atmosphere was very friendly.

The on-ground change resulting from this network is exemplified by the following

In the Punjab on Saturday March 6, 2021, there was another session with the community and about 100 farmers have committed to converting around two acres for each farm to growing pulses rather than rice and other water intensive crops. This is the sense of urgency among the farmers and how they are responding. For the farmers, the biggest influence and impact has been when their peer farmers share the water situation information rather than people sitting in offices or people at the government offices are saying to them your water level is depleting. MA

The idea of stakeholder forums as spaces for a range of people to share ideas will continue to impact practice in Pakistan, for example, through the ACIAR funded Adapting to Salinity in the Southern Indus Basin (ASSIB) project:

…in the proposal development for the salinity project, [another researcher not in the groundwater project] mentioned that the Community is not just farmers it's all those people that work with farmers and that's the community of stakeholders and that's an idea that I think has become a little bit more entrenched and valued .MM

The other important networks formed through the project are various multi-partner alliances. Many project team members have commented on the challenges but ultimately beneficial impacts of working with a large, multi-disciplinary team, and developing wider practitioner networks. For example:

One of the key impacts…is the collaboration among the team, because it is the project in which 11 to 12 partners are basically participating. So, it's quite a big team, it is a challenge as well to work with them, but at the same time, it gives you a strength as well.

This project has also enabled the Provincial Irrigation Departments of Punjab, Sindh and Balochistan to sit on one table, I don't think earlier that they have had any chance to sit down and discuss on various issues. But this project has given them this opportunity, and, similarly, the universities like UAF, BUITEMS, and Sindh Agricultural University, they are interacting and collaborating on things…the cohesion of the technical people, the social scientists and the economic teams. That is the first time this has happened in Pakistan, so I would like to see this kind of approach in future projects as well. FH

Increased networking among agency partners has enabled new projects to be developed more rapidly than they would otherwise; for example, anecdotal evidence from PCRWR midway through the project was that they found the initiation of an unrelated water project in Balochistan was relatively easy because the staff involved could use the network formed in this groundwater project.

Norms

While networks are a key component of social capital, norms, in this case the normalisation of new ways of acting, are equally important. The is some evidence of normative shifts from this project, the most obvious being the norm of collaboration, working across institutions and provinces, and sharing the responsibilities. Numerous examples arose during the project – including the sharing of knowledge among the project team during, and especially after, undertaking the PRAs, and the sharing of resources such as MUET's expertise to assist BID in groundwater modelling. The most notable example of collaboration being accepted as normal practice is the ready acceptance of co-design of the ACIAR ASSIB project.

The design of the Salinity project with the number of partners was heavily influenced by the success of the model provided by the groundwater project. IB

The shape of the salinity project is different than the initial shape of the ground water project because we learned a whole lot to be able to build that synergy project. MM

That the new practices of collaboration are normalised, at least within the project, is also evidenced by the continued implementation and success of the project after the restrictions imposed by the global COVID-19 pandemic:

Even with the challenges of COVID-19 the project activities have continued, the teams are still working together, all original partners are still contributing and will be working collaboratively into the future. IB

6.4 Community impacts – now and in 5 years

The major community impacts relate to the increased opportunity to connect with agency and university staff through the Stakeholder Forums covered above under capacity. This increased connectivity and trust should have positive impacts into the future, as the trust developed through the forums supports other development activities.

6.4.1 Economic impacts

The results of the groundwater monitoring and modelling are having direct impacts on the economic choices of farmers in the case study area. Because the on-farm interventions are developed with the case study farmers through the Stakeholder Forums and RAPs, the actual interventions selected vary across the areas and sites. For example, in Punjab the farmers are interested in growing alternate crops that use less water.

[*the case study trial farmers] are now pumping less water. [Moong bean] is replacing the maize. Maize takes at least 10 to 12 irrigations…For this crop only three irrigations are* *required so saving a lot of water. If we compare the two crops, the cost of production is very low in case of Moong beans, because maize needs a lot of inputs. So …farmers now can invest less and at the same time, by investing less they can earn more.* MA

The response from Sindh case study farmers was not to replace their existing high water use crops, but to use intercropping with vegetables for increased production and profitability without increased water use.

… they agreed to cultivate the wheat crop on ridges. On the Cheeho site… the farmer has wheat on ridges, and then onion and okra inter-row…On the Malwa site they cultivate wheat on ridges, inter cropped with sugar cane, both crops were on the same piece of land. [There are] beneficial impacts; we have shown that it is water saving, it is time saving and it is economical for the sugar cane. TM

Using part of the land for sugarcane nursery, again to reduce input costs, is also being trialled in the Sindh case study areas.

In Balochistan:

[Progressive famers] *have requested high efficiency irrigation systems, soil meters to measure humidity and moisture, to be able to obtain water table data. In three out of the four piezometer sites the stakeholders… are actively involved and are in touch with us. SK*

In all provinces these interventions occurred in conjunction with improved irrigation techniques – formed beds in Punjab and Sindh, and a range of HEIS in Balochistan.

6.4.2 Social impacts

The social impacts are closely associated with the economic and environmental impacts discussed elsewhere and are generally site specific. One impact of approaching farming communities as collaborators in a multi-partner project is that the trust developed enables opportunities to be sought. For example, in Balochistan:

Our interaction helped [villagers] *to develop their links with the other development sector actors like the FAO who are running two projects. For example, in Zarghoon village, one of our sites, seven women submitted applications for solar dryers for apricots and vegetables, especially tomatoes. Moreover, two to three farmers are getting tunnel farms / loans from the FAO THAzA* [The Horticultural Advancement Activity] *project to grow cucumbers and other vegetables, in Zarghoon, Malikyar and Huramzai Balochistan. The tunnel farms are said to have been 80% more efficient in terms of water use than the flooding and traditional irrigation methods. FAO are going to start tunnel farms in the whole area. We informed these farmers and helped them submit their applications for the said FAO project. SK*

The potential positive impact of changed inter-cropping and raised bed cropping for poor farmers in Sindh is exemplified by the following story of change, as told to, and translated by, Tehmina Mangan in March 2021.

EACH ONE OF US CAN MAKE A DIFFERENCE BUT TOGETHER WE CAN MAKE CHANGE

My name is Mehrabzadi I belong to tenant family and under tenancy relationship with landlord and get our share in production. When there is good production we also have good share otherwise our share also reduces when production is low. Since last couple of years we are facing reduction in production and profit from agriculture therefore poverty is increasing.

We are also facing water shortage issues but our methods of irrigation are same since decades. We just know that this issue of water shortage is prevailing in our area and feel deprived and feel it as our fate.

Under this project first time we, females came to know the importance of water and understand that shortage of water is worldwide but due to mismanagement we are facing more problems and possible measures are existing to overcome water shortage issue. And we also came to know that water quality is deteriorating and can be observed by using EC meters provided by the project. In this project we were given EC TDS meters to check water quality of drinking water at our home. Our boys who are educated they help us in this regard.

First time, under this project in our area we have observed wheat cultivation on ridges. Before this we and others have been using flood irrigation. We have also observed that ridge sown wheat is best method of sowing for water saving and quality of wheat plants is better on ridges as compared to flood irrigation plots wheat. Ridge sown method of wheat sowing method is also best suitable for sugarcane intercropping.

It gives me pleasure when I see that two to three crops can be grown on same piece of land Now we feel a hope after getting exposure of demonstrations of different methods of intercropping in our area by the ACIAR Ground water project. We observe that intercropping of wheat with sugarcane, onion and okra with sugarcane are very much beneficial to grow more than one crop on same irrigation water and cost of production of single crop and get better yields and profit. In my point of view we can get 3 times more income now.

Despite the story above, generally the impact on rural women, particularly in Punjab and Balochistan, has related to increased understanding of groundwater issues rather than increased direct action. One important, albeit small, impact is the increasing encouragement of women in research in Pakistan.

I think the biggest impact [of our project on women] has been with women and universities, a lot more have joined the programs we've created because there's some very well-trained women who learned different aspects, not necessarily just modelling the different aspects of water management and one lady, for example, has got a job with WAPDA. JP

And it is to be hoped that social impacts will come via the project's influence on policy. For example:

The groundwater modelling has been used by the planning and policy people in the Punjab government and is reflected in the regulations for groundwater use. I believe that these results, coupled with other studies taking place on the groundwater modelling will have a longer impact on the policy side. IB

6.4.3 Environmental impacts

The major environmental impacts of the project relate to the quality and quantity of groundwater in the study areas, and hence are closely tied to the economic and social impacts described above. The monitoring and modelling are having direct impacts on farmer water use behaviour in the case study areas. For example:

The monitoring is giving them more control and we saw this reflected in the Bari Doab. Previously water was used without any control or restrictions. Through the monitoring the men know that the water level has fallen about six feet in a year and that has created a *sense of some urgency among the people. The people have converted a few of their acres to water saving crops. IB*

Recently I, with two other researchers from our University, had a meeting with the World Food program who are interested to work on minimizing desertification in Balochistan … And we tried to convince them that if you want to avoid groundwater exploitation and to minimize desertification, you need to work on groundwater management and follow the model of the ACIAR LWR 036 project. I also informed them that we have done this work on two sites that can be replicated in other areas of province…. If they agree to fund, we hope to replicate this work in other parts of Balochistan. SK

Increased capacity to monitor and understand groundwater in Balochistan.

This project is developing the capacity of researchers and managers to understand and better manage the precious groundwater resource of the Province.

There is increasing awareness in Balochistan that the aquifers are depleting and managers do not have reliable data.

One important aspect of the project has been the installation of four new piezometers, two each in Kuchlak and Pishin. The Balochistan Irrigation Department is taking control of the piezometers and staff are being trained to collect the data.

The government of Balochistan is considering installing a further 150 piezometers across the different basins across Balochistan, as a direct result of this project.

Monitoring groundwater is just one part of the story- using the data is another. Capacity in groundwater modelling is being enhanced through the close connection with MUET, where the groundwater modelling work for Balochistan is being undertaken.

It is not only water managers and academics who are gaining capacity through the monitoring and modelling. The information is shared with farmers, and through the Stakeholder forums and RAPs awareness and understanding is prompting exploration of new farming systems that better protect the groundwater.

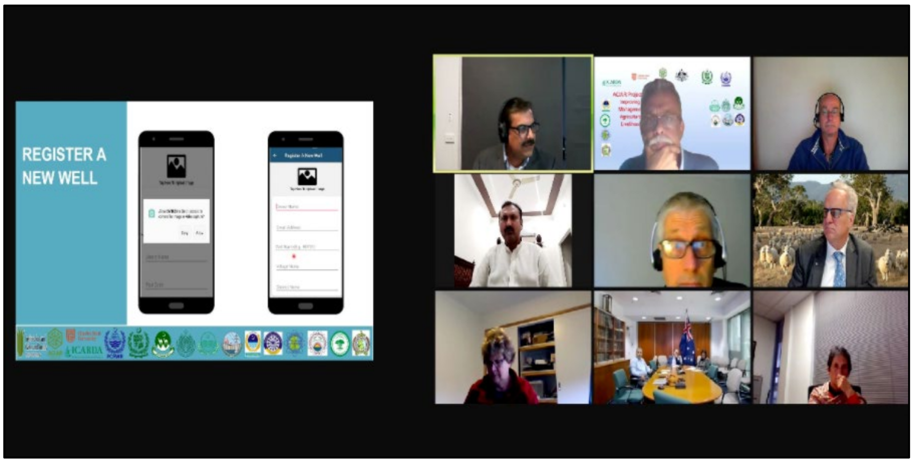
6.5 Communication and dissemination activities

The stakeholder forums, discussed above, provide one important means of communication, information sharing and collaborative design. The communication used within the project- such as posters, booklets, and videos, are detailed in Appendix D (communication report).

Broader dissemination of the project intent and outcomes include

In Pakistan:

- Presentation to dignitaries and farmers at World Water Day activities in Islamabad, March 2017, Lahore March 15, 2018
- Launch of Apna Pani/ Apna Farm , 28 July 2020, via Zoom (see figure below)
- Discussion of project during the visit of Australian High Commissioner He Excellency Madam Margaret Adamson's visit to BUITEMS Quetta on April 12, 2019



In Australia:

- The project was presented to the Pakistan Ambassador to Australia in Canberra
- Media coverage in Australia, including two SBS Urdu stories
- The Institute for Land Water and Society covered the project in its Connections newsletter, and on its website

7 Conclusions and recommendations

7.1 Conclusions

The story of groundwater in Pakistan that we tell in this report is one of hope and despair.

In Balochistan, groundwater levels in Kuchlak have declined at unprecedented rates. In parts of the basin, the declines have exceeded 100 m in the eight years from 2010 to 2018. These rates of decline are not sustainable given low rainfall recharge and non-perennial streams that result in very low rates of recharge to the aquifer. Farmers there have limited choices; wells have already been deepened to chase declining water levels and the cost of pumping has increased substantially. In Balochistan, adoption of low delta/high value horticultural crops such as pistachio, pomegranate and olives has to occur at a faster pace along with drip irrigation to drastically reduce the amount of groundwater used for irrigation.

The groundwater model results from the Lower Bari Doab Canal in Punjab and the Left Bank Sukkur Barrage in Sindh show that the depletion is not uniform over the basin. Parts of the basin in Punjab and Sindh are showing rising groundwater levels, other parts are showing groundwater levels are steady, and the concerning areas are the hotspots where groundwater levels are declining annually.

In Punjab, Sindh and Balochistan, a range of practices need to change, including greater adoption of low delta crops and improved irrigation and land management practices. Trials of low delta crops in Punjab using the Representative Agricultural Pathways (RAPS) approach have shown positive results with profitability maintained using less irrigation water for sunflower and moong bean as compared to wheat and maize. Adoption of good land management practices such as ridge planting, and crop residue management is required along with improving irrigation efficiency.

Our multi-level, multi-disciplinary project approach is vindicated by the various findings of the project. Establishing groundwater management areas and understanding sustainable extraction limits at the sub-basin level will allow resource managers in the provincial irrigation departments to focus on improving management of hotspots in these sub-basins. Stakeholder engagement, particularly with groundwater users in these sub-basins, along with improved knowledge sharing will be required to change practices and to bring about change.

This project has demonstrated that it is possible to have successful projects with large teams, across provinces, that address complex issues. Specifically, we showed it is possible to manage a multi-partner, multi-disciplinary project, and that the benefits from doing so are clear and numerous. To do this required:

- **Sufficient time to develop networks, trust and shared understandings:** Collaboratively building a solid foundation takes time and can sometimes be frustrating in the constraints of short-term projects. But it was essential for making real and lasting impact.
- **A flexible plan:** Having a clear plan was necessary, but its trajectory was more important than specific targets and outputs. This trajectory approach allowed the project to adapt as knowledge and understanding emerged over time. Key examples include the refocusing on modelling prompted by the Mid Term Review, and the use of RAPs. The latter was not part of the original project plan, but the need for such an approach emerged, and the opportunity was taken up with great success.
- **Conscious design of team-building activities, followed by active reflection:** The aim of the collaborative project was built into its activities, from governance

through the Coordinating Team, to joint field activities, to shared writing tasks. Every activity was deigned to incorporate and benefit from collaboration.

- **'Redundancy':** The project may have been able to achieve outcomes with a smaller team, but the large team ensured that there were always capable people somewhere in the structure to lead when necessary, carrying the project as a whole through a range of difficulties. Resilience was built into the project, reducing risk.
- **Substantial investment in internal communication:** An important role of our Communications Manager was bringing and keeping people together, arranging joint activities, but with hindsight the overall task of communicating both internally and externally for the project required more than one person.
- **Collaborating multi-disciplinary leadership:** One of the key successful features of the approach we took was to have co-leaders in their respective fields leading the research – for example, the social research was led by Dr Mitchell and Dr Allan, and the economics component by Dr Culas. Furthermore, our Key Pakistan partners Faizan Ul-Hassan, Dr Khair and Profs Ashfaq, Baig and Mangan provided the leadership in various socioeconomic aspects and in capacity building, and support to our partners.

Importantly, the project has also shown that managing groundwater better in Pakistan is a feasible opportunity. The project highlighted the vast variation in the water situation generally, and the groundwater situation specifically, across different parts of the country – the hope and despair noted earlier in this report. Added to this is the variance in social and economic factors, also highlighted by project activities. Different, customised approaches are required to address these different situations.

The need for customising solutions underlines the central importance of creating and using quality data, both quantitative and qualitative, as the basis for discussion and action. Building the capacity of people in Pakistan for rigorously creating and using data such as that from monitoring, or PRAs, or RAPs, ensures the impact of the project beyond the individual models and reports that have been produced.

This project has resulted in some infrastructure, human and social capital built in some parts of the country. There is some changed awareness and practice in the six sites of the project. These are small steps, and continued investment is needed to turn the small steps into larger ones. Investment is thus the focus of the next section, recommendations.

7.2 Lessons for ACIAR

There are lessons from this project that ACIAR may build on in future project.

Where possible projects should be designed to integrate multiple disciplines. This may require inclusion of one or more experts in the project with knowledge/experience across the disciplines and knowledge of the location to enable focus on high-level connections and foster collaboration across disciplines, and especially to ensure that outputs are transdisciplinary.

Data and knowledge developed by ACIAR projects should be housed in a central repository and archived for ease of access for partners and other ACIAR projects. These products may include: reports, papers, GIS and other data sets, communication products and newsletters.

There would be advantages from providing additional funding for communications in-country. There are many good private sector firms skilled at PR and Communications Pakistan.

Opportunities for post-docs to participate in a 4-year research project on a 50 – 100 percent time basis would add to the capacity built in country.

Projects focussed on research for development should:

- Include outputs that will lead to impact and answer the question "How does this improve our knowledge for investing in socioeconomic development?"
- Encourage 'blue sky' thinking in project teams beyond that within the confines of the disciplines in the project
- Encourage project teams to provide evidence when impact statements are made
- Provide advice to project teams about how to report on capacity building.
- Investment in communications needs to consider the totality of needs- and this may require more than just investment in a single person with a single skill set.

7.3 Recommendations

We recommend that the ACIAR investment in this project is captured and built on in further multi-disciplinary projects in Pakistan, beyond but complementary to the Adapting to Salinity in the Southern Indus Basin (ASSIB) project. Future projects should:

- Use and complement the range of networks already developing.
- Be based on quality research data, and therefore build on the expertise being developed in physical and socioeconomic research and modelling (systemic Inquiry, RAPs, biophysical monitoring, modelling).
- Focus on trajectories rather than targets; this approach is facilitated, replacing log-frame evaluation with Impact Pathways analysis.
- Value research by enabling data storage within countries to ensure accessible data is stored and made available for researchers in the country, as well as for future ACIAR projects.
- Focus on documenting what is happening, and what the impacts are, following the style of the reports from the Farmer Learning Project, with a dedicated person.

Out-scaling of the on-ground and institutional impacts should be approached by:

- Working with established and growing networks from this project.
- Using collaborative design approaches to ensure context is included in the design of solutions.
- Building out from the areas of expertise – in the villages, government departments and universities engaged in this project.
- In country partners seeking ways to continue support of, and involvement in, the existing Stakeholder Forums.
- Ensuring that existing and any future public groundwater monitoring is made accessible to local people, for example, through a large painted graph on a wall on which the groundwater levels are entered over time.
- Extending the groundwater models, and results from the models, as inputs for supporting the National Water Policy objectives that call for a good understanding of the water budgets, groundwater conservation and establishment of groundwater management zones.
- Pursuing RAPS approach and outcomes, which has direct relevance in supporting Pakistan's agricultural policy and its policy of reducing import of vegetable and palm oil.
- Out-scaling the three key aspects of this project (the stakeholder forums, the RAPS approach and the groundwater modelling): one approach is that we will build on these for the ASSIB project. However, on a wider scale, supporting these

activities may require ACIAR to find other donors that are willing to adopt these approaches and possibly co-fund further work in this space.

Policy recommendations

Based on the findings of this project, certain recommendations that could be helpful for researchers and policy makers:

- In formulating policy, farmer representatives, especially farmers with smaller areas of land, must be considered and consulted about water issues so that policies can be implemented at the farm level.
- The most crucial factor for agricultural development is access to agricultural finance. This is particularly important for the adoption of technological advancements regarding water management like sprinklers, drips and farm mechanisation. If the Central Bank could provide special financing schemes for sustainable practices, adoption rates would increase substantially.
- The water allocation for farms must be fair and just and there must be an efficient water market so the malpractices and overuse of water resources can be managed.
- Nature-based solutions that restore natural and modified ecosystems need to be considered in developing and introducing supporting policies for specific zones. The areas with water scarcity must be highlighted and serious efforts should be made to improve ecosystem health.
- An integrated farms system model is a proposed concept to increase the efficiency of farming systems in a sustainable manner. The livestock, crops, fisheries, agroforestry and poultry sectors must all be considered as one integrated system as public policies that are in favour of one crop could suppress the cultivation of other crops. Market solutions are most efficient means to achieving such integrated models and should be preferred to some current subsidies that encourage poor practice.
- If farmers were provided with a complete package of new technology for free, including interventions in the form of HEIS, low delta fruits and crops, and necessary guidance on good agricultural practices, adoption rates of water efficient agriculture would increase, as witnessed in this project.

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Higher Degree Research Dissertations

Masters

Ahmed, A. (2018). *Evaluating the Impact of Solar Tube wells on Waterlogging and Irrigation Intensity in District Shaheed Benazirabad*. MS thesis dissertation submitted to MUET, Jamshoro, Sindh.

Awan, M. S. (2019). *The impact of groundwater use on the health of rural households in District Sahiwal*. Masters thesis dissertation submitted to UAF, Faisalabad, Punjab.

Hussain, S. (2018). *An economic analysis of groundwater use, agricultural productivity and farmers' livelihoods in District Okara*. Masters thesis dissertation submitted to UAF, Faisalabad, Punjab.

Jumani, Z.A. (2018). *Water Balance Assessment for optimum groundwater management strategies in Irrigated agricultural areas of Sakrand Distributary*. MS thesis dissertation submitted to MUET, Jamshoro, Sindh.

Kalhoro, K. (2020). *Determination of Effects of Soil Salinity on Wheat Yield using Electromagnetic Induction Technique*. MS thesis dissertation submitted to MUET, Jamshoro, Sindh.

Kalhoro, M. A. (2019). *Comparative study of solar, diesel and electric operated tube wells on irrigated agriculture command area of Gul Minor in district Naushero Feroz*. MS thesis dissertation submitted to MUET, Jamshoro, Sindh.

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Publications by project team on related ACIAR projects

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Culas, R. (2019). *User allocation and implication on water quality and farm income: The Lower Chenab Canal irrigation system in Pakistan*. 1-7. Abstract from 5th International Conference on Dry Zone Agriculture, Kilinochchi, Sri Lanka.

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8.3 List of Associated Reports

- Report A: Participatory Rural Appraisals: Starting the Co-Inquiry into Groundwater and Livelihoods
- Report B: Improving groundwater management to enhance agriculture and farming livelihoods: Literature review
- Report C: Gender, groundwater and livelihoods in Pakistan
- Report D: Groundwater model for the lower Bari Doab Canal, Punjab Pakistan
- Report E: Groundwater Model for Left Bank Command of Sukkur Barrage in Khairpur, Naushero Feroze, and Shaheed Benazirabad Districts
- Report F: Groundwater Model for the Kuchlak Sub-basin, Balochistan
- Report G: Socioeconomic impact of groundwater resource use on the livelihood of farming communities in eastern Punjab, Pakistan
- Report H: Socioeconomic assessment for improving groundwater management in the Left Bank Command of the Sukkur Barrage, Sindh Pakistan.
- Report I: Socioeconomic Analysis of Groundwater Resource Management for Balochistan, Pakistan.
- Report J: Improving groundwater management to enhance agriculture and farming livelihoods: Representative agricultural pathways and socioeconomic benefits of groundwater management interventions in Punjab, Sindh and Balochistan Provinces, Pakistan
- Report K: Integrating web and mobile based applications for groundwater management

  Report L: Improving groundwater management to enhance agriculture and farming livelihoods: Communications Report
- Report M: Briefing Note: Framework for a groundwater status report
- Report N: Briefing Note: The Application of Indicators for Assessing Aquifer Stress

Full reference details for reports A-K are listed in section 8.2.

Part B
Detailed methods, results and detailed achievements measured against objectives

9 Detailed Methodology

9.1 Inception agreement on shared vision

Representatives from all the project partners were present at the inception meeting, which was held at the University of Agriculture, Faisalabad between Monday 29 August – Thursday 1 September 2016. The fundamental importance of this moment for the project approach is reflected in the five stated workshop aims:

- To nurture and confirm a shared purpose for the project and its impact pathways
- To nurture, confirm and establish practical procedures for an integrating, reflective and participatory project approach
- To ensure each team member appreciate their roles and responsibilities, and has the capacity to start delivering on those roles and responsibilities
- To establish a detailed work schedule until the first annual reporting requirements to ACIAR
- To get to know each other better and build a strong and cohesive team.

Activities over the three days were carefully designed and facilitated to build a team with individuals who had sufficient trust in each other, and the approach of the ACIAR project, to work together, despite the novelty and acknowledged difficulties of such a large, complex project. The inception meeting emphasised group activities (Figure 9.3 Group activities as part of the Inception meeting, Faisalabad, August/ September 2016Figure 9.3), setting the project pattern of cycles of acting in small groups then coming together to share learning and reaffirm purpose.

Figure 9.1 Group activities as part of the Inception meeting, Faisalabad, August/ September 2016

The meeting included some novel activities such as drawing rich pictures to facilitate discussion of gender issues, as well as actions more familiar to participants, including consolidating the immediate works plan. Outcomes of this meeting included confirmation of the Coordinating Team (CT) and preparation for the Participatory Rural Appraisals (PRAs), including the role they would play in assisting with the selection of case study sites.

9.2 Confirmation of co-ordination team

Good project governance is always important, particularly in this project with multiple partners collaborating in inquiry and design. The CT was the heart of this project's governance and whole of team maintenance.

The co-ordination team (CT) originally consisted of key personnel from CSU, PCRWR, Ecoseal, UAF, ICARDA, but by 2020 had expanded to include people who emerged as key contributors to the project from BUITEMS, SAU, NED, MUET, UAA, MNSUAM and PID. The CT met regularly throughout the project, holding 75 meetings, occasionally in person in Pakistan, but mostly via online platforms. Meetings were recorded and minuted, and three important points (information or requests for action) were sent by email to all project partners immediately after each meeting to keep the whole large group involved. Minutes are available from the members area of the project website. The CT co-ordinated the wide range of activities of the project, oversaw the financial expenditure and guided evaluation and reporting.

Ultimate project administration was the responsibility of the Project lead, CSU, with important assistance from PCRWR, the in country 'host'. The project's Communications Officer, and Finance Officer, were employed and managed through PCRWR.

9.3 Participatory Rural Appraisal

PRA is based on co-learning by people from various disciplines and backgrounds. It is a set of approaches, methods and behaviours that help people share reflections on their social and physical environment. The PRA for this project was based on on-site group interviews and walks, undertaken by people with a willingness to listen and to share power and knowledge (Figure 9.4).

Figure 9.2 Learning together, Balochistan

The entire project team, regardless of discipline or experience, were invited to be part of the PRA collaborative learning. Acknowledging that this is a new approach for many in the project, PRA capacity building was provided at a workshop at Mehran University of Engineering and Technology, Jamshoro, Pakistan, in November 2016. Following training PRAs were undertaken in the focus areas of the project as per Table 9.1.

Table 9.1 PRA summary

Province	Districts/ Basins	Number
Balochistan	Pishan Sub Basin and Kuchlak Sub Basin	5
Sindh	Naushero Feroze/ Shaheed Benazirabad	9
Punjab	Lower Bari Doab (male)	14
	Lower Bari Doab (female)	13

Details of the methods and outcomes of the PRAs are included in the report in Khair et al. (2021a) (see section 8.2).

9.4 Collaborative selection of case study sites

The project application approved by ACIAR identified the focal areas within the selected three provinces, but selection of specific case study sites was an early, essential task. An all of team meeting was held in Faisalabad from the 3-6 of February 2016, with the aim of scoping the entire LWR-036 project. A session at the workshop was allocated to discussing the case study purpose(s) and the criteria for selection. From this and further discussions at inception, a list of important hydrological, social, economic and logistical considerations was developed. A PRA reporting template (Figure 9.3) was designed to enable the free flowing, qualitative discussions of the PRA to be standardised to inform the case study selection criteria.

For each criterion, please indicate each site's suitability using the following legend:	(0) Unsuitable	(1) Not very suitable	(2) Has both suitable & unsuitable features	(3) Suitable	(4) Very suitable
Case Study Site					
Groundwater situation					
ESSENTIAL: Availability of groundwater data (e.g. what is known, what is available?)					
KEY: The situation regarding groundwater (e.g. how much stress or exploitation? Are the resources vulnerable or degraded? Is there salinity or waterlogging?					
DESIRED: Features of this site that will make it useful for exploring multiple key issues associated with groundwater management					
What sort of tools or interventions are likely to be accepted/ successful? Could these be easily replicated elsewhere?					
The hydrological system (e.g., is it a closed system?)					
Sources of water for irrigation and their use					
Socioeconomic situation					
KEY: The social, cultural, and economic situation – e.g. Are there farming families, communities and partners who can facilitate change? Is it a place where we can work towards achieving behavioural change, with the presence of a well-organised community willing to participate with us?					
Prevalence of poverty where potential for livelihood impacts are measureable and achievable, and where capacity of stakeholders is low with high prospects for enhancing their capacity					
Potential for high value crops of high economic return/ viability of economic options, and proximity to input (finance) and output market					
Availability of data related to social and economic aspects, or good prospects to acquire/ create such data					
The extent lessons from this village could be applicable in other places					
Features of this site that will make it useful for exploring multiple groundwater-related issues for improving livelihoods					
Logistics					
ESSENTIAL: Accessibility, safety and security					
DESIRED: Features that make this site feasible or not as a place where tools can be tested					
Potential to connect with/ build on the irrigation efficiency improvement Farmer Field Schools established by the ACIAR project LWR/2014/074					
Features that make this site feasible or not to finalise case study activities within the life of the project					

Figure 9.3 Case study selection criteria

After multiple discussions among the project team the six case study areas shown in Table 9.2 were selected. The case studies 'sites' were framed differently depending on the focal activity. When groundwater modelling was the focus sites were at the district or sub-basin scale, while the community engagement occurred at village or local area scale.

Table 9.2 Case studies

Province	District	Case study
Balochistan	Pishin	Malikyar
Balochistan	Kuchlak	Zargoon
Punjab	Sahiwal Lower Bari Doab	(11-L) (focus on specific villages)
Punjab	Okara Lower Bari Doab	(I-R) (focus on specific villages)

Sindh	District Noushehro Feroze	Cheeho Minor
Sindh	Shaheed Benazirabad (Nawabshah)	Malwah Distributary

9.5 Interaction with other ACIAR projects

The ultimate beneficiaries of this project are groundwater dependent Pakistani farmers, but much of the focus of the project was on building agency and university capacity to enable them to better support farmers. Close interaction with two other ACIAR projects though the Australian Water Program was important to ensure impact. The Farmer Learning Project, LWR2014/074 provided linkages with farmers and practitioners working directly with those farmers. Project ADP/2014/045 focused on Participatory Irrigation Management (PIM) provided a link to advances in irrigation policy and practice.

9.6 Impact Pathways Analysis

Impact Pathways Analysis (IPA) enables evaluation of progress towards project outcomes. An effective monitoring, evaluation, reporting and learning (MERL) plan was identified at the outset as crucial for our project. An initial version of the IPA was developed by the CSU team in January 2016 as part of the project proposal. The IPA was updated in on 31 January/ 1 February 2017, during a combined workshop with all three Australian water projects in Islamabad (Figure 9.6).

Figure 9.4 The project's Impact Pathway Analysis being shared with participants from the three projects in the Australian Water Program. January 31, 2017, Islamabad.

The end of project outcome identified were:

- Farmers, farming organisations and partner non-government organisations have started introducing improved groundwater management practices
- Relevant provincial- level government agencies, non-government organisations and farming organisations have developed effective partnerships for ongoing discussion on groundwater management issues and solutions
- Government agencies in Pakistan have started developing/ demonstrating improved groundwater-related planning, monitoring, management strategies/ options and policies

The conversion of the IPA into a MERL plan was finalised in March 2018 and enacted in May 2018. The full Impact Pathway Analysis and MERL plan for the project are provided in Appendix A.

9.7 Developing and sharing a literature review

In developing the project's literature its multiple authors, reviewed literature related to aspects of groundwater management in the case study areas selected for the project. The systematic framework used for the review evolved from an initial structure developed during the project's inception workshop in September 2016, and later revised at an authors' workshop in February 2017. The eventual structure was divided according to case study areas, and sub-divided into the following themes:

1. Irrigation management
2. Socio-political context
3. Gender and youth
4. Role of NGOs
5. Economic context
6. Energy issues
7. Groundwater and hydrology issues

Training in reviewing and synthesising academic literature was provided at intervals in the project, in conjunction with the coaching in quality academic journal writing.

A full report on the literature review is provided in Mitchell et. al. (2021) (see section 8.2).

9.8 Gender systemic inquiry

From the PRAs it was clear that additional inquiry into the potential role for women in groundwater management was warranted. The gender co-inquiry sought to bring women together to explore gender aspects of groundwater management. Two sessions to build capacity in using systemic co-inquiry were undertaken in 2017, the first at MUET, Sindh, on November 10, and the second at UAF, Punjab, on November 16. Following the training the two consultants and lead authors of this report were employed in September/ October 2018 to undertake the gender co-inquires in the case study areas as per Table 9.3.

Table 9.3 Summary of gender co-inquiries

Province	Workshop locations	Facilitator
Sindh	Cheeho Mnor, District Noushehro Feroze. Village Choudhry Nizam-ul-din Arain	Shabana Siyal
Sindh	Malwah Distributary, District Nawabshah, Village Nim Dahari	Shabana Siyal
Balochistan	Pishin district, Zarghoon village of UC Khohab	Rizwana Waraich
Balochistan	Pishin district, UC and Killi (village) Malik yar.	Rizwana Waraich
Punjab	Sahiwal and Okara Districts 130/9-L Dera Rahim	Rizwana Waraich
Punjab	Sahiwal and Okara Districts 9 R-GD	Rizwana Waraich

Figure 9.5 Co-inquiry regarding gender and groundwater, Sindh.

The facilitators were guided by the Project's provincial social leads- Dr Saira Akhtar, Dr Syed Khair and Professor Tehmina Mangan. Their overall approach was to talk with, and listen to, women and men of the villages in relation to women's lives and work (Figure 5.7). In all cases diagramming/ mapping was used to facilitate storytelling. These stories were told in a variety of languages, and in some depth. The 'results' in the report are the distilled stories synthesised and translated to English, as detailed in the report in Waraich et al., (2021) (see section 8.2).

9.9 Collaborative installation of piezometers and data loggers

Spatial and temporal groundwater information are key elements for improving understanding of groundwater resources and for governments to make informed decisions, but there is a lack of long-term groundwater monitoring data in Pakistan. This project made a small investment in establishing 2 monitoring sites at each of our case study sites to monitor depth to water and EC on a daily basis, as per Table 9.4.

Table 9.4 Groundwater monitoring sites established by the project

Site	Measurement	Loggers
1R (Okara)	Depth to water and EC	1xTD,* 1xCTD**
11L (Sahiwal)	Depth to water and EC	1xTD, 1xCTD
Kuchlak	Depth to water and EC	1xTD, 1xCTD
Pishin	Unable to install due to Covid	
Malwah Distributary	Depth to water and EC	1xTD, 1xCTD
Cheeho Minor	Depth to water and EC	1xTD, 1xCTD

* Data logger type TD Diver for measuring and recording groundwater levels/temperatures

**Ceramic CTD-Diver for measuring and recording groundwater (depth 50 m)

The installation also provided additional opportunities for team building and capacity building (Figure 9.8), with PCRWR provided training for Irrigation Departments. The data provides additional opportunities for collaboration, with the logger data held by PID, MUET and BID and accessible to other departments. The meta-data from the project is stored with MUET.

Figure 9.6 Project team members learning about groundwater monitoring, Punjab

9.10 Development and ongoing improvement of groundwater models

Groundwater is a 'hidden' resource and remains poorly understood. Computer-based modelling is an efficient and effective tool to deliver visualization of real systems. Modelling also provides optimization and best management strategies running various scenarios before the implementation; eventually saving time, money, and cost. The project used a current version of MODFLOW, developed by the United States Geological Survey developed MODFLOW.

The conceptual model requires an appropriate set of boundary conditions to represent the system's relationship with the surrounding systems. In the groundwater flow model, boundary conditions describe the exchange of flow between the model and the external system. The boundary conditions for the project models were used to develop groundwater flow models include: river, recharge, evapotranspiration and pumping well as per Figure 9.7.

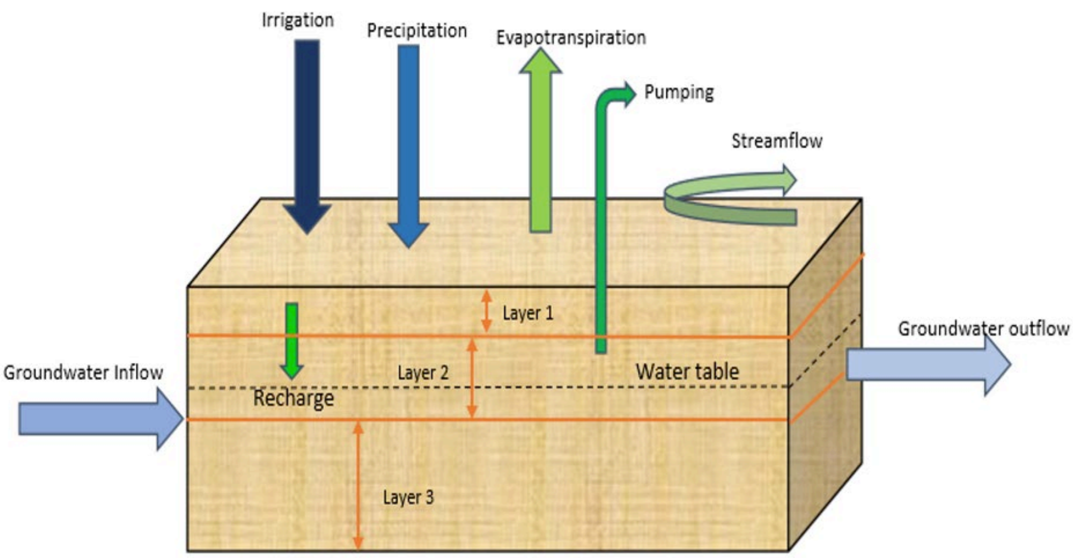

Figure 9.7 Model Parameters, Punjab

Groundwater models have been developed for

1. Punjab: Lower Bari Doab Canal (LBDC)
2. Sindh: Left Bank Command of Sukkur Barrage
3. Balochistan: Kuchlak

Groundwater use is generally not monitored in Pakistan. Primary and secondary sources were used to obtain estimates of groundwater usage. To estimate groundwater extractions a survey of tubewells were conducted to map and quantify groundwater use at head, middle and tail-end reaches of LBDC which was used to estimate groundwater extractions based on average pumping hours. Secondary data for the groundwater models was obtained from respective irrigation departments in each province. This includes canal water supplies, groundwater levels, GIS data for irrigation network, groundwater network, lithological/borelog data. Climatic data was used from PMD stations. The main achievement as mentioned by the reviewer was building the capacity of the Irrigation Departments to monitor groundwater levels and quality using loggers. Two data loggers were installed in each case study area to monitor the groundwater levels and quality at high spatial and temporal resolution. In Sindh a survey was undertaken of the number of tubewells in the areas where pumping is occurring and these estimates were extrapolated based on average pumping hours per tubewell and the average discharge. In Kuchlak estimates of tubewell usage were based on average discharge and times of operation provided by BID.

Details of the methods and outcomes of the groundwater modelling are included in the technical reports (Ahmed et. al., 2021a & b; Anjum et al., 2021) (see section 8.2).

9.11 Groundwater modelling scenarios

To assess the implication of groundwater pumping on groundwater levels in LBDC command area, Left Bank of Sukkur Barrage covering the districts of Khaipur, Naushero Feroze, and Shaheed Benazirabad under several biophysical and socioeconomic scenarios, a regional groundwater flow model (MODFLOW in GW Vistas) was developed. Additionally, a groundwater model for the Kuchlak sub-basin has also been developed, however due to the paucity of data a limited number of scenarios will be undertaken. Simulated scenarios based on potential climate change, using the IPCC's representative concentration pathways (of carbon dioxide) of 2.6, 4.5 and 8.5, and water use changes.

9.12 Formation and ongoing interaction with stakeholder forums

Stakeholder forums can be considered as 'spaces' where people with a shared interest can meet, learn and design new futures together. For this project, stakeholder is a broad term, and may include farmers, villagers, staff from agencies and NGOs, and university academics and students. Women and men, young and old, have been encouraged to be part of Stakeholder Forums. To initiate the formation of the Stakeholder Forums, workshops were held in the case study sites. These initial workshops were based on collaborative

Figure 9.8 Stakeholder forum initial workshop participants, Sindh

problem solving, and combined information sharing with co-design of future activities (Figure 9.8).

Each of the initial workshops was customised to meet the needs of the Stakeholder Forums and the project. For example, the LBDC 11-L stakeholder forum workshop in April 2019 enabled a range of local farmers, university researchers, agency and NGO staff and the project team to discuss the opportunities for their community to benefit from the project, and to guide groundwater related research in the area, and emphasised the inclusion of local young men (Figure 9.9).

Figure 9.9 Young men contributing to the initial 11-L Stakeholder forum workshop

Stakeholder forums are continuing past the ending of this project. For example, in Zarghoon, in Balochistan there is an active Local Support Organization and most of our stakeholder forums members belongs to that LSO. The Zarghoon forum will continue in future, but on other sites the stakeholder forums need a sustainable funding and /or they be engaged in some other project. In Sindh the Malwah Stakeholder Forum is part of the case study for the ACIAR Adapting to Salinity in the Southern Indus Basin (ASSIB) Project. In Punjab

9.13 Developing and sharing farmer booklets, cards and videos

A booklet explaining groundwater was developed by the Communication officer and CSU, and an On-farm Water Management Booklet was developed by MDF. These booklets were designed to help stakeholders and extension workers as a resource guide and knowledge tool. A range of farmer facing information materials were developed which included 'Farmer Cards' on raised beds, waterlogging and conjunctive use, initiated by the CT, created by the communications officer, and improved with consultation with farmers and advisers, especially through Stakeholder forums. The materials were devised in English, and translated into Urdu, and Sindhi.

Videos were developed by Dr Tehmina Mangan and Mustafa Nangraj to document farmer concerns in the Sindh case study sites and to build better understanding of groundwater conditions, and to disseminate improved water management practices. The key issues highlighted in these videos is the focus on salinity and waterlogging in Sindh, and the shortage of water which allows only a portion of the farm to be irrigated.

Videos were also made in Punjab by Prof Ashfaq and Dr Asghar of UAF with Sujad videos on the interventions being undertaken by Mr Sheeraz Sindhu (farmer and Stakeholder, Sahiwal District) on sunflower planting to demonstrate 4 irrigations versus 6 irrigations for maize. Mr Sindhu also discusses the profitability of sunflower over maize and discusses the importance of saving groundwater by using less water as part of this ACIAR project. The Apna Pani App was also featured in a Global News segment with interviews with Mr Sheeraz Sindhu and Dr Muhammad Amin (UAAR).

All the information materials are presented in Appendix D.

9.14 Socioeconomic household survey

Socioeconomic characteristics of all case study farming communities was collected using a survey instrument (questionnaire) that built on similar previous surveys, and information from the PRAs and gender co-inquiry. Before the questionnaire was developed and administered, key members of the economics team attended training in Sydney, Australia 2018, where they learned to use and customise the CommCare app. This enabled Mobile Acquired Data (MAD) to be used for data collection in this project, and potentially in many other Pakistan based projects.

Figure 9.10 Household economic data being collected using mobile tablets, Sindh.

During 2017-18, the household economic survey was carried out across the project locations (Table 9.5 and Figure 9.10).

Table 9.5 Socioeconomic surveys

Case study	Farmers surveyed
Kuchlak sub basin	47
Pishin	57
Malwah Distributary	75
Cheeho Minor	75
Lower Bari Doab Canal system	469

The questionnaire sought information about:

a. Socioeconomic characteristics of the household

b. Land resources

c. Irrigation sources used at head middle and tail of minors

d. Methods of irrigation

e. Cropping patterns

f. Data regarding cost of productions and revenues generated by main crops of area

g. Sources of energy

h. Income sources

These collected data enabled analysis of water use, efficiency technical and economic efficiencies for the major crops and horticultural crops produced in the case study areas of the three provinces. Performances of major crops in terms of Benefit-Cost Ratios (BCRs) and strategies for improving groundwater use and farmers' livelihood approaches have been identified.

The purpose of the socioeconomic analyses was also to inform implementation of on-ground (on-farm) interventions with identified strategies, which has been partly carried-out by the Representative Agricultural Pathways (RAPs). The RAPs methods developed in the project measured the farmers' uptake of the strategies identified from the socioeconomic analyses in relation to low-delta crops and high efficiency irrigation system (HEIS).

The other aspect of the socioeconomic analyses is to integrate the measured water-use-efficiencies with the groundwater modelling scenarios (net-water availability) to plan the future of agricultural/ cropping systems and irrigation management practices based on demand-supply relations for water.

Secondary data were also collected from relevant government departments, local NGOs, national and international agencies.

Full reports on the socioeconomic surveys from each province are provided in the associated technical reports (Ashfaq et al., 2021; Khair et al., 2021b; Mangan et al., 2021) (see section 8.2).

9.15 Distribution and training in the use of EC meters and tensiometers with farmers

Discussions among the stakeholder forum members highlighted the desire of farmers to measure aspects of water quality and quantity, encouraging the development of mobile apps (see next subsection) and the distribution of a range of tools including EC/pH EC/pH and tensiometers for individual farmers, and groundwater depth measuring tools were provided for the Irrigation Departments (Figure 9.11).

Training the use of the tools was provided training to partners, including PID, BID and BUITEMS, and early career researchers at our partner universities. The benefits of using these tools was also shown to farmers, with an emphasis on including and involving young people.

Figure 9.11 EC meters- sharing and training

9.16 Collaborative development of Apps

The DSS created during the project was developed collaboratively, and iteratively. In the initial stages the design leader worked with project team members, with the goal of recording and visualising groundwater depth and quality. This resulted in the Apna Pani (My Water) module, which enabled mobile phones to be used to record spatially referenced readings of groundwater depth and quality. The development and feedback process suggested enthusiasm for expanding the scope of the DSS to an application that could support decisions about district and on-farm water use. Staff from the Agriculture Departments were included in the ongoing iterative design process, and as the prototype developed so too were some individual farmers from the Stakeholder Forums.

In total 10 cycles of design and feedback led to the current two module design, "Apna Pani" (My Water) and "Apna Farm" (My Farm), which when deployed can assist users in calculation of monthly crop water requirements, deficits in surface water supplies, ground water quality and allied information to make decisions on sustainable crop production. A manual was produced to assist users, and the platform is being transferred to PCRWR for continued use and development.

9.17 Socioeconomic scenario modelling and Representative Agricultural Pathways (RAPs)

The Trade-off Analysis, Minimum Data Model (TOA-MD) is a unique simulation tool that can utilize the socioeconomic data sets already collected and combine it further with macroeconomic data sets of farms and project the current and future viability of specific policy interventions proposed in research studies. In this project the TOA-MD assisted in gaining a better understanding of results of the socioeconomic survey in relation to farming systems, proving data to the RAPs process.

Technical, economic and water use efficiency of crops are calculated using Data Envelopment Analysis Data (DEA) and efficiency measurement system (EMS). Data envelopment analysis is a non-parametric approach and the relationship between inputs and outputs is defined by making a linear piecewise frontier. A multi-crops and multi-inputs model are developed to measure the technical and economic efficiency of farms.

- technical (output level/input use),
- allocative (how best to minimize the costs of inputs for the set level of output),
- economic efficiency (the value of output/costs of inputs used).

• Water use efficiency = farm productivity with respect to water use by keeping other inputs constant.

Representative Agricultural Pathways (RAPs) are plausible future biophysical and socioeconomic projections that have been used to help develop adaptations to Climate Change in, for example, the United States. (Mu et al. 2019).

The RAPs process relies on input from a cross section of stakeholders. That input is used to project the biophysical, socioeconomic, and institutional and policy related indicators. RAPs are generated from continuous engagement process among stakeholders; farmers, policymakers, academia, researchers and project team members that helps to formulate the transformative adaptation and future pathways. This interdisciplinary research process brings a holistic approach towards development pathways and adaptations at farm level. The RAPs development process is shown in Table 9.6.

Table 9.6 Steps for RAPS Development

RAPs Development Process
Step 1: Selection of pathways
Step 2: Key indicators identification
Step 3: RAPs narratives, definitions by economic team
Step 4: Key parameters selection and review process by team members
Step 5: Direction and magnitude of change in different variables based on discussed in RAPs meetings, rationale for rate of change and finalization of short narrative
Step 6: RAPs sharing with experts for their feedback

Step 7: Incorporation of feedback from experts and stakeholders in result of continuous engagement process
Step 8: Final RAPs drafting in DevRAP matrix and again sharing with experts for further refinement on certain variables

After project team members were trained in the approach, RAPs sessions were organised with Stakeholder forums in Punjab, Sindh and Balochistan. The discussions informed the co-design of on-farm interventions to reduce groundwater use (Figure 9.12).

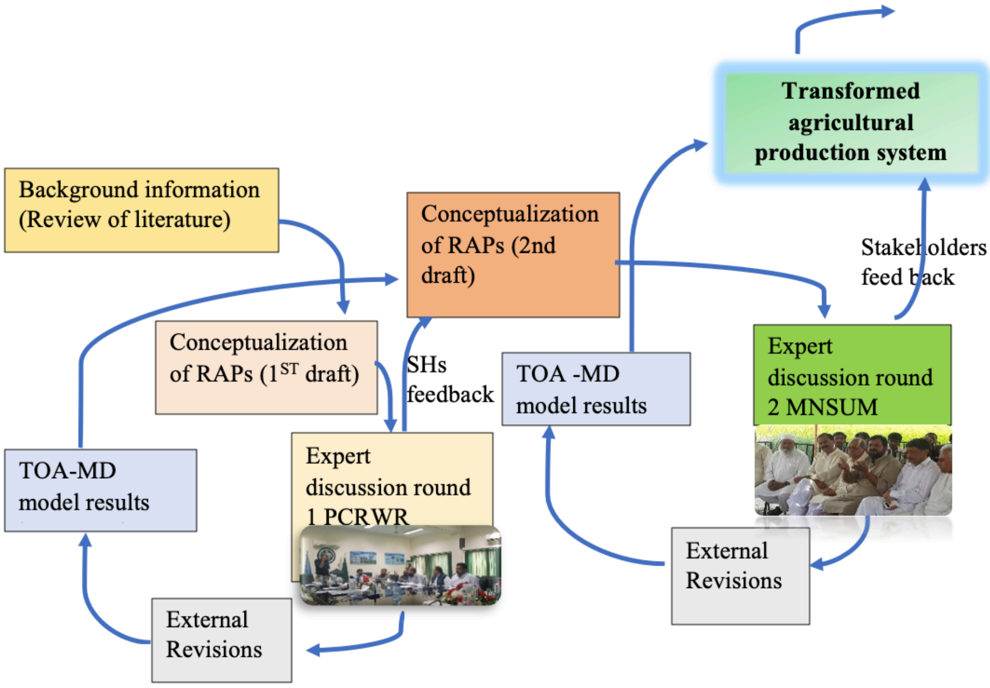

Figure 9.12 The RAPs Development process in Punjab

The RAPs process is showing great potential, as evidenced in this project, but also beyond. How it was used here. For example, being a new discursive ‘space’ RAPs could enable new practice norms to develop. This may be a mechanism for improve women’s participation in groundwater management.

9.18 Trials with farmers with low delta crop and alternative systems

Following the recommendations of the socioeconomic study and ongoing presentation of groundwater monitoring data, the provincial based project teams developed potential on farm interventions through the stakeholder forums. Working with the stakeholder forum members, and understanding needs and preferences resulted in different, but locally appropriate, interventions being trialled.

In Punjab interventions developed in collaboration with stakeholders and farmers have been trialled in Sahiwal with Sunflower and Moong bean, and up and out scaling has commenced (Figure 9.13)

Figure 9.13 Distribution of high-quality Moong bean seed for trials with low water use crops, through the Stakeholder Forum

In Sindh the farmers were unwilling to change their crops, and the focus has been on trialling improved water efficiency through raised bed cultivation and interrow cropping that provides additional income without additional water use.

In Balochistan the focus is on trialling Improved water management practices such as the use of modern high efficiency irrigation systems (HEIS) in fruits and vegetables, introduction of low water use fruits such as grapes, pistachio, pomegranate, and good agricultural practices that achieve water efficiency.

Full reports on the interventions in each area are provided in Nasir et. al. (2021) (see section 8.2).

9.19 Covid impacts on methodology

The COVID-19 pandemic disrupted the project at the stage when the biophysical and socioeconomic modelling, and RAPs, were beginning to drive the local on-farm research, through the Stakeholder Forums. The ban on gatherings temporarily halted interaction with Stakeholder Forums and resulted in postponing RAPs sessions in Balochistan and Sindh and the installation of loggers on two piezometers in Balochistan. Additionally, all Pakistan Universities have undergone periods of complete and partial closer, as have all government agencies. Travel bans also stopped travel to Pakistan by the Australian team members.

10 Key results and discussion

This project involved a number of research activities. The results from these are presented in detail in the individual technical reports that are listed in section 8.2. The following section summarises the key results and discusses their implications. The groundwater explorations, including the models for each province and case area, are presented and discussed first, followed by the results from the social and economic research. The section concludes by synthesising the key findings.

10.1 Groundwater models for sub-basins in Punjab, Sindh and Balochistan

10.1.1 Sustainable groundwater use and management

Lower Bari Doab Canal Command, Punjab

A groundwater model, using MODFLOW, was developed for the Lower Bari Doab Canal (LBDC) command Punjab Pakistan, to improve understanding of the water balance for the model area and the irrigation in districts of Okara and Sahiwal in order to assess the sustainability of groundwater resources and to undertake scenarios for forecasting the impact of future stresses on the aquifer in the LBDC. A uniform grid of 1000m was used to model the LBDC command. A total depth of 300m was modelled with three layers. The model was calibrated over a period of six years from October 2009 to September 2015 with monthly stress periods.

Evaluating the water balance for the LBDC enabled us to better understand the condition of the resource and to estimate the sustainable extraction limits, which in turn can lead to improving the sustainability of the aquifer by informed decision making. The water balance for the irrigation divisions of Okara and Sahiwal, and our case study sites 1-R in Okara and 11-L in Sahiwal also provided an understanding of sustainable extraction levels for these zones. The approach we have taken in this study is to focus efforts in the top two model layers. The top layer is 30m thick and incorporates the rivers and canal leakage, rainfall recharge, evapotranspiration[2] and pumping, making it the most important layer from a management perspective. Layer 2, which is 60m thick, is also used substantially for groundwater extraction so estimation of sustainable yields must also take layer 2 into consideration.

The water balance for the LBDC command area from October 2009 to September 2015 is given in Table 10.1, and for Layers 1 and 2 in Table 10.2 and Table 10.3 respectively. Annual average seepage losses from the rivers and canal system are 1556 MCM/yr. Total recharge (including groundwater returns) is 3164 MCM/yr and tube-well extraction from the LBDC command area is 4316 MCM/yr. These results show that groundwater extraction is higher than the recharge to the aquifer. The groundwater budget component due to evaporation is relatively small due to the water table being deep in the whole of the command except for the areas towards the head end of the irrigation system. This is due to low canal supplies during the modelled period. The net gain in storage in the study area over the simulation period was 87.9 MCM/yr. The simulated results show that there is very

[2] *Another important aspect is understanding how evapotranspiration functions in the groundwater models. Actual evapotranspiration (Eta) is specified in the model which is simply a head dependent boundary condition. If the water table is between the surface and the specified extinction depth, then a specified amount of water is removed. If the water table falls below the extinction depth, the specified amount will not be removed as evapotranspiration. Specifying the Eta and the spatial distribution in the extinction depth allows simulation of the amount of water leaving the model.*

little potential for increasing groundwater extraction thus it would not be advisable as farmers will increase groundwater extraction during droughts and periods of low flow.

Table 10.1: Water balance for the LBDC command (Oct 2009 to Sep 2015) ET=evapotranspiration.

Model	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
River	1556.2	-19	1537.3
Recharge	3164.3	0	3164.3
Well	0.0	-4316	-4315.7
ET	0.0	-298	-298.0
Total	**4720.5**	**-4632.5**	**87.9**

Table 10.2: Water balance for model layer 1 (Oct 2009 to Sep 2015). ET=evapotranspiration.

Layer 1	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
Bottom flow	249.6	-4153	-3903.1
River	1556.2	-19	1537.3
Recharge	3163.3	0	3163.3
Well	0.0	-419	-418.6
ET	0.0	-298	-298.0
Total	**4969.1**	**-4888.2**	**80.9**

Table 10.3: Water balance for model layer 2 (Oct 2009 to Sep 2015). ET=evapotranspiration.

Layer 2	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
Top flow	4153	-250	3903
Bottom Flow	786	-788	-1
Recharge	1	0	1
Well	0	-3897	-3897
Total	**4940.01**	**-4934.17**	**5.84**

The key message from the layer water balances is that over 90% of pumping occurs from Layer 2, and this is probably due to farmers having to deepen tube-wells as water levels declined in some parts of LBDC. The net groundwater storage in Layer 2 is estimated at 5.84 MCM/yr. This does not leave much margin for farmers to increase pumping without initiating further declines in hotspots. The current buffer should be preserved for times of low flow from the supply system and for drought years. Although there is some margin for increasing pumping from Layer 1 we do not recommend this at this stage because the model is calibrated over six years and during this period, a severe drought has not been experienced in this area. Another reason is that farming families depending on the shallow groundwater for domestic and stock water would face additional difficulties if wells needed to be deepened. Another important reason is that inflows from Layer 1 to Layer 2 are substantial and allow pumping from Layer 2 to continue. Decreasing the downward flows from Layer 1 would mean that upward flows from Layer 3 would increase which is not a desirable outcome as salinity in deeper layers will be mobilised into fresh groundwater into Layer 2.

Seepage from the irrigation network (including main and secondary canals) decreases from the head to the tail of the LBDC command. This is due to the decreasing density of the channels (main canal, branches and distributaries) and their discharges towards the tail of the irrigation system. Decreasing rainfall and increasing crop water requirement towards the tail end coupled with decreased canal supplies is resulting in greater groundwater depletion downstream from canals particularly at the tail end. Introducing water saving technologies amongst farmers should be encouraged and for this the Punjab Irrigation Department (PID) and the Punjab Agriculture Department (PAD) need dedicated staff with up-to-date knowledge of modern water savings technologies. The use of selective Managed Aquifer Recharge (MAR) at specific suitable sites in Lower Bari Doab would enhance recharge to the aquifer during the monsoon period. On farm storage facilities could help in rainfall harvesting and storage of surplus canal water. Canal water is currently delivered within a supply-based system; the capture of excess water would allow canal water to be used on a demand basis. This would reduce pressure on groundwater in addition to recharge to the aquifer.

The sustainable yield for LBDC is estimated at 4300±215MCM to allow for adaptive management during times of drought. We recommend that an allowance of 5% (215 MCM) would allow farmers to increase extraction during drought years while allowing replenishment when rainfall and surface water flows recover to normal supply levels. The LBDC districts of Okara and Sahiwal are almost in balance and it is likely that a decrease in rainfall and surface water supplies in response to drought in the future will cause the net balance for the aquifer to become negative which will put further pressure on water levels. It is on this basis that we have suggested a conservative sustainable yield of 4300±215 MCM for the model domain. If the PID designates Okara and Sahiwal as separate groundwater management areas, then the recommended sustainable yield is 740±37 MCM/yr for Okara and 1830±92 MCM/yr for Sahiwal. We recommend that Okara and Sahiwal be designated as groundwater management areas that can be managed to ensure that groundwater depletion is managed within acceptable limits. The overall guidance for recommended sustainable yields is given in the report for Okara and Sahiwal (see Anjum et al., 2021; listed in section 8.2).

We further recommend that as improved monitoring data is collected, the model calibration period needs to be extended to account for the increased number of tube-wells and ensure the robustness of calibration. In Australia, each groundwater area of significance has an agreed long-term sustainable yield. This sustainable yield is revisited after 5 or 10 years depending on the agreement with groundwater users, the level of development in the groundwater management area and the incidence of drought. Given the severe drought experienced in Australia between 2017 and 2019 it is likely that the long-term average annual extraction limits will need to be revised for most groundwater management areas. Incorporating this process of revising and improving groundwater models will offer PID as the Resource Manager improved understanding of the risks to the groundwater from overexploitation and salinity intrusion. It will also allow PID to support the objectives of the National Water Policy 2018, the Punjab Water Policy 2018 and Punjab Water Act 2019.

Left Bank Command of the Sukkur Barrage, Sindh

A regional flow model of the northern part of the left bank command of Sukkur Barrage command was developed, using MODFLOW. This model was designed to improve our understanding of the water balance for the model and for various irrigation divisions in order to assess the sustainability of groundwater resources and to model scenarios for forecasting the impact of future stresses on the aquifer. These stresses include pumping, canal supply and climatic stresses on the aquifer. This modelled area mostly lies in the freshwater zones, where the groundwater is used to supplement surface water. The western boundary of the model is defined by the Indus River and the eastern boundary by Nara Canal. The aquifer is modelled as a two-layer system and the Indus River, Nara canal, major canals such as Rohri, and major distributaries are specified as the river boundary conditions.

The water balance analysis for the Left Bank command of Sukkur Barrage enabled us to better understand the condition of the resource and to estimate the sustainable extraction limits which can then be used to improve the sustainability of the aquifer. The water balance for the irrigation divisions of Khairpur East, Khairpur West, Rohri/Moro, Dad and Nasrat, and our case study sites Malwah Distributary Command in the districts of Shaheed Benazirabad and Cheeho minor command in Nausheero Feroze also provided an understanding of sustainable extraction levels for these divisions and case study sites. The approach taken in this study was to focus efforts in the top two model layers. The top layer is 30m thick and incorporates the rivers and canal leakage, rainfall recharge, evapotranspiration and pumping, thus it is an important layer from a management perspective. Layer 2, which is 95m thick, is also used for groundwater extraction by Salinity Control and Reclamation Project (SCARP) tube-wells for drainage disposal, and because of the increasing salinity with depth in the lower Indus plains, the increasing salinity of groundwater in layer 2 acts as a constraint to over-extraction from Layer 1.

We assessed the water budget for the overall model domain from October 2010 till March 2015 and this is shown in Table 10.4 and Table 10.5 respectively for Layers 1 and 2 respectively. The two major components of the water balance inflows are recharge from rainfall and irrigation, and river leakage and canal seepage, which account for 98.6% of inputs to the system. Evapotranspiration is also a major outflow due to high rates of evapotranspiration and prevalence of shallow water tables in the Lower Indus, Sindh. Evapotranspiration accounts for a substantial 25.8% of the outflows from the system. The net loss in storage over the simulation period is -1.04 BCM/yr.

Table 10.4: Water balance for layers-I average 2010-2014.ET=evapotranspiration.

Layer-I	Inflow [BCM]	Outflow [BCM]	Net [BCM]
Bottom	2.051	2.48	-0.429
Boundary	0	0	0
Drain	0	0.467	-0.467
ET	0	1.606	-1.606
Recharge	3.943	0	3.943
River/canal leakage	1.160	0.033	1.127
Wells	0	2.942	-2.942
Total	**7.154**	**7.528**	**-0.374**

Table 10.5: Water balance for layers-I average 2010-2014.ET=evapotranspiration.

Layer-II	Inflow [BCM]	Outflow [BCM]	Net [BCM]
Boundary	0.071	0.859	-0.788
Drain	0	0	0
ET	0	0	0
Recharge	0.001	0	0.001
River/canal leakage	0	0	0
Top	2.48	2.051	0.429
Well	0	0.307	-0.307
Total	**2.552**	**3.217**	**-0.665**

The key message from the water balances is that over 90% of pumping occurs from Layer 1, as farmers are using shallow tube-wells to exploit the freshwater lens to supplement surface water irrigation. The net groundwater storage in Layer 2 is estimated at -0.665 BCM/yr as outflows are in excess of inflows. Of particular concern is the outflow of 2.051 BCM into Layer 1. At present the net gradients are downwards from Layer 1 to Layer 2, as inflows from Layer 1 to Layer 2 are higher that outflows. Keeping this net gradient downwards is important for preserving the freshwater lenses in the Left bank of Sukkur Barrage. Additionally, the net storage change for Layer 1 is -0.374 BCM which does not leave much margin for farmers to increase pumping without initiating further declines in hotspots and associated salinity problems. In Lower Sindh, the net change in storage should be close to or slightly below zero to ensure a balance as the aquifers are shallow and a small positive balance will ensure that freshwater supplies are available during times of low flow from the supply system and during drought years.

The current average annual pumping from the Left Bank Command of Sukkur Barrage encompassing districts of Khairpur, Naushero Feroze, and Shaheed Benazirabad is 2.942 BCM from Layer 1 and 0.307 BCM from Layer 2, totalling 3.249 BCM. The net decline in storage in Layer 1 is 0.374 BCM and 0.665 in Layer 2. We do not recommend increasing pumping from Layer 1, firstly because the net storage change is already -1.04 BCM for both Layers 1 and 2, and secondly because during this period, a severe drought has not been experienced in this area. Another reason is that farming families depending on the shallow groundwater for domestic and stock water would face additional difficulties if wells needed to be deepened. The sustainable extraction limit is estimated at 3±0.3 BCM to allow for adaptive management during times of drought and inadequate surface water supplies. We recommend that an allowance of 10% (0.3 BCM) will allow farmers to increase extraction during drought years while allowing replenishment when rainfall and surface water flows increase.

We further recommend that as improved monitoring data is collected, the model calibration period needs to be extended to account for the increased number of tube-wells and to ensure the robustness of calibration. Another consideration for the sustainable yield for the Left Bank Sukkur Barrage model is to manage the flows from the lower layer into the upper layer to prevent accelerated salinisation. This may require optimising the SCARP drainage tube-wells to ensure downward gradients are maintained. These freshwater lenses provide a fraction of the groundwater for irrigation as compared to the groundwater used in Punjab, nevertheless they are instrumental in allowing farmers in Sindh to increase cropping intensity and improve livelihoods. Continued use of groundwater in this environment will need to be accompanied by investments in water productivity to minimise adverse impacts of waterlogging and salinisation and to preserve the freshwater lenses for the future of groundwater irrigation in Sindh.

Irrigation Divisions: The water balance for irrigation divisions shows that the inflows from recharge and river/canal seepage, and outflows from pumping are significant in Moro and Khairpur East. Much of this recharge is a result of irrigation return flows, seepage from distributaries, minors and water courses at the farm level. It is recommended that the Sindh Irrigation Department (SID) develop a monitoring strategy for these irrigation divisions to monitor groundwater levels and salinity to ensure continued agricultural productivity. All irrigation divisions are experiencing a net decline in storage, which over time will result in declining water levels and increased salinity from lateral intrusion into freshwater lenses. The freshwater lenses provide groundwater irrigators supplementary water which allows increased cropping intensities. A balance between recharge and pumping is needed in these divisions to ensure continued use of these freshwater lenses. Increased pumping is likely to increase the risk of salinisation which will result in forcing irrigators to reduce pumping and in-turn will exacerbate waterlogging.

The Nasrat Division shows relatively less decline in the net storage due to shallow water tables and high salinity of the underlying groundwater, which limits farmers from using this groundwater. To maintain productivity, farmers in the Nasrat Division will need to increase their acreage of low delta crops and improve irrigation efficiencies. This will help in maintaining a balance between inflows and outflows. SCARP tube-wells and drains also need to be maintained in the Nasrat Division to manage waterlogging and salinity.

The Riverine zone in the model comprises the Indus River and covers an area of 2387 km^2. The Indus River contributes 971.69MCM and is the major inflow to the groundwater system in this zone. Seepage from the canal network contributes 188.31 MCM, thus the total recharge from river and canals combined for the model is 1160 MCM. Recharge also comes from irrigation return flows and rainfall and floods. By far the greatest source of recharge for the Left Bank of Sukkhur Barrage is from irrigation return flow which contributes 3944 MCM of this a minor component from rainfall recharge. What this means is that return flows from irrigated agriculture are the main contributor of recharge and rising water tables in the area. The majority of outflows (670.95 MCM) are from constant head cells which constitute outflows toward from layer 2 towards the right bank of the

Indus, 50% to Left Bank and 50% to Right Bank of the Indus. The other major outflow is from evapotranspiration of 187.76 MCM in this zone.

***Case Study Sites*: **In the Malwah Distributary (District Shaheed Benazirabad case study area), recharge from irrigation return flows is 114.87 MCM. This is the main source of recharge for the distributary canal command area. Canal seepage is negligible as this distributary has been lined. However, groundwater extraction of 143.03 MCM from the shallow freshwater lens in the Malwah Distributary comprises the main outflow from the system. The evapotranspiration component is 36.85 MCM which is indicative of water tables within the root zone for some areas of Malwah. The net balance for the Malwah Distributary is -61.69 MCM which will result in water level declines in the canal command area over time. Moreover, the lining of the distributary means that the seepage which was recharging the groundwater has been curtailed. However, lining of the distributary also results in more surface water for tail end farmers which will result in higher irrigation return flows at the tail end of the system. Despite this, farmers in Malwah Distributary have indicated that insufficient water reaches the tail-end of the distributary.

In the Cheeho Minor (District Naushero Feroze-case study area), recharge from irrigation return flows is 14.68 MCM, and this is the main source of recharge for the Cheeho Minor canal command area. Canal seepage is negligible as this distributary has been lined. Groundwater extraction of 19.12 MCM from the shallow freshwater lens in the Cheeho Minor comprises the main outflow from the system. The evapotranspiration component of 5.5 MCM is the second largest outflow. The net balance for Cheeho Minor is -5.97 MCM which will result in localised water level declines in the Cheeho Minor command over the long term. Moreover, the lining of the Minor means that the seepage, which was recharging the groundwater, was curtailed initially, but during our field visit we observed that the lining was in very poor condition. Lining minors and distributaries is costly, and although it brings short term benefits for tail-end farmers as the distribution is theoretically more equitable, in the long-term poorly constructed liners and lack of maintenance results in seepage from the canal and loss of capital expenditure. A strategic approach to lining is required in Sindh, where only areas which are waterlogged should be lined.

Monitoring of groundwater resources is not being undertaken by SID as there are significant capacity constraints within SID as well as the absence of a groundwater section within SID or for that matter within the Sindh Government. We recommend that SID take up the challenge and establish a Groundwater Directorate dedicated to groundwater *Monitoring, Mapping, Modelling and Management*. Monitoring must be conducted using continuous monitoring loggers which provide SID with up-to-date information on the state of the aquifer. Developing a strategic monitoring strategy and implementing this strategy with sufficient funding for operation and maintenance, along with investment in capacity building in groundwater management, will allow SID to improve management of groundwater in Sindh.

The lack of data on groundwater in Sindh and the lack of technical capacity within SID is a major impediment to improving management of groundwater. This project has taken the first steps towards building capacity by training over 20 SID engineers, several students from the Mehran University of Engineering and Technology, and one engineer from the SCARP monitoring organisation Sindh in groundwater monitoring and modelling. Building on this for the future of groundwater users in Sindh is essential.

We recommend that SID designate each of the five divisions (i.e. Khairpur East, Khairpur West, Moro, Dad and Nasrat) as groundwater management areas to ensure that groundwater depletion is managed within acceptable limits. The overall guidance for recommended sustainable extraction limits is given for the entire model and improving irrigation efficiency and replacing a percentage of high-water use crops with low delta crops will allow adjustments in groundwater abstractions.

Kuchlak sub-basin, Balochistan

A regional flow model of the Kuchlak sub-basin was developed, using MODFLOW. This model was designed to improve our understanding of the water balance for Kuchlak and its three sub-watersheds, namely Surkhab Lora, Rokhi Lora and Sariab Lora, to assess the sustainability of groundwater resources, and to model scenarios for forecasting the extent of controls on pumping that would be required to achieve a sustainable future for the denizens of Kuchlak. These stresses include pumping and climatic stresses on the aquifer, both are of major concern. The major streams in Kuchlak are ephemeral, and the low rainfall recharge in the sub-basin means that farming enterprises have to rely on groundwater for irrigation, which has led to rapid declines in the water table. The model boundaries are bounded by topographic highs as the Kuchlak sub-basin is formed in long narrow valley between mountains. The aquifer is modelled as a two-layer system and although the streams are specified in the top layer, recharge from these streams is minor. Most of the sub-basin boundaries are no-flow boundaries, other than a small section along the southern boundary where flows exit this valley.

Water balance for the Kuchlak model: We assessed the water budget for the overall model domain from October 2010 till September 2018. The water balance for Kuchlak in Table 10.6 indicates recharge is the main inflow to the groundwater system at 32.807 MCM. Pumping from the deeper layer is 427.284 MCM which is the main outflow followed by boundary flows are 56.575 MCM which exit the sub-basin along the southern model boundary.

Table 10.6 Water balance for the Kuchlak sub-basin 2010-2018

Model	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
Recharge	32.807	0	32.807
River	0.030	0	0.030
Well	0	-427.284	-427.284
GHB-in	0	-56.575	-56.575
Net	32.837	-483.859	-451.023

Contributions from the stream network are minor, as it only recharges the top layer which has essentially dried out due to heavy pumping from the deeper layer. Although in the model the top layer dries out it is conceivable that there are localised perched water tables due to seepage from ephemeral streams. The major outflow is from pumping which accounts for 88% of all outflows. The net loss in storage over the simulation period is a very alarming -451 MCM/yr which equates to an average decline in water levels of 5.4 m/yr. This, as many authors have indicated, is a race to the bottom.

There are three distinct watersheds in Kuchlak sub-basin: (i) Surkhab Lora (Major town Khanozai); (ii) Rokhi Lora (Major town Bostan and Kuchlak); and (iii) Sariab Lora, which are shown in Figure 10.1. An analysis of the water balance for each watershed was undertaken to understand where stress on the groundwater system in each of the watersheds.

Water Balance for the Surkhab Lora watershed: The water balance for the Surkhab Lora watershed in the northwest of the Kuchlak model domain shows recharge inflows of 11.285 MCM, and significant inflows from west and east flows in response to pumping (see Table 10.7). The major outflows are pumping at 79.34 MCM and outflows along the southern and western boundary of Surkhab. The groundwater depletion is -86 MCM/yr which results in an average decline in heads of 6 m/yr. There are very few monitoring bores in the Surkhab Lora watershed. Increased monitoring in this watershed is warranted along with strategies to engage with groundwater users and the farming community in Surkhab to co-design cropping strategies of high value low delta crops and high efficiency irrigation systems that reduce the number of irrigations and decrease stresses on the aquifer.

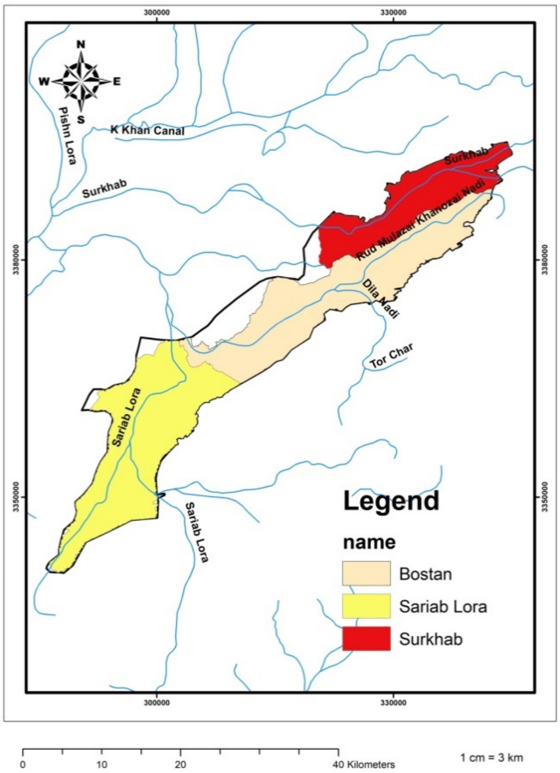

Figure 10.1:Sub-watersheds in the Kuchlak sub-basin

Table 10.7 Water balance for the Sukhab watershed 2010-2018

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
West flows	1.534	-10.828	-9.294
East flows	14.154	-1.848	12.306
North flows	13.270	-1.827	11.443
South flows	1.912	-34.580	-32.669
Recharge	11.285	0.000	11.285
River	0.016	0.000	0.016
Well	0.000	-79.340	-79.340
GHB-in	0.000	0.000	0.000
Net	**42.169**	**-128.423**	**-86.253**

***Water Balance for the Rokhi Lora (Bostan) watershed**:* The Rokhi Lora watershed covers a major part of the Kuchlak model domain. The water balance for Rokhi Lora in Table 10.8 indicates recharge of 7.586 MCM, and significant inflows from north and east in response to pumping. The major outflows are pumping at 230.008 MCM and outflows along the southern and western boundary of Rokhi Lora. The groundwater depletion is -158 MCM/yr which results in an average decline of 6.2 m/yr. In Rokhi Lora groundwater extractions comprise about 54% of total pumping from Kuchlak sub-basin. There are very few options other than to reduce pumping as the groundwater is heavily overexploited. Monitoring bores are not spread out in the Rokhi Lora; almost all the monitoring bores are located along the banks of the Rud Mulazai Khanozai Nadi. We recommend that the Rokhi Lora watershed be closely monitored with a better distribution of monitoring bores. The main town in the area is Bostan and there are likely to be a number of private households with pumping bores in Bostan which are also tapping the deep aquifer for domestic use. Strategic monitoring in this watershed is warranted along with strategies to engage with groundwater users and the farming community in Rokhi Lora to co-design cropping strategies of high value low delta crops that reduce the number of irrigations and decrease stresses on the aquifer.

Table 10.8 Water balance for the Rokhi Lora (Bostan) watershed 2010-2018

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
West flows	4.065	-17.140	-13.074
East flows	26.344	-1.585	24.759
North flows	60.749	-1.463	59.287
South flows	7.745	-14.587	-6.842
Recharge	7.586	0.000	7.586
River	0.004	0.000	0.004
Well	0.000	-230.008	-230.008
GHB-in	0.000	0.000	0.000
Net	**106.493**	**-264.781**	**-158.288**

The Sariab Lora watershed covers the southern region of the Kuchlak model domain. The water balance for Sariab Lora in Table 10.9 indicates recharge of 8.765 MCM, with significant inflows from the west, east and north in response to pumping. The major outflows are pumping at 104.685 MCM and outflows along the southern and eastern boundary of Sariab Lora. The groundwater depletion is -109 MCM/yr; equivalent to a decline in head of 3.9 m/yr. Groundwater is heavily overexploited for irrigation and domestic use in the Sariab Lora watershed. Monitoring bores are not spread out in Sariab Lora almost all the monitoring bores are located along the eastern model boundary. We recommend that this area should be closely monitored with a better distribution of monitoring bores. There are likely to be a number of private households with pumping bores in the region which are also tapping the deep aquifer for domestic use. Strategic monitoring in this watershed is warranted along with strategies to engage with groundwater users and the farming community in Sariab Lora to co-design cropping strategies of high value low delta crops that reduce the number of irrigations and decrease stresses on the aquifer.

Table 10.9 Water balance for the Sariab Lora watershed 2010-2018

	Inflow MCM/yr	Outflow MCM/yr	Net MCM/yr
West flows	11.099	-0.644	10.455
East flows	16.352	-13.003	3.349
North flows	8.455	-1.567	6.888
South flows	3.379	-29.819	-26.440
Recharge	8.765	0.000	8.765
River	0.009	0.000	0.009
Well	0.000	-104.686	-104.686
GHB-in	0.000	-7.598	-7.598
Net	**48.059**	**-157.316**	**-109.257**

Our findings suggest that a suitable approach to managing groundwater would be to first improve monitoring of the resource to improve assessment of the condition of the resource. Improved monitoring can also provide irrigators, groundwater users and stakeholders a better understanding of groundwater resource condition and the temporal and spatial changes occurring in response to intensive aquifer exploitation. Engaging with groundwater users and irrigators is necessary to co-design a sustainable future over a management planning period. An example of this is the RAPs approach adopted in this project in Kuchlak and Pishin which is resulting in adoption of low delta crops like pistachios, and adoption of high efficiency irrigation for pomegranates – both are also high value crops. Adoption of new crops and sustainable farming practices, with improved irrigation management will be a slow process as it takes time to scale out these activities, but it also requires dedicated human and financial resources. A multi-skilled team consisting of social researchers, groundwater managers, hydrogeologists, irrigation and agricultural specialists is required to work with community groups to develop a sustainable future for Kuchlak. BID may wish to adopt a 10-year planning period to increase adaptation in areas where there is a concentration of pumping bores. Again, this will require improved knowledge of pumping in the catchment. At present one of the significant challenges we faced in developing this model is the lack of adequate information on pumping, locations of pumping bores, and monthly usage. Compounding this issue is that we postulate that with the rapid rate of declines many smallholder farmers would have abandoned pumping as water levels would have declined to dry out their wells. So pumping may actually have been forced to decline over time, unless farmers have the capital to deepen wells.

Ultimately though controls on pumping will not be enough to stem this tide. Controls on pumping and improved cropping practices along with low delta crops is part of the solution but not necessarily enough to bring the aquifer to a sustainable level of management. Innovative techniques for recharging the aquifer will be required. In Kuchlak there are a number of check dams and other water control structures that capture and hold stream flows during the monsoon. These areas need further investigations so that rainfall and flood waters can be captured and artificial recharge of the aquifer using injection wells may also be part of the solution. Part of the runoff from mountain slopes needs to be captured and detained to allow captured water to be injected back into the deep aquifer. A distributed network of injection wells can be deployed for enhancing recharge in the sub-basin. Our clear message here is that there is no one solution for Kuchlak which requires a number of different approaches. Of these the RAPs approach is one that needs to be pursued by GoB agencies, better use of flood waters and runoff from mountain slopes including check dams, subsurface dams and other structures, and pilot projects to develop a network of injection wells to inject captured surface water to enhance recharge to eth deep aquifer. Along with the above-mentioned interventions greater focus on capacity development and financing are required. Lastly, a dedicated project that investigates various options for Managed Aquifer Recharge, design of appropriate deep injection wells, and other options to recharge the aquifer need serious consideration.

10.1.2 Scenario analyses

The models enabled some examination and evaluation of the likely consequences of future management plans and under different climate change scenarios. Scenario analysis based on well informed models enables the consequences of 'what if?' questions to be seen.

Each groundwater model is backed by GIS datasets, as they are specific to study locations. These GIS datasets are valuable for any future projects that may need this data both for partners as well as for future ACIAR projects. Additionally, the models themselves are repositories of data. The Punjab groundwater model data is with PID, UAF and ICARDA team. The Sindh model and data are housed by MUET and SID, and the Kuchlak model and data is housed at MUET and BID. However, the data is not centralized at the moment.

The models developed in this project are not perfect, as the data required for modelling is not without issues– these limitations need to be a consideration when designing scenarios. In our case the scenarios were designed by stakeholders and amongst these PID had some very specific needs for the selected scenarios which was essentially in support of the Punjab Water Policy (PWP). The Climate change scenarios were a result of the RAPS Stakeholder workshops and these are useful also from a policy perspective.

This project provides a base tool for irrigation departments to make decision on evidence-based information. Additional projects are needed to further enhance the capability of irrigation departments and academic institutions to use these models to test the efficacy of the schemes that they are introduced in the area to uplift the social status of the community. For example, Sindh Irrigation department has a project of subsidizing 250 solar tube well in the Shaheed Benazirabad (Nawabshah) District. SID can use the model to simulate how this scheme will affect the groundwater dynamics in the Lower Indus Basin.

In future stakeholders may wish to see the impact of low delta crops – this can be achieved in its simplest form by identifying say which irrigation districts or canal commands could change say 10-15 percent of the existing crops to low delta crops (targeting hotspots in particular), and then estimating a decrease in groundwater pumping. As the groundwater models are spatially extensive, we would need to adopt spatial changes on a minimum of 10-15% of the cropped area. Low delta crops on 1 or 2 farms are not going to show any difference in water levels in response to changes in groundwater extractions.

Scenarios undertaken for the Lower Bari Doab, Punjab

Five scenarios were modelled to evaluate groundwater resource conditions under different pumping and canal water supply regimes. Additionally, two climate change scenarios were modelled to understand the likely impacts that Punjab is likely to experience by 2047 under a changing climate regime. The first climate change scenario (RCP 4.5) is based on current emission levels. The second climate change scenario (RCP 8.5) is a more extreme scenario that is predicted to occur if emissions continue to rise. Under this scenario, it is predicted that there would be more rainfall in Punjab but probably also more localised flooding due to rainfall events and farmers may face crop losses due to storm events These scenarios were developed in consultation with PID and the socioeconomics team from the University of Agriculture Faisalabad and the results summarised in Table 10.10.

The scenarios for PID were undertaken from September 2015 to October 2035 and the two climate scenarios (RCP 4.5 and RCP 8.5) from September 2015 to October 2047, to assess aquifer status and availability of groundwater for irrigation and to provide recommendations for PID, indicated below:

i. The Business-as-Usual (BAU) scenario indicated that if conditions remain similar to the September 2009 to October 2016 period up until 2035, then pumping of 4316 MCM/yr will not result in significant drawdowns.
ii. When groundwater usage was increased by 20% in the model, the net groundwater storage was reduced to 146M CM/yr (as compared to 78 MCM/yr in business-as-usual scenario), resulting in continuous declines in groundwater levels. These declines would be likely to induce lateral intrusions of saline groundwater and also mobilise higher salinity groundwater from deeper layers of the aquifer. A 20% increase in pumping is not a sustainable outcome for LBDC and if it occurred, it would cause those farmers who can afford to do so to deepen tube-wells even further.
iii. If a 20% increase in groundwater usage occurred in conjunction with surface water supplies being reduced by up to 5%, the net change in groundwater storage would be the same as for Scenario 2 (-146 MCM/yr for the LBDC area). Intuitively one would expect a larger decrease in groundwater storage however, this scenario would result in further declines in water levels which in turn, would result in a reduction in evapotranspiration from 277 MCM/yr for the BAU scenario to 154 MCM/yr for this scenario. Additionally, the model showed that there would be a substantial area east of the case study site 11-L in Sahiwal with dry cells, indicating that the top layer had dried out. These areas to the east have been affected the most by curtailment of flows in the three eastern rivers and the very

high density of tube-wells in Indian Punjab. This scenario depicts an alarming situation as an increase in groundwater pumping by 20% with an increase in cropping intensities with limited/constant surface water supplies would result in excessive depletion, increases in saline water entering fresh groundwater sources and possibly disruption in livelihoods of smallholder farmers.

Table 10.10: Results from the calibrated model and scenarios (GWS and SEL figures are in MCM/yr). GWS= groundwater storage.

	Model	Okara	Sahiwal	1-R	11-L
C1: Calibrated model Oct 2009–Sep 2015	GWS=87.9 MCM/yr SEL=4300±215 MCM	GWS = 80.9 SEL=740±37	GWS = 5.84 SEL=1830±92	GWS = -0.85	GWS = 7.14
	The calibrated model indicates surplus GWS of 87.9 MCM/yr for LBDC. However, some areas will require management as pumping is likely to keep increasing in the future. For 1-R and 11-L an extended calibration period is required to recommend SEL				
S1: Business-As-Usual (BAU)	GWS = 78.12	GWS= -5.45	GWS= 25.06	GWS= -0.88	GWS= 2.58
	For the BAU scenario, if conditions remained similar to those experienced from Oct 2009 to Sep 2015 up until 2035, then pumping of 4316 MCM/yr will not result in significant drawdowns. The BAU scenario shows surplus GWS of 78.1 MCM/yr for LBDC. However, hotspots are likely to develop in individual areas and will need to be managed as pumping is likely to keep increasing in the future.				
S2: Pumping Increased 20%	GWS= -146.06	GWS= -40.17	GWS= -80.00	GWS=-2.91	GWS=-5.46
	Increasing pumping by 20% will result in water level declines which will likely induce lateral intrusion of saline groundwater and may also mobilise higher salinity groundwater from deeper layers of the aquifer. GWS will decrease by 146.1 MCM/yr				
S3: Pumping Increased 20% and canal supply decreased 5%	GWS=-143.86	GWS= -41.78	GWS= -84.48	GWS=--2.96	GWS=-5.11
	Increasing pumping by 20% coupled with 5% decrease in canal supplies will result in water level declines which are likely to induce lateral intrusion of saline groundwater and may also mobilise higher salinity groundwater from deeper layers of the aquifer. A decrease in canal supplies will also result in falling water tables which reduces evapotranspiration from -204.7 MCM for scenario 2 (20% increase in pumping) to -154.76 MCM for scenario 3 which results in groundwater storage decreasing by 143.9 MCM/yr for scenario 3.				
S4: Pumping increased 10% and Canal supply increased 5%	GWS=44.43	GWS= -11.28	GWS= 7.29	GWS=-1.28	GWS= 0.94
	GWS is positive indicating that if pumping is increased by 10% then canal supples will also need to increase by 5% to ensure sustainability of the aquifer. This scenario results in increasing GWS by 44.4 MCM/yr indicating a suitable long term extraction rate if canal supplies can be maintained.				
S5: Pumping decreased 10%	GWS=162.97	GWS= 8.33	GWS= 68.54	GWS=0.0	GWS=6.34
	Additional net water is available is due to reduced groundwater pumping equating to 116 mm rise in groundwater depth across the LBDC. However, individual areas will recover more depending on the spatial distribution of pumping.				
S6: RCP 4.5	GWS=34.25	GWS= 8.85	GWS= 15.69	GWS=0.92	GWS=6.30
	Recharge will be decreased by about 1% in comparison to the BAU scenario. This decrease is due to the variation of rainfall in the study region. Higher individual rainfall events will result in rising water tables which will have decreased evapotranspiration from the agriculture fields.				
S6: RCP 8.5	GWS=179.20	GWS= 22.38	GWS= 81.47	GWS= 1.67	GWS= 26.65
	Recharge will increase by 460.7 MCM in the LBDC area. Groundwater levels are likely to rise rapidly in response to higher rainfall in the upper aquifer (<30 m) in study area, and PID would need to manage waterlogging in some areas which had largely abated due to the increase in pumping in the Lower Bari Doab.				

Note: GWS – Groundwater Storage MCM/yr; SEL – Sustainable Extraction Limit MCM/yr;

iv. If canal water supplies increased by 5%, due to canal and watercourse lining or the development of new water storage dams, and groundwater pumping increased only by 10 %, then net groundwater storage would be 44.43 MCM/yr. For this scenario, groundwater pumping would be 4491 MCM/yr, which is about 178 MCM/yr more than in the BAU scenario. This scenario indicates that under this combination of increased canal supplies and increased groundwater pumping, the aquifer will be finely balanced with a very small margin for any increase in pumping to cater for drought or below average rainfall years. We recommend that PID undertake a strategic review of lining canals and to avoid lining in areas that are designated as hotspots where groundwater levels need seepage from canals to maintain a healthy balance.

v. Comparing scenario 5 with scenario 1 (BAU), we find that if groundwater pumping was reduced by 176 MCM/yr (10% reduction), an estimated total water saving of 162 MCM/yr would be possible. We find that improved controls on pumping will achieve greater water savings. Thus, PID will need to focus effort on significantly enhancing the level of groundwater management particularly in designated hotspots in Okara and Sahiwal.

vi. The water balance for the RCP 4.5 scenario shows that recharge is decreased by about 1% in comparison to the BAU scenario. This decrease is due to variation in rainfall in the study region, which results in decreased recharge from agriculture fields, as some of the crop water requirements would be met by rainfall. The average net storage for the LBDC command area is 34.25 MCM/yr. The increase in rainfall under RCP 4.5 would reduce the need for groundwater irrigation as crop water requirement would be fulfilled by surface water supplies. The water balance for this climate scenario shows that there is a gain in net groundwater storage of 0.94 MCM/yr and 6.30 MCM/yr in the case study areas of 1-R and 11-L respectively as compared to -0.88 MCM/yr for 1-R and 2.58 for 11-L in BAU scenario. Surprisingly, the RCP 4.5 scenario shows an increase in recharge for our case study sites in 1-R and 11-L as compared with the BAU scenario, whereas over the LBDC it shows a 1% decline in recharge.

vii. Comparing scenario 7 (climate change scenario RCP 8.5) with scenario 1 (BAU), we find that if climate conditions changed as defined in the RCP 8.5 data, an estimated 179 MCM/yr of additional water would be stored in the underlying aquifers of the LBDC. Under this scenario, the water balance shows that recharge would increase by 461 MCM/yr in the LBDC area, due to the extreme rainfall events in the study region, which also results in an increase in evapotranspiration (190.59 MCM/yr increase) from the agriculture fields. Under this scenario, recharge from rainfall increases and recharge from canal supplies decreases due to increasing water levels in Layer 1 which reduces head gradients between the canal and groundwater system. The RCP 8.5 scenario indicates that pumping could increase further in response to increases in cropping intensity, but farmers would be likely to face greater difficulties under a climate regime where flooding and damage to crops may be more frequent due to severity of rainfall events. Under this scenario, groundwater levels are likely to rise rapidly in response to higher rainfall in the upper aquifer (<30 m) in study area, and PID may need to manage localised waterlogging in some areas which had largely abated due to the increase in pumping in the Lower Bari Doab.

PID has already recognized the importance of groundwater management and since 2008 has implemented a systematic monitoring program of water levels and water quality parameters from several hundred piezometers and tube-wells. To make a difference in the management of groundwater, this monitoring program should be rationalised, and key bores need to be fitted with loggers that monitor water levels and salinity. In addition, targeted metering of key tube-wells in the LBDC command area needs to be implemented so that there is a sound basis for future improvement of the model and management of the doab.

When surface water supplies are unequally distributed resulting in less water for farmers at the tail end of reaches, it tends to increase reliance on groundwater despite the fact that the water quality may not be suitable. Thus, there is an urgent need for improved access to surface water supplies for farmers at mid and tail end reaches, in combination with advice to farmers on use of groundwater for irrigation and improved monitoring and governance of groundwater.

Scenarios undertaken for the Left Bank Command of the Sukkur Barrage, Sindh

Scenario assessment was undertaken in consultation with SID to provide guidance for supporting SID's role in implementing the new Sindh Water Policy (*in preparation*) which will require SID to ensure sustainable use of groundwater in Sindh. This will also help in supporting the groundwater policy guidance given in the National Water Policy and will provide SID with guidance in sustaining groundwater use and agricultural productivity in the province. Two sets of scenarios were simulated: one based on historical climatic data; and the other based on the future time-series of climatic data for the RCP 4.5 and RCP 8.5 scenarios, which were undertaken to understand the likely impacts under a changing climate regime that Sindh is likely to experience by 2047 and also, to improve understanding for managing groundwater subjected to the impacts of climate change. Table 10.11 below shows the scenarios and its results.

The simulated water levels for all scenarios show decreasing trends (see Figure 10.2). The groundwater levels in the shallow (1.5-3 m) to moderate (3–10 m) category are trending towards the moderate to deep (>10 m) category.

Table 10.11: Scenarios undertaken from 2010 to 2047

Scenario	Description	Results
Scenario 1 (S1): **Baseline/Business-as - usual**	This scenario assumes that the pumping will remain the same as for the calibrated model. This scenario was used as a base case/ Business-as-usual (BAU) to compare other scenarios to.	The net loss in groundwater storage for baseline scenario was -1.244 BCM/yr.
Scenario 2 (S2) **10 % decrease in surface water supplies**	This scenario was undertaken in consultation with SID to assist in understanding the impact on the freshwater zones. In this scenario, water supplies early in the Kharif period (April to July) were reduced to 10% compared to historical supplies.	Net storage decreased from -1.244 to -1.343 BCM/yr compared to the BAU Scenario by curtailing seepages to the aquifer due to reduced supplies.
Scenario 3 (S3) **10% increased pumping**	In this scenario, pumping was increased for freshwater zones early in the Kharif period (April to July). This scenario will help in identifying the threshold depth and time scale of depletion. It will also set extraction limit for freshwater lens.	A 10% increase in pumping resulted in a decreased net storage from -1.244 to -1.436 BCM/yr due to enhanced groundwater extractions.
Scenario 4 (S4) **10% increased pumping and 10% decrease in water supplies**	In this scenario, pumping was increased from the freshwater zone and overall surface water supplies were decreased during the early Kharif period (April to July).	There was a decrease in net storage from -1.244 BCM for the baseline scenario to -1.535 BCM/yr due to enhanced groundwater extractions and reduced canal seepages.
Scenario 5 (S5) **Climate change Scenario**	In this scenario, future water balance assessment was performed using climatic input data for RCP 4.5 and RCP 8.5. The impact on net groundwater storage and water level responses were analysed for future climatic conditions.	For the RCP 4.5 scenario, the net loss in storage over the simulation period (2010-2047) declined from -1.244 BCM to -2.185 BCM. For the RCP 8.5 scenario, the net loss in storage over the simulation period (2010-2047) declined from -1.244 BCM for the baseline to -2.214 BCM.

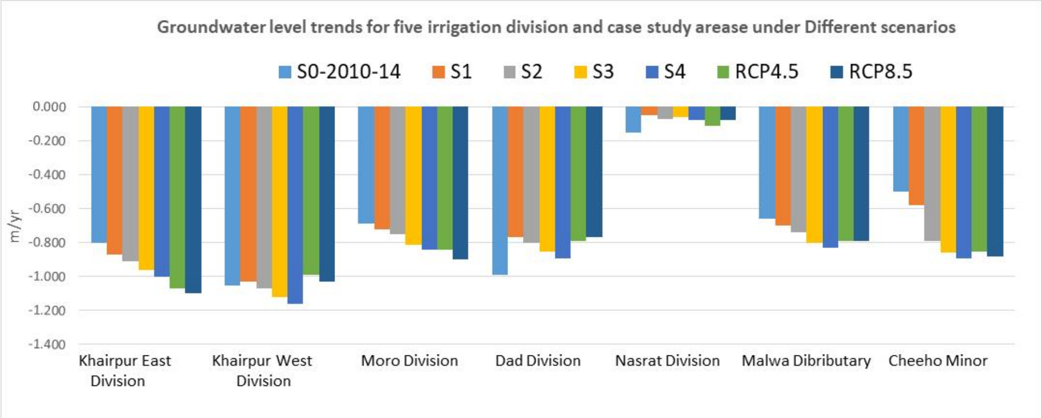

Figure 10.2 Groundwater level trends for five irrigation divisions for calibrated model and six scenarios Note: S0-2010-14 - Calibrated model; Scenario S1 – Business as usual; Scenario S2 – 10% decrease in canal supplies; Scenario S3 – 10% increase in pumping; Scenario S4 – 10% decrease in canal supplies and 10% increase in pumping, Scenario 5a– RCP 4.5; Scenario 5b – RCP 8.5

The depth to water table (DTW) in 2047 for the business-as-usual scenario indicates the Khairpur East (KE) division would move from the moderate to deep category. Most of the KE command would lie in the 10 to 15m category, other than the riverine areas, which would maintain their moderate water levels. The B-39 monitoring points at the head of the KE division show that there would be nearly a 10m drop in water levels. This is critical because of the magnitude of decline in water levels would deteriorate groundwater quality significantly. Here, one assumption is to be noted that in the simulation we have not constrained the pumping, which is to stop pumping due to low quality of groundwater. Realistically, farmers would pump less groundwater or stop pumping of groundwater if the quality of the groundwater declined. Head reaches in the KW division would also experience deep water levels, although this area presently has less pumping due to marginal saline water, but this water level change is seen due to pumping in KE division. This raises another serious concern regarding lateral movement of saline water in the freshwater zone of KE division. Shallow water levels and waterlogging would diminish from Moro and Dad division, most of the area would lie in the moderate water level (5-10m) category. Middle and Tail reaches of the Malwah Distributary (our case study site) and the Sakrand Distributary would have deep water tables (10-15m). Shallow water tables would prevail in the Nasrat Division as there is not much use of groundwater for irrigation there due to poor groundwater quality. Waterlogged areas would increase in the East of Nasrat Division, which is the area where natural depressions occur.

Scenario assessment shows that the decreasing water level conditions would remain the same as the BAU scenario. There would be localised changes in the area where there is increased pumping and decreases in surface water recharge. Water level declines would increase in the Moro and Dad Divisions and this would put their canal command areas into the moderate water level category. Climate change scenarios also showed a decreasing trend, but the gradient of the water level decline was not constant, it showed periods of decreasing and increasing water levels, although the water level in 2047 is nearly same as for the BAU scenario. The monitoring bores in KE and KW would show an increase in water levels from 2028 until the end of the simulation. In the Nasrat Division, the climate change scenario shows decreasing trends until 2022 then an increasing trend is observed.

Scenarios undertaken Kuchlak, Balochistan

The Business-As-Usual (BAU) scenario indicated pumping from the deep aquifer accounts for most of the net loss in storage from the aquifer. This very high rate of groundwater extraction results in 309.81 MCM of loss in storage from the aquifer which is equivalent to 4.7 m/year decline in average water levels.

Reduced Pumping scenarios

A 20 percent gradual reduction in pumping over three decades from 2017 to 2047, results in an average reduction in pumping of 12.5 MCM/year with only marginal benefit. The net storage loss over 30 years is 309.8 MCM/year which is equivalent to a 4.5 m/year decline in average water levels. This suggests that a more aggressive reduction in pumping needs to be implemented.

A gradual reduction in pumping by 50 percent results in an average reduction in pumping of 35.2 MCM. This results in a net storage decline in the aquifer of 275.2 MCM which equates to an average yearly decline in heads of 4.19m. By 2047 the overall reduction in pumping is 197.7 MCM per year for the final year of the simulation in 2047. The overall stress on the aquifer will be considerably reduced, however, the net decline in storage will be 102.7 MCM which is equivalent to an average decline in head of 1.56 m/year. To achieve this level of reduction in pumping for the sub-basin over a three decadal planning horizon will require Balochistan's irrigation and agricultural departments to work with the farming communities in Kuchlak to co-design a sustainable future.

Climate Change Scenarios

The RCP 4.5 scenario with a 50 percent reduction in pumping results in a net storage decline in the aquifer of 274.5 MCM which equates to an average yearly decline in heads of 4.18m. By 2047 the annual reduction in pumping is 197.7 MCM per year in comparison to the BAU scenario (Scenario 1). The overall stress on the aquifer will be considerably reduced, however, the net decline in storage will be 82.41 MCM which is equivalent to an average decline in head of 1.26 m/year.

The RCP 8.5 scenario with a 50 percent reduction in pumping results in a net storage decline in the aquifer of 271.4 MCM which equates to an average yearly decline in heads of 4.13m. By 2047, the 50 percent gradual reduction in overall pumping will result in an annual reduction in pumping of 197.6 MCM per year for the final year of the simulation in 2047 in comparison to the BAU scenario (Scenario 1). The overall stress on the aquifer will be considerably reduced, however, the net decline in storage will be 87.63 MCM equivalent to an average decline in head of 1.33 m/year.

A comparison of the RCP 4 and RCP 8.5 scenarios for 2047 indicates that by 2047 the rainfall will decrease from 49.2 MCM for RCP 4.5 to 44.7 MCM for RCP 8.5 or a corresponding reduction of 9.2%. Under the extreme scenario (RCP 8.5) Balochistan will experience a drier climate.

Options available for Kuchlak's groundwater users

There is no single solution to tackle the high rates of depletion in Kuchlak. Reductions in the volume of groundwater extracted for irrigation are necessary but are going to be difficult to enforce due to the prevailing political economy and the dire need for food security and protection of livelihoods. The introduction of Representative Agricultural Pathways (RAP's) in this project provides one possible pathway for a sustainable future (Nasir et al. 2021). A suite of solutions is required, which includes phased reduction in pumping accompanied by widespread adoption of High Efficiency Irrigation Systems, introduction of high value – low delta crops (e.g. pistachio, apricot, and pomegranate), improved irrigation and land management practices, and improved capacity of farming communities for water conservation and management.

10.1.3 Overall discussion of groundwater research

This project has had a positive influence on the capacity of the provincial Irrigation Departments to understand groundwater systems and the need for improved monitoring of groundwater resources. In addition, the project has assisted in building capacity for groundwater modelling within the Irrigation Departments. Our influence has not been limited to Irrigation Departments alone as capacity has also been built in Universities and the Pakistan Council of Research in Water resources. The fundamental change we have observed over the project period is threefold: firstly, a willingness of all partners to listen to the needs of irrigators; secondly, improved understanding of how water quantity and quality is affecting farming enterprises; and thirdly, the most beneficial change is community support and engagement in monitoring water levels and water quality in the case study areas which is creating awareness about the condition of the resource and need to change practices to ensure sustainable groundwater use in the future. These are tangible benefits from this project as the Punjab Irrigation Department has the enormous challenge of regulating production from over 1.2 million tube-wells, which can only be achieved with community support. In Balochistan groundwater levels are declining by about 8m year on year, the decline is so alarming that communities are willing to adapt to a future where less groundwater will need to be shared amongst all users and uses. In Sindh, caution is needed in regard to pumping from the freshwater lens along the main canals due to upconing and lateral intrusion of saline groundwater. Here, farmers are supporting improved groundwater monitoring and management practices. It must be noted that in Sindh there is virtually no monitoring of groundwater and under the new Sindh Water Policy (under development) it will be a requirement for the SID to monitor groundwater resources. This project has also supported training and capacity building of several early and mid-career irrigation professionals from SID, BID and PID in monitoring and modelling of groundwater resources.

Data collection is the responsibility of the public sector agencies (not research departments). However, the agencies (e.g., PID, SID and BID) require additional capacity building in designing strategic monitoring networks which will serve their institutional requirements. The Irrigation Departments also lack the resources to collect adequate and reliable data. Some data can be collected by communities, for instance with over 1 million tubewells in Punjab farmers can monitor EC of groundwater periodically to test their irrigation water and enter the data into Apna Pani. Other than EC communities can also provide information on irrigation water application, pumping hours for each tubewell and In some cases depth to water table may be possible if dedicated monitoring bores are available. However, to make this happen over the long term and out-scaling will require a sustainable funding model.

At present, due to the lack of good quality data at spatial and temporal scales, the models we have developed are simple and straightforward to reduce unnecessary complexity. Where possible, the spatial variability in aquifer parameters incorporates some of the heterogeneous nature of the aquifer, the depth variation of salinity and the huge pumping volumes amongst other complexities need to be considered when making recommendations. Our partners think (and we are in agreement) that understanding the modelling results is an important step for improved management. Spatial maps that are developed as a result of modelling can provide valuable information for the department and community. This can also be used for delineating groundwater management zones together with community representatives. Again, here we need to emphasize that the regional model results are more useful to irrigation departments and policy makers rather than individual communities. Furthermore, the model simulations need to be effectively communicated in ways that are more easily accessible for local officials to understand and use. This was on our Big Agenda, and, with the longer-term plan for ASSIB, we should keep it on the agenda. This would be a whole long-term project in itself, and one that could surely attract funding.

10.2 Socioeconomic analysis of case study sites in Punjab, Sindh and Balochistan

The collaborative inquiry across the project was based around three forms of social and economic research activity: (1) Participatory Rural Appraisals (PRAs); (2) gender inquiry; (3) household economic surveys and Representative Agricultural Pathways (RAPS). These are described in detail in the individual reports (see Ashfaq et al., 2021; Khair et al., 2021b; Mangan et al., 2021; listed in section 8.2). The key findings and discussion for each is summarised in turn below.

10.2.1 Key findings from the PRA and Gender inquiry

It was important for all members of the project team to develop a shared understanding of the issues addressed by the project, including how the issues are experienced and understood by farmers. PRAs were undertaken early in the project to start the process of shared understanding and to allow multi-disciplinary teams to be built around gathering social information to underpin decision making in the early stages of the government/community partnership.

The PRAs provided an opportunity to begin the collaborative process that was so essential for this project. Although following well documented PRA methods, the PRAs fit into a larger systems-framing that we are calling an on-going process of co-inquiry. Co-inquiry moves research beyond individual projects led by research academics into a process of inquiry that draws on, and enhances, the skills of multiple co-inquirers.

PRA was used to provide a sound basis for a number of approaches and activities within the project's three focal areas which comprised of different agro-ecological settings across the three provinces: Pishin Lora Basin in Balochistan, Lower Bari Doab Command area in Punjab; and Shaheed Benazirabad and Naushero Feroze Districts of Sindh. This includes foundational understanding for the case study site selection; understanding the groundwater situation; the development of the socio economic (household) survey and the development of forums. Each of these is discussed briefly below.

Key findings of the PRAs in Punjab province

Punjab province contributes about 80% of the total cotton production in Pakistan and around 75% of the national agricultural production. The Lower Bari Doab Canal (LBDC) irrigation system is the second largest irrigation system in Punjab and covers a gross command area of 0.80 million hectares. The main cropping systems in the study area are Rice-Wheat, Cotton-Wheat and Maize-Wheat. Keeping in view the above-described cropping systems, the LBDC irrigation system is divided into head (Rice-Wheat), middle (Maize-Wheat and Cotton-Wheat) and tail ends (Cotton-Wheat). Given that there were multiple cropping systems, 14 PRAs were conducted in the head and middle ends of LBDC irrigation system. The two sites in the LBDC irrigation system were selected because agricultural productivity in these areas is constrained by water shortages, marginal groundwater quality, poor agricultural management practices, and groundwater depletion particularly in the southern reaches of the doab. Additionally, climate change is likely to have further impacts on water availability in the LBDC. Groundwater is used as a major source of irrigation and groundwater depths range from 14 to 20 m. From the PRAs it was apparent that groundwater quality in the study area varies along the canal and distributaries from the head (fit quality) to tail ends (marginally fit-unfit quality). Due to excessive lowering of the water table at the tail ends, the installation costs of tube-wells are much higher. The PRAs also found that many farmers adopted various groundwater management strategies such as changing cropping patterns, sowing dates, raising crops on beds, laser land levelling, conjunctive use of water and drainage management, crop rotation and suitable improved crop varieties that are more stress tolerant, or flood, or heat/cold stress tolerant.

This project had a significant impact in this study area because adaptation strategies such as adopting low delta crops and improved groundwater management helps to increase productivity, enhance farm income on sustainable basis, improve water and nutrients use efficiency, resilient to climatic stresses, and improves livelihood of farming community.

Key findings of the PRAs in Sindh province

The Information collected through PRA in Sindh revealed that:

- Both groundwater and canal water are used but canal water is the major source of irrigation.
- The area of fallow land is higher at the tail reaches of the canals due to a shortage of water.
- Bore depths were also greater at the tail reaches.
- Flood irrigation is the most common method of land irrigation.
- Decreases in yield were reported at middle and tail sites due to shortages of water. However, fertilizer, pesticides and machinery were linked to an increase in yield.
- Overall law and order was found to be good at all sites and communities have good relation within and outside.

Key findings of the PRAs in the Balochistan province

Five sites located in Pishin and Quetta districts were selected for consideration for inclusion in the project. These villages are located in the uplands at an altitude of more than 5000 feet from the sea level. From a hydrological point of view, these sites are located in the Kuchlak and Quetta sub basins of Pishin Lora Basin. The population number of these villages varies from some 2,000 to 22,000. The occupation and main livelihood source of the people of the study sites is mainly agriculture. Approximately 70 % of people derive their livelihood from agriculture, followed by business, mining, government services and laborers. There is no industry near the study sites, however, a few industrial units exist in Quetta town which is some 50-70 km away from different sites. The summary of their characteristics against the case study criteria are shown in Figure 10.3 as an example of the process. The Malikyar and Zargoon sites eventually selected as case study sites.

BALOCHISTAN	Unsuitable	Not very suitable	Mixture of suitable & unsuitable	Suitable	Very suitable
For each criterion, please indicate each site's suitability using the following legend:	(0)	(1)	(2)	(3)	(4)
Case Study Site	**Zarghoon**	**Khanozai**	**Aghbarg**	**Maghotian**	**Malikyar**
Groundwater situation					
ESSENTIAL: Availability of groundwater data (e.g. what is known, what is available?)	Don't know	Don't know	Don't know	Don't know	Don't know
KEY: The situation regarding groundwater (e.g. how much stress or exploitation? Are the resources vulnerable or degraded? Is there salinity or waterlogging?	Not clear	Not clear	Not clear	Not clear	Not clear
DESIRED: Features of this site that will make it useful for exploring multiple key issues associated with groundwater management	4	2	3	2	4
What sort of tools or interventions are likely to be accepted/ successful? Could these be easily replicated elsewhere?	4	3	4	3	4
The hydrological system (e.g., is it a closed system?)	Don't know	Don't know	Don't know	Don't know	Don't know
Sources of water for irrigation and their use	Not clear	Not clear	Not clear	Not clear	Not clear
Socioeconomic situation					
KEY: The social, cultural, and economic situation – e.g. Are there farming families, communities and partners who can facilitate change? Is there a well-organised community willing to participate with us?	4	2	3	2	3
Prevalence of poverty where potential for livelihood impacts are measurable and achievable, and where capacity of stakeholders is low with high prospects for enhancing their capacity	3	2	3	2	3
Potential for high value crops of high economic return/ viability of economic options, and proximity to input (finance) and output market	4	4	4	4	4
Availability of data related to social and economic aspects, or good prospects to acquire/ create such data	4	3	3	3	3
The extent lessons from this village could be applicable in other places	4	3	4	3	4
Features of this site that will make it useful for exploring multiple groundwater-related issues for improving livelihoods	3	2	3	2	3
Logistics					
ESSENTIAL: Accessibility, safety and security	3	3	4	3	3
DESIRED: Features that make this site feasible or not as a place where tools can be tested	4	2	3	2	3
Potential to connect with/ build on the irrigation efficiency improvement Farmer Field Schools established by the ACIAR project LWR/2014/074	4	3	3	4	4
Features that make this site feasible or not to finalise case study activities within the life of the project	4	3	3	3	3

Figure 10.3: Selection criteria summary for Balochistan province

Summary and conclusions from the PRAs

Overall, the PRAs showed that there were individuals and communities willing to learn more about their groundwater, and how to manage it.

In each province, separate PRAs were undertaken with women, leading to a gender co-inquiry in each selected case study area. This is detailed in the full report in Khair et al., (2021a) (see section 8.2). This relatively small exercise draws attention to the almost silent voice of rural women in relation to agricultural water management in Pakistan. It also highlights the complexities and difficulties of understanding the overall situation, especially given the diverse range of women's activities and positions in society. Extensive research is needed to understand women's economic and social activities as they vary greatly in different contexts. To help women and their families we need to understand better how they operate within agriculture enterprises, where they have influences, and their modes of accessing the financial resources and how they undertake business dealings. We also need to know where, when, how and why women are included or excluded from the businesses due to local traditional, social, cultural and religious reasons.

The co-inquiry found there is particular desire to develop the rural women entrepreneur's capacity, thereby stimulating job creation that will be contribute to overall economic growth and reduce their dependence on groundwater.

Summary and conclusions from Gender Co-inquiry

This project showed that women in all the case study areas are concerned about water availability and quality related challenges, especially but not limited to drinking water. Women currently have limited involvement in irrigation water management generally, as well as in relation to groundwater specifically. Some women in Sindh and Punjab indicated that they would welcome future opportunities for their involvement.

The results of the gender co-inquiry informed the development of the Aik Saath's gender inclusiveness strategy, and further work on gender outside of, but related to, this project. Specifically, the results of the gender co-inquiry guided the development of the SRA scoping activities during through a dedicated workshop held in July 2019 as part of the ACIAR WAC/2019/012.

Key themes developed at that workshop are:

- Recognition that engaging women from communities in project interventions challenges cultural norms, so it is preferable that the engagement of women has support from their male counterparts.
- Because of cultural norms that can prevent women meeting with men, female researchers and/or students will need to be engaged in project activities that involve women in communities.
- Women can be/ are effective co-learners who can support the project's investigations, and can contribute to the delivery of intended project outcomes.
- Women who co-investigate adaptation options and strategies are well-positioned to influence other family and community members drawing on their experiences, and are thus empowered as local knowledge brokers.
- There is great entrepreneurial experience and potential among women in farming communities.

10.2.2 Key findings from socioeconomic analysis

The key results and conclusions of the socioeconomic aspects of all three provinces, based on the analysis of the data from the socioeconomic survey are described in detail in the associated reports (see Ashfaq et al., 2021; Khair et al., 2021b; Mangan et al., 2021; listed in section 8.2). A summary of the results is presented in the following section.

Note that in the following efficiency terms were used as technical (output level/input use), allocative (how best to minimize the costs of inputs for the set level of output), economic (the value of output/costs of inputs used).

When defining WUE, different people can use different interpretation and its application as a measure. For example, agronomists refer it somewhat different to what economists do. In our case it refers the technical efficiency of water.

Lower Bari Doab, Punjab

The socioeconomic study in the Punjab province was carried out in the Lower Bari Doab Canal irrigation system. Here, water-smart practices for groundwater management such as raised bed planting, laser land levelling, conjunctive use of available water, drainage management, zero tillage, crop rotation and the use of improved crop varieties have been developed, but uptake of these practices is low. Data was collected from two of the four distributaries in the system, the 1R (Okara) distributary and the 11L (Sahiwal) distributary.

Interviews were conducted with 469 randomly selected farmers from the head, middle and tail reaches of two distributaries, the 1R (Okara) distributary and the 11L (Sahiwal) distributary. These interviews were focused on gaining an understanding of the socioeconomic and demographic characteristics of farming households as well as current irrigation and cropping practices of farmers and impediments to adopting water-smart practices. Logistic regression models were used to analyse the factors that influenced the probability of adoption of water-smart practices for groundwater management. An economic analysis was also undertaken to determine water productivity and resource use efficiency, including technical, economic and water-use efficiency, for the major crops that are grown in the province. The key findings are summarised below:

- The average age of farmers was 46 years with very small difference between the two distributaries which shows that experienced persons are heading the households on both sites. However, very few farmers had received any training from agricultural extension officers or from NGOs.
- The majority of farmers (> 80%) reported that they didn't have access to credit to acquire their crop inputs (seed, fertilizer, pesticide and diesel fuel). Those that did access credit most commonly did this using non-institutional sources such as inputs dealers, *arthis*[3], and friends/relatives due to difficulties in accessing institutional credit.
- The findings of this study revealed that farmers from the tail end of both distributaries had higher financial/economic benefits compared to middle and head farmers. This study also found that head farmers of both distributaries have improved resource use efficiency, including technical, economic and water-use efficiency.
- Most of the farmers who had adopted water-smart practices for groundwater management attributed their adoption to the limited supply of canal water, climate change, proclivity to drought, massive groundwater extraction, rapidly declining groundwater table and increasing soil salinity over the time. Results revealed that uniform germination, higher yield and financial returns, concentration of inputs and increase in resource use efficiency are the main advantages of water-smart practices.
- The results of the logistic regression model revealed that farm characteristics, economic and social capital, technical training and sources of information affect the adoption of water-smart practices for groundwater management by the farmers of wheat-based cropping systems. The pseudo-R^2 and Wald-chi-square test values indicated that the selected model for this study is fit and adequate. Further, literature supports the notion that the variables included in the model had significant impact on the probability of adopting water-smart practices. The results showed that the head farmers were using inputs more efficiently with higher water and crop yield from per m^3 of irrigation water, than middle and tail farmers.
- Major problems reported in crops production were shortage of water, unavailability of inputs on time, high prices of inputs and lack of awareness regarding the quality of inputs. Over 70% of farmers reported that they experience water shortages in the Rabi (winter) season. This may be related to the fact that conventional agricultural practices that require intensive use of external inputs (e.g. irrigating the unlevelled fields and flood irrigation methods) were common in both sites.
- The average water use efficiency (WUE) was 63% in 1R whereas it was 55% in 11L, implying that there is room to improve WUE at both sites. Similarly, water

[3] Is a marketing functionary also called Commission agent who charge a certain rate of commission for selling the produce through auction process

productivity analysis showed that in both distributaries, under the current irrigation management system farmers are using 50-60% more water than the actual crop water requirement, suggesting that farmers need to be educated and trained and irrigation practices be changed to use irrigation water efficiently and avoid waste full use of water. Among both distributaries, head farmers of both sites were more water efficient than middle and tail farmers.

- This study has shown that farmers can save inputs (such as water), increase their production and earn more profit, by adopting water-smart practices. As such, it is recommended that the government and other relevant institutions devise and implement policies that adequately address the importance of and enhance the use of water-smart practices in Punjab and beyond. The study found that poor access to farm services (e.g. availability of resources, access to credit, market and agricultural extension services) limits the adoption of water-smart practices. This indicates that strategies to provide financial support and training to farmers would be beneficial in increasing adoption rates. This would enhance resource use efficiency, net farm income and livelihood of rural masses.

Shaheed Benazirabad and Naushero Feroze Districts, Sindh

Sindh Province, with 5000 years of civilization, is the second largest province of Pakistan with a population of 47 million people. As a province that's located in the lower end of the Indus Basin, Sindh is facing issues of grave surface and groundwater shortage, and soil and groundwater which is exacerbated by the mismanagement of groundwater. Some research has been undertaken in relation to groundwater modelling in Sindh Province, but there is a lack of information about how the availability and use of surface and groundwater in differs between the head, middle and tail ends of irrigation systems. In addition, the social and economic aspects of groundwater management are not well understood. The study aimed to aimed to (i) examine socioeconomic characteristics of farming communities from two irrigation systems in Sindh (ii) explore groundwater availability across head, middle and tail areas of the systems (iii) examine the cropping patterns and irrigation methods practiced by farmers in the study areas (iv) explain problems faced by the farmers with reference to availability and management of groundwater (v) calculate farm level technical, economic and water use efficiencies of the main crops grown in the area (wheat, rice, cotton and sugarcane). Six villages were selected in total, one from the head, middle and tail areas of two irrigation systems: Cheeho Minor, in the Naushero Feroze district, and Malwah Distributary, in the Shaheed Benazirabad (SBA) district. Farmers were categorised based on the size of their farms as: (i) small farmers (own 1 to 12.5 acres of land) (ii) medium farmers (own 12.5 to 35 acres of land) and (iii) large farmers (own more than 35 acres of land). Stratified random sampling was used to select respondents. The results are summarised below:

- In the SBA district, the average number of milking animals owned by farmers at the tail end of the system area was higher (2.68) compared to farmers from the head (1.39) and the middle areas (0.23). The per day average milk production was also higher in tail areas (23.75 litres) compared to mid (16.05 litres) and head areas (18.66). Farmers at the tail area owned higher number of milking animals and were getting higher average per day milk production. However, they were earning less average monthly income from selling milk (Rs. 16680 at head and Rs. 14306 at tail in Naushero Feroze and Rs.17119 at head and Rs. 14086 at tail in SBA). This is because tail area farmers mostly sell milk to shopkeepers in local villages to avoid transport costs. The distance between tail farms and the nearest markets prohibit efficient transportation. Head and middle farmers are closest to markets and hence receive higher prices. In contrast, in both districts, the average monthly income obtained from selling livestock) was higher at tail areas of the system as compared to head areas (average monthly income from livestock: Rs. 12816 at head, Rs.27615at middle and Rs.21814 at tail).

- Cotton, wheat and sugarcane are the major crops of both research sites. Rice is also grown in some parts of Naushero Feroze as well as small scale vegetable and fruit crops.
- In both districts, the majority of farmers depend on informal credit (mostly from traders, middlemen, relatives and friends).
- Farmers at both sites ranked storage of water as the most significant issue and difficulty in purchasing water and difficulty in purchasing inputs for cropping was ranked second. A high shortage of irrigation water was reported in both research areas, particularly during the Kharif (summer/monsoon) season.
- Per acre irrigation cost at tail areas are higher compared to head areas at both research sites. This can be attributed to the fact that tail farmers mostly purchase diesel and lubricants on credit which is more expensive when compared to head farmers who purchase diesel and lubricants for diesel engines for cash.
- Data revealed that higher gross margin per cubic meter of irrigation water was earned by the wheat growers at head and middle areas as compared to tail areas. Similarly, margins were higher for cotton and rice crops in both districts.
- Irrigation practices also play a significant role in groundwater and surface water management. Results of this study show that a significant majority of farmers use flood irrigation, which is inefficient in terms of water use, at both research sites. In both systems, head areas, flood irrigation was used to irrigate an average of 8 to 15 acres of land, furrow irrigation was used on significantly less land area (0.9 to 4.8 average acres). Similarly, at the middle of both systems, 9 to 11 average acres of land were irrigated by flood irrigation, while in same area fewer acres of land (0 to 1.89 average acres) were irrigated by furrow irrigation. This shows that flood irrigation is common practice in research areas and the literature suggests that flood irrigation is an important contributing factor in the mismanagement of available water for irrigation.
- Time allocated for irrigation at tail areas is greater than head and middle areas. Water is allocated when water starts to flow from the watercourse, in tail areas, the distance to the watercourse is greater meaning that it takes longer for water to reach the farm. In addition, in head areas, water flow is higher than in tail areas. Therefore, despite the fact that more time is allocated to tail flows, less water is available. At the head, middle and tail reaches in the Naushero Feroze district, the allocated timing of canal water was 9.32, 12.37 and 20.47 minutes per acre, respectively. Likewise, in the SBA district, farmers indicated that in the head, middle and tail reaches the allocated time was 7.97, 11.13 and 15.29 minutes to fill per acre, respectively.
- Diesel engines were the main source of energy for tube-wells at both research sites. More than 88% of tube-wells in Naushero Ferozeand 85% of tube-wells in SBA, are powered by diesel engines.
- The availability of canal water is not equal at head and tail areas of the irrigation systems. Farmers from the tail areas of both systems are highly dependent on groundwater and farmers from the head areas of both systems use canal water for irrigation. In Naushero Feroze 73% and in SBA 64%of respondents from head areas use canal water for irrigation. Conversely, the majority of tail reach farmers depend on tube-well water for irrigation, 83% in SBA and 59 % in Naushero Feroze.

Kuchlak and Pishin Sub-Basins, Balochistan

This work aimed to gain an understanding of the current agricultural and irrigation practices and sources of livelihood of farming families in the Balochistan Province and to provide recommendations for improved water use and agronomic practice. Interviews were conducted with 104 farmers from the Kuchlak and Pishin sub-basins of Pishin Lora Basin in Balochistan to gain an understanding of the socioeconomic and demographic characteristics of farming households and the current irrigation and cropping practices of farmers. Analysis was also undertaken to determine: (1) the relative cost of different production inputs for different crops; (21) the efficiency of water, seed and fertilizer use; (3) the technical, allocative and economic efficiency of different crops; and (4) the degree to which over-watering of crops occurs. The summary of results is presented below:

- In both the Kuchlak and Pishin sub-basins, the average age of the farmers was 38 and they had an average of 17 years farming experience. This indicates that experienced persons are heading the households. However, very few farmers had received any training from agricultural extension officers or from NGOs. The average family size was quite large, around 23 persons, and this was due to joint family system (rather than nuclear or extended family) prevailing in the area in which people prefer to live together for many socio-cultural reasons
- Income is generated from both cropping and livestock (e.g. sheep, goats, cattle and buffalo). The income generated from livestock can be particularly important in the off-season. Livestock are mainly used for milk and meat production. Animals are sold in the markets to earn income. Milk is also sold in the markets, but some is consumed at home. Over 90% of what is produced from crops is sold at the markets indicating commercial farming.
- The majority of farmers (> 80%) acquire their crop inputs (seed, fertilizer, pesticide and diesel fuel) through credit from non-institutional sources such as inputs dealers, *arthis*[4], and friends/relatives due to difficulties in accessing institutional credit. In addition to the need for credit to purchase crop inputs, unavailability of inputs on time, high prices of inputs and lack of awareness regarding the quality of inputs lead to difficulty in attaining crop inputs.
- For cropping, traditional irrigation practices are used and much of the area is irrigated using the traditional flood irrigation method. However, water shortages do occur and 53% of farmers reported that water shortages were most common in the Kharif (summer/monsoon) season while 16 % reported it in Rabi (winter) season. The majority of farmers (96%) use their own tube-wells, while the remaining (4%) were using Karez/spring as source of irrigation. The tube-wells are reliant on the national grid for electricity supply which is rationed and supplied for six hours a day, so during periods of water shortage, some farmers rent electric generators.
- The gross margin analysis showed that the largest cost incurred cost was associated with irrigation which ranged from 45% to 70% of variable costs for different crops and fruits. The cost associated with renting electric generators during times of water shortage (such as the drought in 2018) further increases the cost of irrigation.
- The average water use efficiency was 76% in the Pishin sub-basin whereas it was 70 % in the Kuchlak sub-basin. This indicates that water use efficiency can be improved in both areas. Among the crops grown, wheat crop production was more water use efficient while tomato, apple and apricot were less efficient with significant scope for improvement.
- In line with the water use efficiency results, the analysis of technical, allocative and economic efficiency showed that there was room for improvement for all of the crops (apple, apricot, tomato and wheat). In addition to inefficiency in relation water, there are some inefficiencies in fertilizer and seed use. For example, the average fertilizer use efficiency was 70 % in the Kuchlak sub-basin whereas it was 81 % in the Pishin sub-basin.

[4] Is a marketing functionary also called Commission agent who charge a certain rate of commission for selling the produce through auction process

- The water productivity analysis showed that under the current irrigation system (mainly flooding) farmers are using 50% more water than the actual crop water requirement. The tomato growers in the Kuchlak sub-basin achieved the highest productivity (2.59 kg/m³ of water). However, the comparison of results of this study with those of other studies undertaken nationally and internationally shows that water productivity in Balochistan is below the national and international levels.
- The results from this study indicate that there is a need for farmers to be educated and trained and for irrigation practices to be changed so that irrigation water is used more water efficiently and wasteful use of water is reduced. The installation of high-efficiency irrigation systems would increase crop yields and help minimize groundwater stress in the basin.

Adequate and reliable data is pre-requisite for establishing a reliable groundwater model. Water levels and EC are the two basic parameters needed. WL are needed for model development and calibration. EC is needed to understand impacts on water quality in response to pumping and in future for solute transport modelling. EC of tubewells can also help individual farmers with making decisions on conjunctive use. Beyond this data on groundwater extractions is needed. Climate data to estimate rainfall recharge is important, though adequate records of historical rainfall data is not readily available in Sindh and Balochistan. River/Canal stage and flows which are monitored by irrigation departments are important for simulating river/canal and groundwater connectivity. Borelogs with sufficient depth (not just shallow borelogs) are crucial for understanding flow and solute dynamics in the Indus Basin. Cropping patterns and irrigation applications are also required. Cropping patterns can be obtained from remote sensing. A crucial bit of data is the need to monitor actual groundwater use in the area. Presently, we used tube well density to estimate the initial pumping and estimated pumping rates. • Thickness of freshwater lens based on adequate monitoring and depth profile of groundwater salinity are important for improving management of freshwater lenses. River and canal bed conductance is estimated as a calibration parameter, but this data is rarely available in any country and if it is it is for specific research studies. Even where monitoring may be adequate as in the canal commands in Punjab, there is little known about groundwater levels in the non-irrigated area. Strategic monitoring and wider use of loggers will improve data required for modelling.

10.2.3 Key findings from the Representative Agricultural Pathways (RAPS) studies

Full details are provided in the associated report (Nasir et al., 2021; see section 8.2).

Lower Bari Doab, Punjab

In Punjab, RAPS were developed for the irrigated, mixed cropping system of central Punjab. The interventions that were considered by workshop participants were:

- Substitution of high delta crop with low delta crop
- High efficiency irrigation practices (e.g. drip or trickle irrigation, sprinklers, bubblers)
- Soil conservation practices for better water holding capacity (organic manuring, mulching, conservation tillage and cover crops)
- Improved cultivars (drought & heat tolerant varieties, short duration varieties)
- Improved Agricultural Practices (fertigation, balanced fertilizer, drainage)
- Plant Population (seed rate, number of plants)
- Construction of water storage

- Agricultural insurance/finance
- Water Harvesting

Of these, the two interventions that were most strongly endorsed by all stakeholders were the substitution of high delta crop with low delta crops and the adoption of high efficiency irrigation systems (HIES). These two interventions were modelled using TOA-MD to estimate the likely adoption rates and economic impacts (net farm returns, per capita income and poverty rates) of the proposed management interventions.

Adoption rates and economic benefits associated with the use of low delta crops

Two scenarios, replacement of maize with moong bean crops and replacement of wheat with sunflower crops were assessed and these were compared to a no-change, business as usual scenario. Sunflowers and moong beans are highly recommended crops based on the climatic and biophysical conditions in the study area. The suggested management interventions were that 5-10% of the area currently under wheat crop be replaced by sunflowers, and 5-10% of the area under maize be replaced by moong bean. The proposed area of 5-10% was based on the fact that generally farm sizes are small.

The TOA-MD model results showed that under both scenarios, poverty would decrease, and farm livelihoods would increase. The models indicated that there would be a substantial increase in net return (NR) and per capita income (PCI) and a 24% decrease in poverty (Table 10.12). The potential adoption rate for sunflower and moong bean replacing 5-10% of the area under maize and wheat would be 49% and 59% respectively.

Table 10.12: Economic benefits of adopting of low delta crops. NR=net return; PCI=per capita income.

Scenarios	Crop Substitution	% change in NR	% change in PCI	% change in poverty	% potential adoption rate
Scenario 1	Maize replaced by moong bean	32.51	28.75	-23.86	49
Scenario 2	Wheat replaced by sunflower	33.89	30.05	-24.50	59

Note: Poverty line was calculated based on (Rupees/ person/ time) that was 21900 rupees for one season.

The moong bean has great potential as a cash crop in in Pakistan, but availability of water, sowing high yielding cultivars, improved management practices and improvement in the value chain are crucial factors in moong bean cultivation. Currently, the cultivation of pulses, especially moong beans, is low and this is mainly due to marketing issues and inconsistent policies.

Adoption rates and economic benefits associated with the use of High Efficiency Irrigation Systems (HEIS)

The TOA-MD model showed that the adoption of HIES would result in poverty decreasing between 18-31% depending on the type of crop that is grown. The highest decrease in poverty is associated with wheat, maize and cotton crops (Table 10.13). Results show an increase in net return and per capita income for all the major crops. Likely adoption rates are high ranging between 56-87%.

These results clearly show that water savings and a high net return are possible by shifting from conventional irrigation to improved irrigation technologies (e.g. sprinkler and drip irrigation). On the basis of these results, it is recommended that apart from the proposed water-saving strategies, other alternative management techniques, directed to off-farm (i.e., improved infrastructure to reduce water losses due to poor conveyance efficiency) and on-farm (e.g., deficit irrigation or soil mulching) management, should be evaluated in future studies as these play an important role in sustainable use of farm resource and farm livelihoods.

Table 10.13: Socioeconomic impacts of adaptations benefits of high efficiency irrigation systems for different crops *NR=net return; PCI=per capita income.*

Crop type	% change in NR	% change in PCI	% change in poverty	% potential adoption rate
Cotton	28.31	23.00	-26.32	72.00
Maize	40.80	36.59	-27.67	76.03
Wheat	19.82	18.05	-30.64	63.13
Rice	37.95	31.41	-17.78	87.04
Sugarcane	37.94	35.36	-21.62	55.77
Overall	34.89	30.56	-23.10	73.80

Conclusions

Based on these results, the impact of adopting HIES and some substitution of high delta crops with low delta crops would have a positive impact on net farm returns and per capita income and a reduction in farm poverty within the study area. The results further show that water savings and high net return are possible by shifting from conventional irrigation to improved irrigation technologies (sprinkler and drip irrigation). Overall, for 75% percent of farmers it would be economically feasible to adopt these management interventions. Wheat, maize, rice, sugarcane and cotton are the most important cash crops, but this needs to be balanced against the social cost of water-loving crops. Oilseed and pulses are potential alternatives in terms of resource conservation and crop diversification.

Farmers tend to adopt technologies and conservation techniques when it will result in increased profitability. However, the decision to adopt new technologies and techniques is also influenced by a farmer’s socioeconomic status, cultural background, social norms and access to natural resources. Policy can also influence adoption of new technology and practices. Policies must be formulated in favour of institutional development that is, policies must strengthen the farmers and institutions working with farmers and ensure long term sustainable allocation of resources. As current policies target the trade orientation (like export of rice and cotton crops), domestic support (the local industry for farm inputs), price control policies (wheat and sugarcane). These are not linked with farm and farmers’ future in the long run. Policies should promote HEIS rather than, for example, export tax rebates.

RAPS Sindh

The first RAPs session was organized in Karachi in November 2020, to formulate the RAPs for Sindh. The interventions that were considered by workshop participants were:

- High efficiency irrigation system (ridge and bed sowing, drip and sprinkler)
- Substitution of crops (low delta crops like Quinoa)
- Developing the water markets
- Enterprise diversification (livestock farming, olericulture, fisheries, argo forestry)
- Crop diversification (vegetables like onion, okra, chilies, black pepper)
- Intercropping (sugarcane and wheat; okra and onion)
- Cultivation of high value crops

These interventions were considered because groundwater extraction is linked with cropping intensity and cropping patterns in the area. The selection of crops is linked with farm income and availability of resources. Cotton, rice and sugarcane are profitable crops and wheat is also an important crop. Cash crops are important in terms of farm profit and agro-based industrial sectors in the economy. Wheat and sugarcane contribute to food security and rice and cotton crops contribute to foreign exchange earnings. The water utilization is high in sugarcane and rice as compared to cotton and wheat as described in Table 10.14.

Table 10.14: Gross margin per unit of water used for cash crops in Sindh.

Crop	Gross Margin (PKR/ha)	Volume of irrigation (m3/ha)
Wheat	109246.6	6056.8
Rice	140390.6	8224.7
Cotton	151082.8	6410.1
Sugarcane	250048.6	13891.5

Source: Calculated from survey data and ACIAR socioeconomic report

Adoption rates and economic benefits

Considering the cost benefit analysis, the adoption of high efficiency irrigation systems would increase the farm returns and sustain the farm livelihoods in the long run (Table 10.15). The other adaptation option such as crop substitution and cultivation of high value crops needs time for development of market infrastructure and industrial development. Rice, cotton and wheat are also important in terms of food security and foreign exchange earnings. The HEIS is not a superior system of irrigation for crops like sugarcane that are water intensive, especially when water is unfit for irrigation. The high installation cost, breakage and clogging would result in net economic loss.

Table 10.15: Socio Economic Impacts of Adaptations Benefits of High Efficiency Irrigation System in Sindh

Crops	% Change in NR	% Change in PCI	% Change in Poverty	Potential adoption rate
Wheat	33.64	42.27	-8.6	43
Rice	23.53	31.41	-5.1	31
Cotton	21.77	29.83	-3.23	36
Sugarcane	38.06	46.65	-2.04	19
Aggregate	29.25	37.54	-4.74	32

Calculations are based on RAPs and TOA-MD calculations

Conclusions

The results from this study show that, over time, the adoption of HIES such as ridge and bed sowing and using drip and sprinkler irrigation in the study area would substantially increase farm yields, improve net farm returns and per capita income However, this would not be of benefit for sugarcane crops. The adoption of improved irrigation techniques such as sprinkler and drip irrigation would be economically viable, but farmers face technical, financial and administrative issues in making this shift. Crop substitution (e.g. low delta crops like Quinoa) and cultivation of high value crops may be of benefit, but require market development and crop infrastructure.

RAPS Balochistan

An initial RAPs session to formulate the RAPs for Balochistan was held in Quetta. Biophysical, socioeconomic, technological, institutional and policy variables trends were discussed in specific areas. Researchers, policymakers, farmers and officials from different disciplines were invited to assess the trends for important indicators which helped to formulate. Adaptation options already available in the literature were accessed and consultative sessions were designed to formulate adaptations for future agricultural production systems in the study area. The suggested management interventions for efficient allocation of water in Balochistan are presented in Table 10.16.

Table 10.16: The ground water management interventions in Balochistan

Location	Proposed farm management interventions in Balochistan
Kuchlak sub basin	Introduction of low delta crops such as Pistachio, pomegranate and grapes and High efficiency irrigation system (HEIS). The details are as follows: o Tomato planted on drip Irrigation for efficient water use in Zarghoon o Apple and Apricot orchard planted on drip irrigation to improve water use efficiency in Zarghoon o Distributed 20 tensiometers among farmers to enable them to measure soil moisture level and plan need based irrigation schedule and avoid over irrigation
Pishin sub basin	Plantation of low delta crop such as pistachio, grapes and pomegranate on drip irrigation to introduce low delta crops and high efficiency irrigation systems (HEIS) to improve water use efficiency and promote sustainable agriculture: o Planted young vineyard with improved grapes variety on (HEIS) in Malikyar o A mature apple orchard (14 years old trees) converted from flood irrigation method to drip irrigation to improve water use efficiency in Malikyar o Planted new vineyards with improved grapes varieties on (HEIS) in Huramzai o Planted new pomegranate orchard with improved grapes varieties on (HEIS) in Huramzai o Pistachio planted as intercrop in mature grapes orchard to replace them in long run in Huramzai, that will increase farmers' incomes and improve water use efficiency o Distributed 20 tensiometers among farmers to measure the moisture level in soil and plan need based irrigation schedule and avoid over irrigation.

Adoption rates and economic benefits

Agricultural production in Balochistan is largely linked with water availability and all farming activities largely depend on groundwater. Groundwater is a limited resource and over time; without any legal framework and careful management; its availability has declined and pumping cost have increased substantially. Rational use of water is required in such a drought prone area. The stakeholders suggested that provision of high efficiency irrigation system (HEIS) for orchards could increase the farm income in the long run. The HEIS could contribute largely to sustainable use of groundwater in the mid-century scenario. The economic analysis done for technological interventions showed that the installation of such infrastructure would ensure efficient allocation of water use and increase the net farm returns substantially. Farm poverty would reduce by 8 percent for apple farmers and 12 percent in grapes growers in the study area for mid century scenario. Socio economic impacts of adaptations benefits of high efficiency irrigation system in Balochistan is listed in Table 10.17.

Table 10.17: Socio-economic impacts from the adoption of high efficiency irrigation systems in Balochistan

Crops	% Change in Net Returns	% Change in Per capita income	Change in Poverty*	% Potential adoption rate
Apple	29.96	27.45	-8	42
Grapes	34.38	37.30	-12	48

Note: Calculations are based on RAPs and TOA-MD calculations

Conclusions

Pakistan is facing serious threats with respect to food security due to water shortages associated with climate change. Balochistan has the potential to be the leading province in terms of fruit production, but the lack of good cultivars, proper marketing and poor infrastructure means that its agricultural production is not increasing substantially. Karez and tubewells are important for the sustainable socioeconomic development of farming communities, however, the results from this study indicate that farmers must adopt sustainable practices regarding ground water extraction and recharge. The following recommendations are formulated based on the results of this study:

- High efficiency irrigation systems should be provided at affordable prices to farmers to increase water use efficiency and decrease the rate of groundwater pumping.
- Greater awareness and engagement of farming communities is required in order to achieve sustainable agricultural production systems in the long run.
- Poverty is a serious concern in Pakistan and there is a high level of disparity among provinces. Poverty is especially high in Balochistan. Adoption of sustainable agricultural production systems could provide sustainable farm livelihoods and decrease the poverty in the long run. Public policies should link the markets with more geographically isolated places in Balochistan to enable efficient production.
- The suggested management interventions at the farm level include support of low delta crops such as pistachio, grapes and pomegranate instead of apples; improvement in the management of existing orchards; checking bunds for water storage; the provision of dwarf varieties of apples and; tunnel farming.
- The provision of subsidies regarding tubewell tariff differentials must link with certain regulations to protect the groundwater aquifers.

Implications for poverty reduction

Overall, these RAPS results show the benefit of combining ways to better measure and model groundwater, and to raise awareness of groundwater issues, with practical options for mitigating groundwater decline and/ or improving livelihoods. Over the course of the project, multi-disciplinary teams were able to work with selected farmers- these individuals emerged over time through interactions in the PRAs and the Stakeholder Forums, and especially through their interest in the results from the groundwater monitoring activities. By the time the RAPs were undertaken, there was some trust in the project and interest in trying to change, making ongoing adoption of the suggested changes more likely.

Results in Punjab showed that there would be a significant reduction in the poverty status of farmers as a result of adopting low delta crops and HEIS. The replacement of maize (a high delta crop) with moong bean (a low delta crop) would result in a poverty reduction of 23.9% and similarly, replacement of wheat with sunflower would result in a 24.5% reduction in poverty based on calculations from the TOA-MD model. Furthermore, the percentage decline in poverty due to adoption of improved irrigation management practices was estimated to be 23.1% for all crops. The key to seeing this change is farmer adoption of these low delta crops and improved water and land management practices which is possible with increased engagement of groundwater users.

The poverty rate in Balochistan is higher as compared to other provinces. The 2019 household integrated economic survey (HEIS) data estimates show 56.8 percent poverty in Balochistan as compared to 36 percent of national average. In this area, rural poverty is lower than urban poverty which indicates that improvements in the agricultural economy have the potential to eradicate poverty. In this area 70 percent of the population is vulnerable to poverty thus strengthening and supporting the agricultural economy will assist in reducing poverty (Jamal, 2021). The adoption of water efficient practices also has the potential to increase production substantially. Awareness regarding water and soil conservation in farming communities must be increased in order to sustain farming livelihoods.

Trials and demonstrations

The Stakeholder Forum/ RAPs process led to a number of trials across the three provinces were initiated with farmers. These are shown in Table 10.18.

10.3 Knowledge products/ platforms

The project has created increased awareness within the Irrigation Departments and within farming communities of the need to understanding the condition of groundwater resources. We have assisted in this through a number of knowledge products and tools to help farming communities and other key stakeholders start the conversation on sustainability of groundwater systems and begin to take steps that will help farming enterprises to use less water and to invest in more profitable alternative crops via the RAPs process.

10.3.1 Monitoring data and Apna Pani App

Monitoring Data and Loggers: Without access to reliable and appropriate information and data, resource managers are unable to accurately ascertain whether the condition of the resource is improving or deteriorating. For the management of groundwater resources, an accurate assessment of the water balance is needed, and monitoring data is required to calculate these water balances. Improving the frequency, accuracy, quality and reliability of the input data reduces the number of assumptions and as a consequence, decrease the uncertainty in modelling results and this allows for improved decision making. Data loggers provide data to accurately calculate water balances and to monitor water level declines and salinity changes over time. Clear demonstrations of declining water levels in Sahiwal provided a catalyst to trial low water use crops that are also more profitable for farmers. The use of loggers has also reduced the cost of monitoring as there is less travelling and manpower involved. Our modest investment in loggers in our case study sites has created greater awareness that the monitoring strategy will need to change from monitoring large number of bores to more strategic monitoring using loggers to understand water level declines and changes in water quality.

Loggers have also been useful during COVID-19 as it has allowed continuous logging of data for our case study sites. The Stakeholder forums are playing a crucial role in helping to understand changes in groundwater levels in the respective case study areas over time.

Table 10.18: Trials and demonstrations arising from collaborative co-design as part of this project

Province	Location	Trial
Punjab	11-L	• Low water use crops such as Moong bean, sesame, sunflower and garlic replacing maize to reduce water use and other inputs, with good returns • Ridger for community use to improve Irrigation efficiency
Sindh	Cheeho	• Wheat on ridges to increase production with less water than traditional method of cultivation on flood irrigation. • Intercropping of Okra with onion on ridges, to increase production from same water use and reduce cost of production and get more income. • Quinoa: a low delta crop cultivated on small scale for introduction and testing of adaptability in new area use
	Malwah	• Wheat on ridges intercropped with sugarcane to maximise production from water and increase profitability • Intercropping of sugarcane with okra and onion to get maximum utility of irrigation • Sugarcane nursery raising to ensure timely gap filling of sugarcane crop and get maximum production from given water • Introduced low delta Quinoa crop • Introduced 5 colour fruit tree plantation for environment improvement and nutrition production
Balochistan	Kuchlak sub-basin	• Introduction of low delta crops such as Pistachio, pomegranate and grapes and High Efficiency Irrigation system (HEIS). • Tomato planted on drip Irrigation for efficient water use in Zarghoon • Apple and Apricot orchard planted on drip irrigation to improve water use efficiency in Zarghoon • Distributed 20 tensiometers among farmers to enable them to measure soil moisture level and plan need based irrigation schedule and avoid over irrigation
	Pishin sub-basin	• Plantation of low delta crop such as pistachio, grapes and pomegranate on drip irrigation to introduce low delta crops and high efficiency irrigation systems (HEIS) to improve water use efficiency and promote sustainable agriculture: • Planted young vineyard with improved grapes variety on (HEIS) in Malikyar • A mature apple orchard (14 years old trees) converted from flood irrigation method to drip irrigation to improve water use efficiency in Malikyar • Planted new vineyards with improved grapes varieties on (HEIS) in Huramzai • Planted new pomegranate orchard with improved grapes varieties on (HEIS) in Huramzai • Pistachio planted as intercrop in mature grapes orchard to replace them in long run in Huramzai, that will increase farmers' incomes and improve water use efficiency • Distributed 20 tensiometers among farmers to measure the moisture level in soil and plan need based irrigation schedule and avoid over irrigation

The Apna Pani App: The Decision-Support System (mobile and web based) created during the project was developed collaboratively, and iteratively. This resulted in the Apna Pani (My Water) and Apna Farm (My Farm) modules. Apna Pani enables mobile phones to be used to record and view spatially referenced readings of groundwater depth and quality. Apna Farm enables users to estimate water requirements of different crops. This allows farmers to choose a crop based on the availability and quality of water in their area. Apna Farm also enables farmers to view land characteristics such as soil type, current weather and past history of crop profitability in their district. Currently, the past history of crop profitability is available for the stakeholders from Punjab. A full report on the development of these applications along with user manuals is provided in Khan et al. (2021) (see section 8.2).

Estimating multiple crop water requirements:

The graphical user interface (GUI) makes use of Google API for Google maps, which enables users to interactively use, and host google maps on the World Wide Web. After geo-locating a farm, the user is able to select multiple crops, type in the area in acres under cultivation to estimate the crop water requirements for multiple crops. The crop water requirements based on the outputs from the Apna Pani and Apna Farm Apps were validated by using the International Water Management Institute (IWMI) recommended crop water requirements. The results showed a close association between the crop water requirement results from the mobile app and the IWMI data. The crop water requirements for two different crops, wheat and maize, at two different locations were calculated using the developed applications and compared with IWMI data and the error percentage varied from 1 to 18% (Tables 1 & 2 in Khan et al., 2021).

Estimated Crop Profitability:

Users from the Punjab province can access crop profitability data in order to make optimal decisions about which crops to sow. In the crop profitability module, the district-wise average data was used. The computed crop profitability was compared for Maize and Moong crops at a farmer's site in Chichawatni in Sahiwal, Punjab. The cost of production was calculated from sowing to harvesting by the farmer and compared with those calculated by the Apna Farm App. This comparison showed a good agreement between the crop profitability embedded in the Apna Farm and that of calculated at farmer's site.

The district-wise crop profitability for a Moong crop in Chichawatni (Sahiwal) net return available through the Apna Farm module was 9967 rupees per hectare. Whereas the return calculated at the LWR036 farmer site was 15956. PKR. (Figure 16 of Khan et al., 2021). The reasons for the difference are:

- In the case of profitability computed at farmers' field, the cost of labour is not included.
- The farmer, who was working with the ACIAR project, had adopted good practices (i.e. was a progressive farmer), whereas the profitability available through the app is the average for the district.
- Some farmers reported yield in the area are 4000 PKR per acre (i.e. 9880 PKR per Hectare).

A similar agreement was also found in validation of crop profitability of the maize crop (Figure 17 of Khan et al., 2021).

The information provided by the Apna Pani and Apna Farm App provide the potential for collaborative development to continue beyond the life of the project. Their use is being currently championed by younger members of farming families as well as researchers and extension workers. Together with a shared understanding of future pathways for agricultural development, the utility of these applications can be summarised as:

- Farming communities are better placed to consider ongoing adaptations in practice.
- Farming communities, together with extension agents and others with expertise, are now better equipped in on-farm water management and cropping decisions.
- Provincial irrigation departments are able to integrate their (and allied departments') relevant data with the water availability data. This is demonstrated through integration of soil and crop profitability data. This will enhance the interoperability of the relevant government agencies.
- Last but not the least, the applications also provide a platform for the researchers from the research institutes and universities to further explore socioeconomic and physical modelling research. This will enable the operationalisation of modern agri-practices in Pakistan.

The Mobile and Web applications (Apna Pani & Apna Farm) provide information, to farmers and extension works (including irrigation staff), important for optimal decision-making regarding land-use. Through this system the users are firstly, enabled to report and visualise the spatio-temporal variation in their groundwater status (currently EC and depth to water). The users can visualise their reported data both on mobile and web applications. Secondly, the users can access important agro-meteorological data of their locations which is important for crop husbandry. This data is used by the application to estimate crop water requirements by calculating evapotranspiration using FAO's Penman-Monteith equation. To estimate crop water, users have to input their location of farm, and intended crops. They can estimate crop water requirements for multiple crops at a time. Thirdly, the system enables the users to visualise soil quality data for their locations including soil organic matter, potassium, pH, Phosphorous, Soil type, EC. The users are also provided information regarding distance to actual sampling location. Fourthly, the users are provided with the profitability of all crops which can be and are grown in the relevant district. Lastly, after running one analysis the user can save the output in pdf form to compare it with next run (this is specifically, for researchers and extension works benefit to have real time farm data).

In a nutshell, the applications address the following needs of the user while he/she is making decision on what to grow and where to grow on his/her land:

- What is the status of my soil?
- What are current weather conditions?
- How much water I would need for various crops? so that I can compare this with availability
- How much profitability I can get for various crops which I can grow on my land.

Acknowledging the usefulness of these applications, PMAS-Arid Agriculture University has adopted the applications and started using it under its National project on Pilot Project For Data-Driven Smart Decision Platform (DDSDP). https://ddsdp.uaar.edu.pk/ The application is hosted here.

There are more than 50 active users in the LWR-036 study areas. This can be verified at http://mriaz-khan.com/LWR036-CWR/api/checkLocations.php which contain location of wells and last reported EC and depth to water.

Currently, the researchers at PMAS-AAUR and Charles Sturt University are collaborating for further development these applications.

A full report on the development of the mobile apps is provided in Khan et al. (2021).

10.3.2 Groundwater booklets and farmer cards

The Groundwater booklet and the On-Farm Water Management booklet were designed to provide our partners and stakeholders with improved understanding of groundwater resources and management. These documents have been produced in the Urdu language so that the stakeholders at grassroots level can understand. These are providing value to regional staff in explaining issues around groundwater to communities. However, their value can be enhanced by developing a training and capacity enhancement program for extension staff in agriculture and irrigation departments as well as staff from local government, community development, community-based organisations and Khal Punchayet Authorities. Having feedback from the communities will enable future improvements.

The farmer cards are a simplified extract from the booklets to pass on key and compact messages to farming communities and groundwater users. These resources have been used in the stakeholder forums however, we are not able to ascertain the extent of adoption and awareness raising from the Farmer cards.

10.3.3 Stakeholder Forums

Stakeholder forums are a space for on-going collaboration and sharing of information, so the ‘results’ of conversations in those spaces is also on-going. Each Stakeholder Forum was initiated with a co-design workshop intended to provide guidance to the project in relation to undertaking research activities of immediate relevance to the case study farming communities. The results from those workshops helped to direct the RAPs discussions, and are summarised below:

Sindh Stakeholder Forum collaborative design workshops outputs (combined from the two workshops):

- Participants showed a high need for field-based training on strategies for optimum use of groundwater and the partners who deliver training (e.g. PCRWR, SID) can benefit from the education materials that have been developed by this project. Consequently, PCRWR and SID may now be better placed to deliver training and we can offer them support (e.g. in the design, delivery and analysis of surveys; analysis of impact of changed practices).
- Groundwater use restrictions: our project should be identifying opportunities to have a policy impact. However, we have not been able to focus sufficient contextual research in this area for us to offer anything new, so it may have to be a request for action that we pass on to others such as SID or the planning department.
- As 80% of groundwater is saline, it is critically important that there are measures to purify water and to prevent further salinity and most importantly, to determine how this salinity can be removed
- Because of poverty, it is essential to suggest interventions that are low cost and feasible in the local conditions
- Training regarding skills and machinery should be provided in villages.

One stakeholder forum in Punjab is likely to continue as a ‘space’ for ongoing discussions among agronomists, farmers and academia. The Malwah Stakeholder Forum in Sindh will continue as part of the ACIAR ASSIB project.

There is also provision of SH forums and experts group in ASSIB which can be connected with the existing SH forums for continuity. The Punjab LBDC 11-L Stakeholder Forum collaborative design workshop outputs are presented in Table 10.19.

Table 10.19: Punjab LBDC 11-L Stakeholder Forum collaborative design workshop outputs: opportunities identified from small group discussions

Sr.#	***Group 1***
1	Awareness/Motivation
2	Good Practices Awareness – Develop Mechanism
3	Provision of Instruments Subsidy on water saving
	Group 2
1	Improved method of irrigation including high efficiency system (Drip, Sprinkler)
2	Revisiting Cropping Pattern (Excluding high delta crops)
3	Efficient Monitoring System for groundwater and information sharing through mobile app
	Group 3
1	Instrumentation
2	Outcome information of Groundwater, Economic and Social Modelling
3	Mobile App
	Group 4
1	Apna Pani App (Awareness Generation, Timely and effective provision of information)
2	Usage of Monitoring Tools(EC meter)
3	Socioeconomic Understanding (Provision of Training)
	Group 5
1	Water and soil testing for cropping
2	Soil testing before installing tube-wells
3	Cropping on ridges

The Balochistan Stakeholder Forum collaborative design workshop outputs are presented in Table 10.20.

Table 10.20: Balochistan Stakeholder Forum collaborative design workshop outputs: Most important groundwater issues that need to be addressed through this project and possible solutions

Sr.#	**Issues**	**Possible solutions**
	Group 1	
1	Non judicious water use	Increase awareness for behaviour change
2	Lack of rainwater harvesting	Rainwater harvesting/watershed management
3	Water table decline	Construction of dams
	Group 2	
1	Groundwater over exploitation due to improper cropping pattern, poor irrigation techniques	i) low delta crops such as pistachio, olive, dwarf apple varieties etc.; ii) improved irrigation techniques (HEIS + mulching); iii) Government to control illegal tube-well installation; iv) check dam construction for groundwater recharge
2	No alternative source of livelihood except to grow crop using groundwater	i) provide alternative livelihood sources in the vulnerable sub basins; ii) agro-based industries for fruits/vegetables food processing
3	Less awareness about modern farming and agronomic practices	Awareness campaign/trainings about water conservation and adoption of High efficiency irrigation systems and modern agriculture practices
	Group 3	
1	High depletion rate of groundwater due to extensive pumping	Rehabilitation of Karez irrigation systems, construction of water conservation structures (check dams)
2	Subsidy on electricity and promotion of solar pumps	The government should revisit the subsidy policy
3	Deforestation resulted reduction in rainfall	Reforestation under the prime minister's afforestation project
	Group 4	
1	Lack of awareness about water conservation	Training and development for modern conservation farming
2	Lack of storage capacity causing wastage of surface runoffs	Construction of dams
3	Non-functioning of Karezes has motivated extensive groundwater pumping	Rehabilitation of Karezes
	Group 5 (female)	
1	Shortage of water for crops, livestock and drinking	Provide support to recharge groundwater
2	Low precipitation	Depend on nature
3	Drying of fruits trees	Alternate livelihood

10.3.4 Agency networks

A significant impact of this project is the development of networks in the provinces between the Irrigation Departments, the universities and PCRWR. In addition, wider connections at a professional level between researchers and partners between provinces has occurred. This project is a good example of vertical and horizontal collaborations, learnings, sharing of experiences, exchange of ideas/innovation. It provided an opportunity for collaboration at international, national, provincial, and local grassroots levels in a vertical chain. Stakeholder forums at study sites consisting of many departments (federal/provincial/district/tehsil level), universities, NGOs, farmers, extension workers, drillers, youth, women provide examples of horizontal linkages. Bilateral and cultural relationships between the experts from Australia and Pakistan is an added benefit from the project. An example of this was best seen in the capacity development workshops held at PCRWR, UAAR, PCRWR Lahore, and at Mehran University.

10.4 Supporting GoP Water Policy objectives

Our story is one of hope – as groundwater management practices can be implemented together with stakeholders, irrigators and communities who are dependent on the abundance of this resource. Specific actions that can support GoP water policies are as follows:

The establishment of groundwater management areas is recommended to improve management of groundwater resources by adopting an inclusive model that allows all stakeholders to be involved in improving resource condition. In the Lower Bari Doab, there should be a designated groundwater management area and Okara and Sahiwal should be managed as separate zones under the plan. Although managed separately stakeholders need to take into account their interdependence as shown by lateral flows from Okara to Sahiwal.

Similarly, we recommend that each of the five divisions (i.e. Khairpur East, Khairpur West, Moro, Dad and Nasrat) be designated as groundwater management areas that can be managed to ensure that groundwater depletion is managed within acceptable limits. The overall guidance for recommended sustainable extraction limits is given for the entire model and improving irrigation efficiency and replacing a percentage of high-water use crops with low delta crops will allow adjustments in groundwater extractions. We further recommend that by 2022 the model calibration be tested by extending the model from 2015 to 2021 and to update the model and to undertake improvements in model calibration where required. Extension of the model will also allow review of the sustainable yields recommended in this report.

In Balochistan, the Pishin and Kuchlak sub-basins should be designated as groundwater management zones. Considering the rate of decline in groundwater in Kuchlak where some bores are indicating that there have been 100 m declines between 2010 and 2018, it is imperative that stakeholder groups that have been established under this project be nurtured and encouraged to adopt improved water conservation and land management practices and to change cropping practices to high value, low delta crops such as pistachio and pomegranate. Additionally, capacity development and knowledge transfer for groundwater users is essential.

The most significant impediment to improving groundwater management in all three provinces is the lack of reliable data on water levels, groundwater usage and climate data. A strategic approach to groundwater monitoring in Pakistan will provide the requisite data for monitoring the condition of the resource. For example, the Sindh Irrigation Department does not have a Groundwater Division and does not undertake any monitoring of groundwater resources. In Balochistan, some groundwater monitoring is undertaken with water levels measured in a few bores once per year, which is wholly inadequate. In Punjab there is more systematic monitoring in the eastern doabs, but this is limited to water levels monitored biannually in pre and post monsoon. Effective monitoring and analysis of data is essential to support sustainable management of water resources, and for providing resource managers with key information on availability of water resources, and the risk to the groundwater source. The Irrigation Departments in Sindh, Balochistan and Punjab need to take the lead on establishing a groundwater monitoring strategy for regular and strategic monitoring of the resource base. This should be addressed by the respective provincial departments on an urgent basis. Good spatial and temporal monitoring data are key elements for improving understanding of groundwater resources and for governments to make informed decisions.

The models developed in this project for all three provinces can provide the basis for further investment to allow improved understanding of water budgets at the sub-basin scale as well as for various irrigation districts. The water budgets also allow an estimate of sustainable extraction limits, which will need further testing and revision as models are extended. These estimates can be used to manage hotspots rather than imposing a single allocation limit for a sub-basin and will be a more flexible approach for adoption. Moreover, the RAPS approach adopted in this study has indicated that farming enterprises could substitute low delta crops on 5 to 10% of their land holdings.

Climate change is another looming unknown that is likely to impact on water resource availability. The RCP 4.5 and RCP 8.5 scenarios for Punjab show much greater rainfall recharge as compared to the Business as Usual (BAU) scenario. Although rainfall recharge is project to increase by 2047, the intensity of storms may result in crop damage and/or increased waterlogging. In Sindh, the RCP scenarios do not show much difference in 2047, however, the net decline in water levels under both RCP scenarios are larger in Khairpur East, Khairpur West and Moro Divisions. Scenarios such as these can guide policy makers and stakeholders towards a better future by adapting cropping, water and land management practices.

So as not to go down the path of *permission and punishment* we have introduced RAPS where a combination of interventions are co-developed with farmers. These comprise

1. Low delta crops (improving sustainability)
2. Ridge sowing using efficient irrigation methods
3. Improving soil health through the use of organic matter
4. High Efficiency Irrigation system (drip)

So rather than regulating groundwater extractions some farmers are opting for low delta crops in part of their land holdings which is resulting in fewer irrigation applications. the point here is farmers are applying 4 irrigations for Sunflower instead of 6 to 8 for maize. In its simplest form as canal water is limited – farmers tend to use groundwater to supplement irrigations. Since groundwater irrigation is expensive as compared to canal irrigation which is virtually free, then it is reasonable to assume that farmers will use less groundwater if they are applying 4 irrigations instead of 6 to 8. In the LBDC farmers have small land holdings and with cropping intensities already reaching 180 percent there is little opportunity to expand irrigation in hotspots. The recent EU funding initiative in Balochistan is also looking at promoting Low Delta Crops in Balochistan.

Balochistan is a special case as there are limited options – as shown GW levels have declined by 110 m in some parts of Kuchlak.The use of HEIS and low delta crops in Balochistan, farmers would not need to pump the amount of groundwater they would extract with traditional flood irrigation method and high delta crops. Moreover, the HEIS according to an impact assessment study carried out by PIPIP Monitoring and Evaluation Consultants during 2018 for its evaluation, reveals following impacts at the farm level

- Water Saving: 50 percent
- Crop yield enhancement: 20–100 percent
- Fertilizer use reduction: 40 percent

- Orchards maturing earlier: on-two years
- Early picking of vegetables: 10–15 days
- Value addition: Improved produce quality
- Increase in net farm income per acre per annum: PKR 75,000
- EIRR: 35.1 %

10.5 Linkages with other ACIAR Projects

This project is associated with the Australian Water Program for Pakistan, launched in Islamabad on the 31 January 2017.

The project has particularly strong linkages with the ACIAR project on Farmer Learning (LWR 2014/074) led by Dr Sandra Heaney-Mustafa, which exemplifies farmer centred approaches to engaging with farming communities to improve irrigation practices at the farm level. The SMS service provided by PCRWR for farmers in Punjab, which gives farmers timely information on rainfall and irrigation requirements, is another example which needs to rolled out to other provinces in Pakistan. During our project farmers in our stakeholder forums have approached us to provide instruments such as Chameleon and EC meters.

Participants from LWR 2015/036 participated, by invitation, to two World Water Day events organised by the project LWR 2014/074, in Islamabad in 2017 and Lahore in 2018.

Some Pakistan based project team members, participated, by invitation, in a tour of the Murray-Darling Basin in February 2019, organised through the Project ADP 2014/045, Led by Professor Lin Crase.

This project has also contributed to the Aik Saath activities, including development of the ACIAR Gender Inclusiveness Strategy for Pakistan 2018, and contributions to the Aik Saath Impact Story competition in 2019, including entries ‘Safe Water for my family’ and ‘learning in the field together.

This project led directly to the collaborative development of the ACIAR funded project LWR/2017/027 Adapting to Salinity in the Southern Indus Basin (ASSIB) which commenced in early 2021. This project will integrate with a range of other existing projects, notably ACIAR projects on small ruminants.

11 Achievements against activities and outputs/milestones

Objective 1: To develop and articulate a shared understanding of sustainable groundwater use for agriculture and the need for improved management in Balochistan, Punjab and Sindh provinces through a participatory and integrated systems approach

no.	activity	key outputs/ milestones	completion date	comments
1.0	Activities to get the project started	• Signed contracts • Agreement on dates, venue, and participants in inception workshop and co-ordination with other projects • Agreement on internal communication with partners • Agreement on modes of co-operation with ACIAR sister project(s) • Inception workshop held and report delivered • Impact pathways analysis activities undertaken together with all partners, stakeholder communication plans • Plans for stakeholder communication, impact pathways and project monitoring and evaluation.	These activities were completed between September 2016 and July 2019	Meetings with partners in Pakistan were essential as partners from 12 different GoP agencies, Universities and ICARDA needed to get to know each other to enable useful and ongoing collaboration for managing groundwater, even though the approaches and issues may differ. Being together from project commencement was fundamental to how this project needed to proceed. All early events were carefully planned, structured and facilitated using participatory processes to build a project team with shared understandings, so that plans and activities were embraced by all partners. The scoping workshop in Faisalabad in February 2016 secured the support of multiple partners, and we began to co-create a shared understanding of groundwater management and what our project could contribute. Developing and articulating shared understanding continued as a focus of the inception workshop in August/ September 2016, and the Impact Pathways. Subsequently the field trips organised in Sindh, which allowed all partners to familiarise themselves with groundwater issues in another part of the country, were important in developing a shared sense of purpose. A key aspect to both the Inception workshop and the field trip to Sindh was the team building involved. The Inception workshop involved dedicated team building activities and having the whole team together for the trip to Sindh. This added to the cost but had a significant impact for team conviviality. Such team-building activities are time and money well spent and are not just luxury add-ons to the research endeavour. They are necessary to overcome key barriers to effective delivery of transdisciplinary research, as they can help smooth through differences in disciplinary language and culture, differences in cultures when researchers seek to collaborate with research users, and the basic physical separation involved in large research programs (Mitchell et al. 2017). The need for this becomes all the more important when travel restrictions undermine opportunities for face-to-face interaction.

1.1	Compile and review groundwater systems information in each province	Database for hydrological and economic modelling of relevant groundwater systems in each case study area and documentation of relevant site data as follows below: a. Initial collation of data b. literature database c. Database and GIS system d. Additional data sources and/or data collection such as from field sites and household surveys	June 2018	The literature review (see 1.2 below) helped us understand that cultural differences influence how groundwater is used. An important learning was that each province is at a different stage in understanding of groundwater resources condition and management needs. For example, Punjab is leading as it has a basic monitoring program for groundwater and use of models is more widespread. Balochistan has some monitoring but very little use of data for analysis and modelling. And Sindh has no monitoring program, and very little knowledge of the condition of the resource. All information for developing groundwater models are built in a GIS framework, which will allow access to a wider range of researchers at the end of the project. The database & GIS system will be housed at MUET for full access by partners in this project. At this time there is no central place where this data is archived, however, we believe this would be advantageous from an ACIAR perspective as it would allow other projects access to these data sets (e.g. the LWR-2017-027 project), and it will allow partners and researchers to use these data sets particularly for post-project uptake.
1.2	Conduct literature review to identify relevant related research experiences locally and globally.	• Literature review for each case study site and district. • Update with additional sources and in-house review • Conversion of literature review draft into a published report Conversion to or use in published articles	July 2020	The literature review was essential in helping partners to develop a better understanding of the differing social, socioeconomic, and groundwater issues in each province. The literature review was both process and document. Initial review of literature informed some of the early activities, but the process of reviewing literature and adding it to the shared site continued over the life of the project. It became a capacity building and team maintenance activity, as team members reviewed each other's work, were trained in use of Endnote, and in synthesising ideas and information for themselves and others. Arguably, the greatest impact arising from this literature review has resulted from its iterative development that involved all authors collaborating in the processes of structuring, writing, improving, and learning how to improve each individual review of the literature. That the review includes contributions from staff in government agencies underlines the critical aspects of this process as an example of the project's approach to promote co-learning. Parts of the literature review were incorporated into the Mitchell et al. (2021) book chapter.

1.3	Facilitate Participatory Rural Appraisals (PRAs) with collaborating stakeholders to determine baseline information and an agenda for improving groundwater management	• Training workshops held • PRAs conducted and process documented • Proposals for case study sites documented based on justification against selection criteria • Documented rationale for refinement of project questions and foci • Guidance for refinement of socioeconomic assessment instrument and its administration • Provincial-level baseline snapshots of practice use to enable change monitoring • Increased research capacity among PRA teams • Increased participatory research capacity among project team, partners and participants • Indication of the type of information sharing platform required for the project • Research reports based on Participatory Rural Appraisals conducted in each province	These activities were completed between December 2016-July 2019	Participatory Rural Appraisals were the first major collaborative activity, and they cemented the central project objective of developing and articulating shared understanding. The PRA workshop provided opportunities for project partners from the three provinces, and from many diverse organisations, to learn together about ways of listening to farmers and their communities. Informing the detailed site selection through PRA indicated how the social and biophysical aspects of the project were integrated, and actually part of a single system. Developing a participatory research methodology and the stakeholder engagement strategy with our stakeholders at our field sites provided the foundation for developing a shared understanding of the issues, and also a mechanism to learn from others. The outputs of this objective, which includes the PRA reports, are a key part of helping to develop groundwater models with a better understanding of stakeholder concerns. See Khair et. al. (2021a) for the full report.
1.4	Build on PRA and reviews in each region to establish collaborative relationships with stakeholders	• Case study sites selected with documented rationale • The start of professional and practical networks through shared contact information • First meetings of stakeholder forums held	These activities were completed between November 2017-June 2019	The final sites were selected on biophysical, social and logistical considerations, and proved to be useful choices through the time of the project. The creation of stakeholder forums around those sites took some time - with the concept of labelling agency and NGO staff as 'stakeholders' being novel. The idea that staff of organisations are part of the 'community' as key stakeholders has influenced the LWR-2014-074 and LWR-2017-027 approaches to community engagement

1.5	Identify with farmers (men, women, youth and relevant minorities): (i) monitoring sites at strategic locations at the three case study sites and (ii) the level and range of related on-farm activities relevant to the mutual needs of farmers in each case study site and the fulfilment of project objectives	• Proposed schedule for what can be monitored over the life of the project (this is an output/milestone in the Annual reports but not in the project proposal) • Provisional plan outlining the level and range of on-farm activities that can form the basis for further discussion, budgeting, modification and evaluation	September 2019	Monitoring sites were selected for each of our case study sites in collaboration with partners and stakeholders. The project made a modest investment in instrumenting the study sites with loggers, which was a step up in current monitoring. Moreover, seeing the data trends from loggers was a learning process for partners and the farming community as it showed intra-seasonal variation in water levels and electrical conductivity. Farmers at our case study sites in Punjab began to understand that groundwater declines were going to impact them. The conversations around the sites for monitoring continued through the extent of the project loosely based around Stakeholder Forums. Stakeholder forums are emerging as a useful space in which ideas are shared and solutions to issues co-created, including the mobile apps and options for reduced water use on farms (see section 8 (impacts) for details).
1.6	Systems inquiry workshops in each case study site building from a gender-related focal issue identified through PRA discussions.	• Summary reports on outcomes of each workshop • Recommendations for inclusion of gender-related issues on project schedule	June 2019	The systemic inquiry process achieved two aims. There was some additional capacity built in UAF, SAU, BUITEMS and some private providers in relation to systemic inquiry and how it complements more traditional household surveys and PRAs. The inquiry with women in the case study areas showed their interest in groundwater planning, and some of the constraints on their participation. Women remain quite hidden, and despite their contributions in some stakeholder forum activities it is difficult to say if the inquiry did any more than document a situation and contribute to the ACIAR Gender inclusion strategy. The strategies used to explore systems issues were innovative, and worth replicating for other projects. The full report on gender is provided in Waraich et. al (2021).

Objective 2: To develop, with collaborating stakeholders in each case study, groundwater management tools and options that have the potential to enhance livelihoods of farming families

no.	activity	outputs/ milestones	completion date	comments
2.1	Use stakeholder forums established as part of Objective 1 activities and preliminary discussions with farmers/ farmer organisations to determine their input and ownership of each of the activities under Objective 2	Stakeholder forums held in each provincial case study area	May 2017	The discussion on groundwater use and impacts on the resource was presented and discussed at the initial Stakeholder Forum workshops in Sindh and Punjab by the CSU and respective provincial teams. In Balochistan this discussion was undertaken by the Balochistan team, with videoed inputs from the CSU team. The key stakeholders led the discussions, and farmers in our case study sites in Balochistan were very supportive of drilling new monitoring bores and participated in establishment of drilling sites for monitoring bores. Similarly, there was support from farmers at our case study sites in Sindh for establishing monitoring bores in secure locations on their property. One later benefit of collaborating across ACIAR projects was that we drew on and modified the LWR-2014-074 FILM approach as a means to secure co-design and co-ownership of the research action plans with each case study community, and this will be further advanced through the LWR-2017-027 project.
2.2	Develop hydrogeological models for each case study site	• Establish monitoring sites for each case study area. • Assess DEM and bore logs and develop conceptual models for each case study/districts • Develop framework for estimating recharge, ET, canal – groundwater interaction and estimating pumping • Develop hydrological models for each case study location	June 2019	Groundwater models have been developed in each Province, with the pace varying in each due in part to capacity and human resource constraints. It was a challenge to overcome data limitations and to develop models. Considerable capacity development activities were undertaken during model development, both in training as well as working together to develop skills.

2.3	Develop economic models for each case study site	• Develop and conduct field surveys • Descriptive analysis of survey results • Econometric analysis of data	June 2020	Economic models were developed for the case study sites. The household surveys and analysis preceded the development of socioeconomic models and required capacity building sessions with the socioeconomics team in each province. A key achievement was training in the use of mobile devices to acquire, store and check data. This training was held in Sydney and provided added opportunities for international networking of participants. The subsequent design of the survey using software for mobile devices, and its delivery greatly enhanced skills of the researchers - including many students - who took part. The refinement in the research strategy for the socioeconomic component, while challenging at the time given engrained thinking around research processes, also demonstrated willingness for the project team as a whole to adapt. The adoption of Representative Agricultural Pathways (RAPs) as the primary way forward also shows a willingness among the project team to allow local expertise to take the lead.
2.4	Calibrate hydrogeological models for each case study site	Report on model calibration	October 2019	Calibration involved developing and understanding model outputs, critical questioning of those results and changing input parameters to ensure that model outputs could be explained. Capacity development activities were undertaken together with working one-on-one with partners to develop strategies to improve calibration.
2.5	• Use hydrogeological models to conduct scenarios through iterative discussion with farmers and other collaborating stakeholders • Develop together with stakeholders' specific scenarios (e.g. climate change impacts, drought impacts, different groundwater management scenarios, environmental impacts etc.)	• Scenarios developed • Scenarios run and discussed with stakeholders	April 2021	Two types of scenario analysis were undertaken. One directed by the Irrigation Departments to assist in understanding different groundwater conditions in response to increased pumping and decreases in surface water supplies, and two climate change scenarios to develop an improved understanding of climate change impacts on groundwater.

2.6	Conduct training of partners and other collaborating stakeholders to increase local research capacity using models for assessing and managing groundwater use and quality issues	Training in modelling delivered	June 2020	Significant capacity development in groundwater modelling was undertaken for staff from Irrigation Departments and universities (including some university graduate students.
2.7	Provide a framework to Pakistan groundwater management agencies for assessing aquifer stress	A brief report on a framework for considering aquifer stress	April 2021	This activity was not progressed as part of the Mid Term Review, however, a brief report on these techniques is included as part of the Final Reporting (see Appendix C).
2.8	Test the use of mobile and web applications for researchers and policy makers and test the use of mobile applications by farmers which informs quantity of irrigation applications required for crops grown on their farm.	• Mobile and web applications developed and tested • Training on using developed applications at village level selected groups from the study areas	February 2021	The Apna Pani and Apna Farm Apps provided a useful platform to engage with farming communities and with some youth. This activity will need support by partners for wider use of these tools. Gaining farmer confidence in understanding the App was a key focus area. Apna Pani and Apna Farm were developed iteratively with agency staff and others from the stakeholder forums. The platform used during development is being transferred to PCRWR, and the use and development will continue. See Khan et. al (2021) and note that the further development of these applications has been incorporated into the LWR-2017-027 project. Sharing experience across ACIAR projects of similar research efforts would be useful to explore.

2.9	Conduct workshops with case study stakeholder forums using Representative Agricultural Pathways (RAPs) to discuss future agricultural planning options	Reports on the development and use of scenarios as part of RAPs	Draft reports completed April 2021. The final reports will be completed in May 2021.	The RAPs framework and approach built on participatory planning that started in the initial Stakeholder Forum workshops. The RAPs approach, supported by the household economic survey data, has been the key to initiating the adaptive activities adopted by farmers in Punjab, Sindh and Balochistan. The adoption of low delta (low water use) crops is showing promising results in Punjab. In Balochistan new pistachio plantings have been undertaken (which was delayed by 1 year due to Covid) and adoption of drip irrigation for pomegranate and mature apple plantings. In addition, inter-cropping was done in pomegranate plantings using grapes and vegetables. Similarly in Sindh where farmers were reluctant to adopt low delta crops, a new inter-cropping approach is being adapted with okra and other crops grown along with sugarcane. The RAPs workshops were interrupted and set back by Covid-19 and the restrictions in place to contain it. Initial RAPs workshops in Punjab are complete, with ongoing activity likely through the Stakeholder Forums
2.10	Conduct training in: a) Socioeconomic analysis b) Econometric analysis c) RAPs towards identifying the economic impacts of efficient groundwater use strategies, farming options, agronomic options, etc for farming communities.	Training programs delivered	June 2020	Significant capacity development in the RAPs approach has been undertaken by Profs Ashfaq, Baig and Mangan and by Dr Khair. Their leadership has been instrumental in the acceptance of RAPs (which built on the PRA and socioeconomic work) and adoption of low delta crops by farming communities in our case study sites. Training and related capacity building was aimed at ensuring that there is a range of appropriate tools and approaches available to develop and co- develop livelihood options. The socioeconomic training included key researchers in Pakistan learning how to use the Commcare app to write surveys that could use tablets in the field to collect data (MAD). The economic teams supported each other to undertake econometric and RAPs analyses, supported by specific training as required.

2.11	Explore feasibility of investment in water conservation technologies using existing models for potential future research, such as: d) Managed Aquifer Recharge (MAR), e) Conjunctive use	Documentation of stakeholder forum discussions on suitability of water conservation technology options	June 2020	There was interest in researching high efficiency irrigation systems in Balochistan, and the use of innovative cropping practices in Punjab and Sindh. Water conservation is a continuing topic of discussion in the Stakeholder Forums and was a focus of the initial Stakeholder Forum workshops undertaken in Sindh, Punjab and Balochistan. Managed Aquifer Recharge was not discussed directly in this project but is the focus of a PhD undertaken in parallel with the groundwater project.

Objective 3: Enhance capacity and institutional arrangements for post project adoption of tools and options developed in Objective 2 by collaborating stakeholder organisations

no.	activity	outputs/ milestones	completion date	comments
3.1	Synthesise lessons from case studies to determine opportunities for expansion of groundwater management	Guides provided to responsible agencies on use of modelling and decision support tools and processes	Due June 2021	In our planning, reports were often deemed the most effective output to produce for most activities. Often our ability to deliver high quality reports was constrained due to capacity and interest of team members to contribute. But there were other, possibly more effective ways that lessons were communicated during the project, especially through videos and local networks. We will explore how to communicate and demonstrate evidence of positive impacts arising from our activities in ways that are more effective than the traditional report. It does provide food for thought: how do we effectively disseminate the learnings and strategies we would recommend as a result of our co-designed research?
3.2	Develop awareness, information and capacity regarding groundwater problems and options for improvement with partners and local NGOs: a) with farming families b) with community c) with government agencies/ departments d) with NGOs and community-based organisations e) with policy makers"	• Summary report on tools and their practical applications • Education materials and programs delivered	April 2021	A range of farmer-focused materials were developed, including booklets, 'farmer cards' and videos, in English and Urdu. Importantly, these were developed with Agriculture and Irrigation Departments, and were discussed at Stakeholder Forum events. See details in the results, impacts and the Communications Report (Appendix D).

3.3	Develop and use approaches to increasing farmer and community understanding/ participation regarding groundwater for case study areas	• Report outlining best practice strategies for engaging farmers in discussions on groundwater management • Best practice strategies implemented • Analysis of strategies delivered, with recommendations for improvement	Note that while the completion date of June 2021, will be met with current activities, activities will be on-going by partners.	The project and the engagement with farming communities in our case study sites, led by our in-country partners, has been instrumental in improving understanding of groundwater and the capacity to act in response. Farmers in Sahiwal (Punjab) and Kuchlak (Balochistan) are acutely aware that groundwater declines are occurring year on year and are keen to adopt new strategies to ensure viability of farming. In Sindh new crops such as quinoa are being tried which is a low delta crop, and although there is reluctance to replace high delta crops among farmers in our case study sites in Sindh, they have been willing to adopt intercropping and are introducing okra and other crops with sugarcane. Importantly the adaptive actions are developed with farmers rather than imposed on them, hence the different approaches at different sites. Real adoption is more likely because of the contextualising and participatory development of options.
3.4	Demonstrate how groundwater levels and salinity measurement, and measurements of discharge in water courses and discharge of tube-wells, can provide useful guidance to farmers/ communities for managing groundwater resources at local level.	• Field demonstrations • Public awareness and communication material • Report on best practice community awareness strategies	April 2021	The trials with low water use crops, and improved irrigation in the case study areas grew from enhanced local capacity in groundwater monitoring, and in being able to share this with farmers and advisory staff in accessible, meaningful ways. The Apna Pani/ Apna Farm Apps have been part of this story, as have the farmer cards, booklets and videos that have been produced and shared in appropriate languages. Wide distribution of simple tools, such as water EC meters, and the forums at which to discuss and learn about their use, has added to local capacity. Importantly, the human capacity (knowledge and skills) of the Irrigation Departments and other advisory staff, NGOs and farmers is built in conjunction with social capacity - the networks and norms that help support change.
3.5	Develop framework for a groundwater status report	Framework developed, and its potential use tested and evaluated	April 2021	A simplified framework has been developed for groundwater status reporting and is included with the aquifer stress report (see Appendix B).

3.6	Conduct capacity building training of partners and stakeholders to increase local research capacity	• Journal writing workshop • Other data management training as required	Completed throughout the life of the project and ongoing	Capacity building and training activities have included: • Training in developing a groundwater model report was provided as part of our modelling training sessions in Sindh and Punjab. • CSU provided two sessions of online training in the use of EndNote literature database software to interested team members • , Training for the socioeconomic team in the use of mobile apps for data collection. • Formal training for academic writing held in Islamabad • Iterative development and delivery of 10 oral presentations at the Australasian Groundwater Conference 2019 with follow-up writing workshop in Australia to convert these 10 oral presentations into academic publications. • Iterative drafting and review of 8 other publications, with more to come. • Two journal writing workshops were held, one in Pakistan, and one at CSU in Albury. These were very positively received by participants and had a practical focus: the learnings were constructed around actual research outputs that participants were working on. The literature review is the main associated output. Many of these chapters were conceived and improved during the first workshop. We are yet to see any specific high-quality output emerging from the second workshop, and it would be good to follow up on this.
3.7	Synthesise individual and shared lessons and experiences regarding integrated research	• Strategy for documenting learnings developed and implemented, including training as required • Analysis and documentation of learnings	Will be completed in May 2021	This will be provided as video presentations at the final review, with a legacy website.

3.8	"Review and evaluate Objective 3 activities in terms of achieving objective 3 Including discussions on how our project is or might impact on different groups in society, including women, and how we could improve fairness of impact"	• Report on outcomes of evaluation • Workshops with key stakeholders to discuss future research opportunities and needs	Will be completed in May 2021	As we wrap this project up we need to consider the challenges and achievements of achievements from the initial Stakeholder forum workshops involving development of co-designed research action plans, the groundwater and socioeconomic models and the achievements of the RAPs. The RAPs helped to cement action plans already co-designed by situating them in an agribusiness planning context - confirming the business potential of the research interventions being studied. However, did they achieve more that this? How has the socioeconomic data been used to better inform planning, and what ongoing capacities have emerged among our case study communities as a result? Has it enabled new ways of thinking, decision-making or planning futures? Our achievements in this area needs to link to the broader literature on scenario planning.
3.9	Review and evaluate overall project against end of project outcomes	• Project evaluation • Future research needs identified and funding applications in process • Academic publications submitted reporting on experiences and learnings from integrated and participatory research methods adopted	April 2021	Evaluation was predominantly qualitative. Social researcher Catherine Allan interviewed Co-ordinating Team members individually via Zoom in 2021. The interviews were transcribed, and the software NVivo was used to assist with deductive thematic analysis, using the structure of the final report sections 7, 8 and 9.

Appendix A - Impact Pathway Analysis and Monitoring, Evaluation and Reporting and Learning (MERL) Plan

1. Impact Pathway Analysis

Goal	**Improved farming family livelihoods**						
Longer term outcomes (beyond life of the project)	**Some farmer/ farm incomes have increased**			**Effective, fair GW management**			
Impact pathway themes	Improving GW management with farming families (6 case studies)		Improving GW management with provincial irrigation departments		Collaboration and partnerships for improved GW management		
Key end of project outcomes	GW management by some farmers and/or farming organisations has improved		Partner government agencies have improved GW planning, monitoring and management strategies, and guidelines for legislative change		Relevant provincial government agencies, NGOs and FOs have developed partnerships for discussion of GW issues/ solutions		
Other intended and intermediate outcomes **Group and institutional practice change**	Management of GW has improved at local study level	Increased and effective participation of women and youth in groundwater management	Provincial government departments have started to develop improved GW management policies	FOs, NGOs and other CBNRM groups are working with relevant government agencies for improved GW management	Relevant government and non-government agencies participating in GW forums		All partner organisations have abilities to develop, plan, implement, analyse and publish high quality research
Key individual practice change (increase in confidence, sharing knowledge)	Some farmers and study sites have improved their water use effectiveness and farm productivity	Some farmers have started to adopt better GW management approaches, including those related to cropping patterns	Farmers, NGO and provincial agency staff skills have increased for GW management	Knowledge on GW shared across farmers, NGOs, FOs, Water Users Associations and provincial agencies	Key farmers are working with NGOs and provincial agencies for improving their water use effectiveness and farm productivity		Individual team members are developing personal research plans and receiving training
Skills change **Information access change**	Better availability and access to social services that interact with farm productivity/ income	Increased community and partner awareness of groundwater issues impacting farming family livelihoods	Access to GW information increased	Key agencies and farmers, young and old, are using mobile app to monitor groundwater			
Outputs	Strategies identified for improving farming family incomes	Case studies on GW in 3 provinces completed and resources shared	GW database for case study sites developed and available	GW models developed, calibrated and tested in case study sites	GW management tools and techniques develop and tested in case study sites	Provincial agencies, NGOs, FOs, other CBNRM groups and leading farmers in partnership for GW management	Publications, presentations and communication of results by individual team members to key peers and stakeholders
Activities	GW stakeholders engaged in all relevant project activities	Effective participation of key women and youth in GW management and inclusion of women in water groups	People trained in GW management and models	Operational plan developed and tested; activities scheduled by partner organisations; operational plan and activity schedule is reviewed and updated to reflect learnings and changed circumstances	Smart phone apps developed		Team members trained in and reflecting on how they can improve their research techniques

Inputs	Monitoring and reporting templates established	Expertise accessed, including from government, NGO and private sector research and extension services	Project management, coordination commenced and operational plan and work schedule developed	ACIAR funding and Pakistan 'in kind' contributions	
Getting started	Partnerships and relationships established and commitments agreed		Engagement, communications and M&E plans developed, standards for governance reporting, management (OHS, HR, performance) and skilled training established with participation of partners	IPA, proposal, partner agreements, MOUs and timelines agreed; contracts signed	

2. MERL Plan

	PERFORMANCE QUESTION	INDICATOR	TARGET	METHOD	WHEN	WHO
INPUT 1	Have monitoring and reporting templates been established?	Reporting template	A template for monitoring and reporting exists and has been made available to all project team members	The template's availability via email communication and shared Intranet site (if available) or similar	No later than June 2017, preferably earlier	Michael with support from Kanza
INPUT 2	Has the expertise of government, NGO and private sector research and extension services been accessed?	Database of collaborators and their expertise	Database of key individual collaborators from partner and non-partner organisations, and the expertise they can offer to the project	Develop, read and disseminate database, with a process established for regular updates	Start 2017	Kanza, Naveed, Michael and Jay
INPUT 3	Has project management, coordination commenced and the operational plan and work schedule been developed?	Access to project proposal and activity schedule	All team members have access to project proposal and updated project work schedule	Develop, read and disseminate project project proposal, with a process established for updating work plans	Start 2017	Michael, Jay and Kanza
INPUT 4	Have the ACIAR funding and Pakistan 'in kind' contributions been secured?	Funding secured	ACIAR funding In-kind contribution is secured and agreed to by all partners documented	Develop, read and disseminate reports, with a process established for regular updates	Annually in July	Dr Ashfaq and Aamir liaising with each partner submitting annually
ACTIVITIES 1	Has an operational plan been developed and tested? Have activities been scheduled by partner organisations?	Activity schedule	An up-to-date project plan and activity schedule is accessible to all team members with an appendix that list all changes made to the plan and schedule, and the reason for these changes	Documentation of all decisions made that affect project plan and schedule and the reflections/ learnings that led to these decisions	Ongoing, with quarterly full review of plan and schedule	Coordinating team, led by MM, with Kanza responsible for documentation
ACTIVITIES 2	Are the smart phone apps developed?	Application availability	Apps are available	Record of notification to partners and other key collaborators on how to access apps	Mid 2018	Mobushir, Usman, Kanza and Naveed

	PERFORMANCE QUESTION	INDICATOR	TARGET	METHOD	WHEN	WHO
ACTIVITIES 3	How many people trained in GW management and models? In what?	Number and type of training participants	Number of Irrigation Department and early career professionals competent to develop and apply GW models; and GW management tools	Provision of training in remote sensing, and GW monitoring modelling and management to enhance capacity of early career professionals from Irrigation Departments and Universities.	Ongoing with bi-annual review and progress recorded	Jay, Usman, Shafqat, Mobushir, Naveed
ACTIVITIES 4	Have GW stakeholders been engaged in all relevant project activities?	Numbers of participants	Numbers of GW stakeholders (as identified in stakeholder analysis) participating in activities	Spreadsheet record listing names of all participants in all activities, and any organisations/ categories they belong to (and where names are not available, numbers of participants in categories)	Ongoing record, summarised quarterly/ annually	Kanza and Dr Ashfaq
ACTIVITIES 5	Is there effective particpation of key women and youth in GW management, and inclusion of women in water groups?	Numbers and trajectory of participants	Numbers and trajectoris of womens inclusion and roles in water groups and governance structures	Spreadsheet record listing names and activities of women in water governance activities numbers and types of categories	Ongoing record, summarised twice annually	Kanza and Catherine
ACTIVITIES 6	Have team members been given opportuntiies for training in and reflecting on how they can improve their research techniques?	Training activities held	Annual training in research planning and assessment of research training needs	Training will be directed at enabling team members develop their own research plans to help achieve project outputs and outcomes	June 2018, 2019, 2020	CSU & ICARDA with communication support from Kanza
OUTPUTS 1	Are provincial agencies, NGOs, FOs, other CBNRM groups and leading farmers in effective partnerships for GW management?	Numbers and frequency of engagements	No. of forums, agreements; frequency of meetings; change arising from activities	Set up mechanisms to keep PRA leaders informed; appreciative inquiry and observations	Ongoing	Kanza, co-inquiry team leaders
OUTPUTS 2	Is the GW database for case study sites develped and available?	Data base and its use	Database has been developed; data is being entered and verified by relevant partners; database is being accessed and used by partners for GW model development	Read reports	Towards end of project	PCRWR and PIDs
OUTPUTS 3	Are the case studies on GW in 3 provinces completed and the resources being shared?	Written reports	Written reports completed for each case study	Monitoring of groundwater, economics and social	End of 2017	All partners led by provincial leads and coordinating team
OUTPUTS 4	Were GW models developed, callibarated and tested in case study sites?	Groundwater models	Groundwater models developed and calibrated for each site	Read report.	Stats on quality of callibration	GWMT - led by Jay

	PERFORMANCE QUESTION	INDICATOR	TARGET	METHOD	WHEN	WHO
OUTPUTS 5	Have strategies been identified for improving farming family incomes?	List of strategies	A list of strategies beginning to be adopted, or potentially ready	Read report.	End of year 2, 3 and 4	Provincial leads and coordinating team
OUTPUTS 6	Have GW management tools and techniques been developed and tested in case study sites?	Number and type of working tools	There are an effective number and type of tools	Rapid qualitative assessment of effectiveness; read report.	Towards end of project	GWMT - led by Jay
OUTPUTS 7	Have team members produced publications, presentations and other means of communicating results to key peers and stakeholders?	List of communication activities and materials including workshops, presentations, news releases and media reports; with data on levels of access and feedback	Communication activities are accessed by key peers and stakeholders, who offer constructive feedback to improve project activities and outcomes	Compile list, access data and records of communication in response	Ongoing	Kanza
INTERMEDIATE OUTCOMES 1a	Has access to GW information by provincial irrigation departments improved?	Ease of access to information	Information accessed; ease of access	Compile usage data and focus groups, appreciative inquiry	Annually from second year	Mobushir & PCRWR Staff in collaboration with co-inquiry team leads (Syed, Saira and Tehmina)
INTERMEDIATE OUTCOMES 1b	Has access to GW information by farmers improved?	Ease of access to information	Information accessed; ease of access	Compile usage data and focus groups, appreciative inquiry	Annually from second year	Mobushir & PCRWR Staff in collaboration with co-inquiry team leads (Syed, Saira and Tehmina)
INTERMEDIATE OUTCOMES 2	Are key agencies and farmers, young and old, using mobile app to monitor groundwater?	App downloads and usage impact	Increase in app downloads; app usage is having a positive impact for farmers and agencies with up-to-date availability of GW data	Compile data on app downloads including age of users; interviews and discussions with app users and those receiving data from apps	End of 2018 and 2019	Mobushir & PCRWR Staff in collaboration with co-inquiry team leads (Syed, Saira and Tehmina)
INTERMEDIATE OUTCOMES 3	Is there better availability and access to social services that interact with farm productivity/ income?	Social services access and availaibilty	Case study particpants' perceptions of access and availability of relevant social services	Interviews and discussions as part of on going dialougue/ forums in the case studies	Ongoing, opportunisitic	Catherine to compile with assistance from co-inquiry team leaders. Interviews undertakn by provincial team members
INTERMEDIATE OUTCOMES 4	Are individual team members developing personal research plans and receiving training?	Research plans	Each team member has a research plan, and uses it to identify trainng needs and to achieve research outputs	Annual training in research planning and assessment of research training needs	June 2018, 2019, 2020	CSU & ICARDA with communication support from Kanza
INTERMEDIATE OUTCOMES 5	Have some farmers started to adopt more efficient GW use management approaches e.g. changed cropping patterns?	Change in farmers' practices	Evidence of changed practices by farmers which contriibute to more effective use of water that could improve farming family livelihoods	Questionnaire surveys coupled with in-depth interviews in each case study location	End of 2019	Richard, Prof Ashfaq, Irfan, Syed and Tehmina

	PERFORMANCE QUESTION	INDICATOR	TARGET	METHOD	WHEN	WHO
INTERMEDIATE OUTCOMES 6	Have farmers, NGO and provincial agency staff skills for GW management been increased?	Data from mobile apps and training	Mobile apps feeding data on local GW conditions on weekly basis; training provided by NGO and extension staff has resulted in GW management skills acquisition	Analysis of app use on local GW data acquisition and availability over time; post-training questionnaires and interviews on participant learning and skills acquisition	Dec 2018 and then half yearly	Mobushir, Jay, Usman, in contact with PID, BID, SID and NGO extension staff
INTERMEDIATE OUTCOMES 7	Is knowledge on GW being shared across farmers, NGOs, FOs, Water Users Associations and provincial agencies?	Numbers of edcuation materials and reach	Numbers of newsletters, presentations and other forms of information sharing, and the means of communication, number of recipients	Annual tallies of spreadsheet data; annual interim reporting to project team	Annual reporting on numbers and any evaluation feedback available.	Kanza, with support from project team
INTERMEDIATE OUTCOMES 8	Are key farmers working with NGOs and provincial agencies for improving their water use effectiveness and farm productivity?	Collaboration levels	Evidence of increased collaboration between key farmers and irrigation departments/ NGOs on matters related to GW use effectiveness	Interviews and discussions as part of on going dialougue/ forums in the case studies	Ongoing, opportunisitic, culminating in final analysis to be undertaken end 2019	Richard, Prof Ashfaq, Irfan, Syed and Tehmina in collaboration with PCRWR staff
INTERMEDIATE OUTCOMES 9	Have provincial government agenices started to improve their implementation of GW management policies?	Policy initiatives and improvements	Evidence of provincial irrigation departments policy initiatives and/or improvements	Progressive review of provincial irrigation department policy documents	Early 2019 and early 2020	PCRWR staff with input from CSU team members
INTERMEDIATE OUTCOMES 10	Has management of GW improved at local study level?	GW irrigations and ASI application	Number of GW irrigations, rate, time of GW irrigations managed conjunctively with SW availability; application of ASI and Stress Indicators	Assess if SW+GW use match crop water use; monitoring of GW levels and assessing against stress indicators; ASI maps showing spatial impact of GW stress	Preliminary assessment in Dec 2018 followed by annual assessments	Jay, Naveed, Usman, Qureshi, Javed, Khilji
INTERMEDIATE OUTCOMES 11	Is there effective particpation of key women and youth groups in groundwater management?	Participation levels and engagement capacity	Number (and trajectory) of women and young people attending specific (eg 'women's') and general project events; capacity to engage and influence through these events	Review of attendenace records for each event, and evaluations if undertaken; opportunisitc observations and interviews with women and youth to hear their views on their effectiveness; reflective journals	Annual tallies. Annual interim reporting to project team	Catherine with assistance form co-inquiry team leaders
INTERMEDIATE OUTCOMES 12	Are FOs, NGOs and other CBNRM groups working with relevant government agencies for improved GW management?	Cooperative working relationships	Informal and cooperative working relationships have been established between our partner government agencies and key NGOs, FOs and others	Assessment undertaken via interviews with project team members from partner government agencies, and key contacts in relevant NGOs, FOs and others	December 2017, July 2018 and December 2018 (pre-cursor to end of project outcome assessment)	Catherine, Michael and Kanza

	PERFORMANCE QUESTION	INDICATOR	TARGET	METHOD	WHEN	WHO
INTERMEDIATE OUTCOMES 13	Are relevant government and non government agenices particpating in GW forums?	Participation records	Database or records of participants in GW forums and the organisations they represent; evidence of their perceived positive impact from participating	Compilation of GW forums participant lists; analysis of post-forum evaluation questionnaires	1 month after each GW forum, with a final report provided in early 2020	Kanza and Dr Ashfaq
INTERMEDIATE OUTCOMES 14	Are some study sites starting to show improvements in water use efficiency and farm productivity?	Water use	Evidence of reduced water use (e.g. via fuel bills or other data that shows water use) compared with level of income from farm produce aggregated at case study site scale	Compilation and aggregation of water use and farm produce income data over time	Bi-annually 2018 to 2020	Richard, Prof Ashfaq, Irfan, Syed and Tehmina
END OF PROJECT OUTCOMES 1	Has GW management by some farmers and/or farming organisations been improved?	Groundwater use data	Evidence of some positive changes in GW use data (more efficient, effective and/or fair) between the start and the end of the project	Estimation of the effectiveness and fairness of groundwater use at the sites before and after the project by using evaluation surveys etc	End 2020	PIDs with the assistance of PCRWR
END OF PROJECT OUTCOMES 2	Have partner government agencies improved GW planning, monitoring and management strategies, and guidelines for legislative change?	GW regulatory frameworks, policy and legislative guidelines, and management strategies	Evidence of GW policy guidelines and recommendations submitted to policy processes; drafts and guidelines for regulatory frameworks have been developed; case study level GW management strategies being developed, and GW monitoring systems in place and being used effectively	Drafts of the regulatory frameworks and policies by the governmental and non-governmental agencies	start 2020	PCRWR and PIDs
END OF PROJECT OUTCOMES 3	Have relevant provincial government agencies, NGOs and FOs developed effective partnerships for discussion of GW issues/ solutions?	Partnerships and forums	Formal and informal partnerships, including a national forum, exist and are seen as effective	Effectiveness assessment undertaken via interviews with key informants from all relevant provincial government agencies, NGOs and FOs	July 2019 and July 2020	Catherine, Michael and Kanza
END OF PROJECT OUTCOMES 4	Has community and partner awareness of groundwater issues increased in ways that could positively impact on farming family livelihoods in the future?	Awareness	Farming communities in each case study location and project partners can offer evidence of an increased awareness of GW issues, and can elaborate on how they believe this might help enhance farming family incomes in the case study location	End of project PRA	2020	Michael, Catherine, Usman and Jay

	PERFORMANCE QUESTION	INDICATOR	TARGET	METHOD	WHEN	WHO
END OF PROJECT OUTCOMES 5	Have some farmers improved their water use effectiveness and farm productivity?	Farmer productivity and water use effectiveness	Case study accounts of an improvement in water use effectiveness and fairness and farm productivity by individual farmers	Presentation and discussion as part of end of project PRA on analysis of reduced water use compared with level of income from farm produce; documentation of case studies in brochure format for promotion	End of 2019	Richard, Prof Ashfaq and Irfan in collaboration with provincial co-inquiry leads and Kanza
END OF PROJECT OUTCOMES 6	Has participation of women and youth increased in groundwater management?	Engagement capacity	Evidence from women and youth that their capacity to engage in GW management has increased, with accounts of how their engagement has had a positive influence, and net positive experience	End of project PRA	2020	Catherine, Saira and Tehmina
END OF PROJECT OUTCOMES 7	Are all partner organisations able to develop, plan, implement, analyse and publish high quality research?	Publications list	From Year 2 onwards, at least one publication per year in an internationally recognised academic journal covering groundwater research, economic research, social research, environmental management research, and integrated research (i.e. at least 15 publications)	Annual writing workshops and ongoing editorial support	June 2018, 2019, 2020	CSU & ICARDA
LONG TERM OUTCOMES 1	Have some farmer incomes from farming increased and by how much?					
LONG TERM OUTCOMES 2	Is GW management fair and effective?					
GOAL	Have farming family livelihoods improved?					

Appendix B - Briefing Note: Framework for a groundwater status report

Briefing Note

Framework for Groundwater Status Reporting

JF Punthakey

We recommend that the provincial irrigation departments establish a dedicated Groundwater Division staffed with groundwater managers that can produce a Groundwater Status Report annually to apprise the irrigation departments management team on the status of groundwater in each of the designated Groundwater Management Areas. The framework for the groundwater status report is provided as a starting point for consideration. The report can be tailored to meet the needs of a particular region, the aim being to propose a framework for a Groundwater Status Report that needs to be provided to management annually to enhance planning and decision making within the Department.

1.1 Designation of Groundwater Management Areas

We recommend the Punjab Irrigation Department establish Groundwater Management Areas in the doabs in Punjab. These would be at the sub-regional level initially and later based on the groundwater status reports specific groundwater management areas can be designated for irrigation districts or specific canal command areas, for instance designating Okara, Shaiwal and Khanewal as Groundwater Management Zones in the Lower Bari Doab.

It is imperative that the Balochistan Irrigation Department establish a dedicated Groundwater Division as groundwater depletion is impacting livelihoods and increasing poverty in Balochistan agricultural areas. Kuchlak sub-basin in Pish Lora Basin is one of the most affected sub-basins due to groundwater depletion. Establishing Kuchlak sub-basin as a designated Groundwater Management Area will focus attention on the depletion of groundwater in this sub-basin. And similarly the Pishin sub-basin needs to be declared as a Groundwater Management Area.

In Sindh, the groundwater modelling and water balance analysis undertaken has shown that the irrigation districts in Sindh require the establishment of Groundwater Management zones for the irrigation division encompassing Khairpur East, Khairpur West, Moro, Dad, and Nasrat Divisions needs to be established. Additionally a separate Riverine Groundwater Management Zone is recommended to improve management of groundwater and environmental aspects in the riverine zone along the Indus. The Indus is also a major recharge source for the Left Bank of Sukkur Barrage which covers our model domain.

Concurrently a strategic monitoring program needs to be developed for each of the designated Groundwater Management Areas. Because without reliable monitoring data it will not be possible for the irrigation departments to produce a groundwater status report that is meaningful for management purposes. Strategic monitoring of the resource will require a short term and long term investment plan with sufficient investment in staff capacity development for the irrigation departments.

Inclusivity is important and the Irrigation Departments need to adopt a GEDSI policy to accelerate its commitment to Gender Equality, Disability and Social Inclusion (GEDSI) by undertaking a policy review and incorporating better disability inclusion to address the capacity shortcomings within the provincial irrigation departments.

1.2 Purpose

The purpose of this report is to:

- Provide stakeholders with a brief, factual statement of the status of groundwater conditions in the respective Groundwater Management Areas. Stakeholders also groundwater users, farmers, researchers, and other government and civil society stakeholders.
- Response of water levels and salinity for key bores and pumping history and trends to understand impacts on the aquifer.
- Highlight the current level of key trigger parameters and compare them to the relevant trigger levels.
- Recommend action in relation to these trigger parameters.
- Current status of the aquifer and guidance for management of the aquifer.

1.3 Report Structure

1.3.1 Key Locations

The report should include a brief statement covering the area and key monitoring bores for the designated Groundwater Management Zones.

Several monitoring bores need to be selected to be key representative locations. They should be selected to represent the various aspects of the dynamics of the groundwater regime and the quality of the water in the shallow and deeper regions of the aquifer. For each groundwater management area monitoring bores should be sufficiently spatially distributed to develop maps of water levels, EC, SAR and RSC maps.

The plots of water levels at these locations over the relevant time period shows how the aquifer is responding when subjected to various stresses, the most important of these being rainfall, irrigation, evapotranspiration, local pumping for irrigation or municipal supply purposes and, in some cases, the storage history of nearby water storages. Selected hydrographs which are useful for the reader to understand impacts on the aquifer should be shown here.

Depending on how many monitoring points are available, how big the status report ought to be, and what resources are available for its preparation, we would suggest selecting as follows:

i. downstream of each barrage, both sides of river (where appropriate)
    - close to the river,
    - midway between river and aquifer boundary,
    - part way along each weir pool, same pattern as above

ii. along main, branch and link canals and selected major distributaries

iii. near aquifer boundary (where inflows/outflows are expected)

iv. areas where water levels are declining, and control points
v. areas where salinity, SAR and/or RSC is increasing, and control points
vi. areas where cropping intensity, rice, sugarcane and other high water use crops are grown each season.

This is an ideal arrangement, and practical monitoring would require strategic decisions on where to monitor and how many monitoring points are affordable. The guidelines can be used when selecting which of the existing monitoring points should be included when compiling data for the status report. If there are obvious locations where monitoring data would add crucial information to the report, additional wells should be contemplated.

1.4 Climatic and Land Use Context

1.4.1 Climate

During the period covered by this report, figures of the important climatic factors (including rainfall and evapotranspiration tabulations) should be shown.

1.4.2 Land use

Changes in land use (or land management) during the past year should be detailed in the report including any changes to the pumping regime.

The report should include tabulations of pumping data, and any relevant information about the withdrawal of groundwater from the aquifer.

1.5 Current Status - Storage

1.5.1 Calculated volumes

The most objective parameter available for determining the current overall status of the groundwater storage is the volume of saturated alluvium. This value can be estimated by using the underlying bedrock surface and the number of water level measuring points available. A numerical model can be used to estimate the change in aquifer volume over time.

The groundwater status report would generally include a figure showing the time series for calculated volume of saturated alluvium extended to the reporting date. Additionally, the calculated volume of saturated alluvium is reported at particular times such as in the Rabi and Kharif seasons, and an explanation is provided to help understand the status of the aquifer.

1.5.2 Cross sections

For some regions or types of aquifers it is also useful to present cross-sections with a profile of the water table shown on each cross section, to help with visualization of the current status of the aquifer.

Key locations: Hydrographs from monitoring bores at key locations should be shown with appropriate discussion.

1.5.3 Trigger Points

Insert a discussion of which trigger points, if any, have approached or exceeded the trigger value, what the implications are, and what action is recommended. The discussion should also include how trigger points have been selected and communicated to farmers, groundwater users and rural households.

1.6 Current Status – Quality

Spatial distribution of key water quality parameters in particular EC, SAR, RSC, nitrate, and other water quality parameters (eg. Arsenic) should be shown as hotspots for each Groundwater Management Area. If enough data are not available for contouring color-coded dots can be shown. Similarly time series data from the monitoring sites needs to be included to help understand changes to water quality parameters at specified locations in the aquifer.

For the report to be useful for decision and policy makers, the report should include a discussion of the current distribution of these parameters, with reference to any trigger points that have been established. For instance Pakistan water quality standards could be used to establish upper limits. An important aspect is to ensure a discussion is included in respect to water quality hot spots that have been monitored and remedial/management action that needs to be undertaken should be recommended.

A comparison of current levels and distribution of these parameters to preceding data needs to be presented to demonstrate effectiveness of current management strategies. This should follow a discussion of programs and/or interventions that have been undertaken during the year, in the ongoing effort to minimize the impact of nitrogen on the groundwater quality.

In the future, strategic monitoring can provide better water quality information which can be used to develop a nutrient management plan and adoption of best practices may be highlighted. The important point here is to benchmark improvement in groundwater quality.

1.7 Conclusions and Recommendations

- Assess changes to the volume of groundwater in storage within the designated groundwater management areas – where it has increased or decreased since the previous Status Report.
- Assess if the variation is within the expected range or not.
- Assess the operation of the aquifer: No change to operating procedures is recommended or groundwater withdrawal rates should be decreased by a specified percentage, and importantly the process that needs to be adopted which must include stakeholder consultation and consent.
- Assess if trigger points have been breached. No volumetric trigger points have been exceeded, or the following volumetric trigger points have been approached/exceeded.

- Recommend action to be implemented as recommended in the Groundwater Management Plan for implementation if a trigger level is breached should be implemented as follows:
- Recommendations following assessment of the pattern and occurrence of salinity and other water quality parameters such as nitrates and arsenic for the Groundwater Management Plan areas.
- Recommended actions in accordance with the Groundwater Management Plan including and policy recommendations based on the Status Report.
- The next annual Status Report should be prepared as provided for in the Groundwater Management Plan.

Appendix C - Briefing Note: The Application of Indicators for Assessing Aquifer Stress

Briefing Note

The Application of Indicators for Assessing Aquifer Stress

JF Punthakey

The indicators in this briefing note is designed to help water planners systematically approach groundwater storage utilisation and management in developing management arrangements for groundwater systems. The ultimate aim should be to transform groundwater aquifers to a level where the long term extractions from the aquifer are determined based on the level of drawdown such that the risk of impacts is considered to be within acceptable limits. The technical aspects can be determined and long term extraction limits can be determined however, this acceptance has to be gained with consent from the participation of the community of groundwater users.

Some of these techniques have been developed in research projects to investigate the issues associated with groundwater storage utilisation in selected groundwater management areas in Eastern Australia where decline in groundwater storage is of concern. Groundwater storage overexploitation refers to system wide extraction of groundwater at rates that cannot be matched over the long term by recharge and other inflows from the aquifer. Under these conditions, groundwater is drawn from storage, resulting in lowered groundwater levels/pressures and reduced volume of groundwater in the aquifer. Groundwater storage can be used to provide for seasonally varying water demands and for longer term drought relief in the absence of adequate surface water supply. It can also be drawn on to meet high value requirements over longer timeframes – such as for a specified planning period where there is capacity in the aquifer to reach a new equilibrium, or for urban and domestic water supply as an interim source until alternative supplies can be developed. The main driver for allowing short-term storage utilisation is variable demand. Agricultural demand variability is largely driven by variability in precipitation and crop water demand and in availability of surface water supplies. Urban and industrial water demands are somewhat less climate dependent. Demands for storage utilisation from these sectors tend to be longer term, and associated with growth in population and/or increase in demands due to transformative changes in the economy which is driven by industrialisation.

Extraction from a groundwater system draws on groundwater storage, which in turn induces changes in recharge and discharge, altering the system dynamically. Understanding this dynamic behaviour is key to understanding the potential for groundwater storage utilisation and should be addressed during the water planning processes. The extraction regime that is selected in the planning process should be determined by weighing up the benefits of extraction versus the risks associated with changes to water levels, pressures, recharge and discharge, both on a short term and long term basis. A range of possibilities need consideration to assess the level of risk that is considered acceptable and the ability to mitigate risks.

The nature and extent of the hydrologic changes associated with a proposed extraction regime can be uncertain, and where groundwater is overexploited there needs to be a strong emphasis on monitoring and modelling, with thresholds and triggers to address risks due to uncertainties in system behaviour and future climate events. The hydrologic changes associated with groundwater exploitation and decrease in groundwater storage can in turn result in environmental, social and economic impacts, both long-term and short term. These impacts need to be fully explored in the water planning processes.

1.8 Indicators for Assessing Aquifer Stress

The development of indicators for managing water resources has been recognised as the cornerstone of the World Water Assessment Programme (WWAP). Although difficult to identify and develop, indicators are increasingly playing a significant role in assessment of water resources. Indicators can be used to serve a variety of technical and policy goals, such as the improvement of water resource management policy through better assessment of the water resource situation.

Indicators are supposed to incorporate the complexities of interacting and competing forces in the water sector and to present the information in a simple and straight forward manner so that decision-makers and the wider community can understand it. In addition, benchmarks can be established so that changes can be analysed spatially as well as temporally, which can then be used to promote effective governance of the resource. Good indicators help water sector professionals to step "*outside the water bo*x", in order to take account of the social, political and economic issues affecting water (UNESCO 2003).

Although difficult to identify and develop, indicators are increasingly playing a significant role in assessment of water resources. Recognising this difficulty the World Water Development Report (WWDR) stressed the need for developing strategies to improve data collection and for developing a conceptual framework for indicator development.

Indicators can be used to serve a variety of technical and policy goals. Indicators help in the improvement of water resource management policy through better assessment of the water resource in a given hydrological, hydrogeological or spatial unit, through identification of critical problems and their causes and by providing a basis for comparison, Vrba and Lipponen (2007). This in turn leads to improved reporting on monitoring of progress against set targets and improved evaluation of water policy strategy and actions. Indicators also provide a basis for setting more appropriate national targets linked to policy goals and national legislation reforms and may provide for better mobilization of resources.

Selecting suitable indicators for assessing groundwater management requires an understanding of key groundwater management issues. These include the use of groundwater, the demands on the aquifer, possible threats to the aquifer, and the impacts of measures on the overall functioning of the aquifer systems under consideration. For groundwater indicators to be useful they must be able to support sustainable management of groundwater resources. Indicators can provide information about the present state and trends in groundwater systems, analyse the extent of natural processes and human impacts on the groundwater system in space and time, and facilitate communication and public participation in resource planning and policy. Groundwater indicators can be based on monitoring and assessment of the aquifer system, and developed and applied for use with simulated data based on model scenarios (Punthakey 2012).

An important role for the use of indicators which is very advanced in the financial and business world, but is an emerging issue in resource management is their use as an early warning indicator of system stress. Taking this a step further is the development of a framework for assessing the level of stress on the aquifer system so that it can provide guidance to Resource Managers and communities on how best to manage stressed systems.

This paper explains the development and application of the Aquifer Stress Index (ASI) for the Lower Murray region in New South Wales. The ASI can be used as an indicator to quantify the level of stress on the aquifer and to provide early warning of the onset of stress on the groundwater system. The ASI is defined in Box 1. The context in which the development of new indicators is proposed in this paper is primarily focused on sustainable management of groundwater resources. We hope that the successful development, formulation and application of indicators although designed primarily to meet technical goals will eventually provide a framework for influencing policy. Our main focus here is to have a set of tools that can be easily applied, are simple to understand and adopt, and which can be used with a set of agreed targets to improve management of the resource.

Box 1: AQUIFER STRESS INDEX

The Aquifer Stress Index (ASI) enables the potential level of stress in various locations of an aquifer to be compared against a target stress level set by the resource management agency. The ASI can be used across a range of spatial scales to determine the level of stress being experienced at a particular point in time. The ASI can also be applied to identify a level of stress which should not be exceeded, and then to use this criterion to manage pumping for individual cells in an aquifer, zones or layers (Punthakey 2005, Punthakey 2012).

ASI is defined as the ratio of modelled drawdown for a target area relative to the target drawdown for that area that has been determined to meet a desired management strategy. The ‘area’ can be a model cell, spatial zone, or entire layer. The target drawdown can be selected intuitively, or by other means such as using plotted distribution of probability versus modelled drawdown for the base scenario for different planning timeframes.

1.9 Application of the Aquifer Stress Index to the Lower Murray Region in New South Wales: A case study

For this case study of the deep, confined aquifers of the NSW Lower Murray alluvial groundwater system, a base scenario is represented by modelled sustainable yield of 82 MCM/yr. A management objective for this aquifer system is to ensure drawdown does not exceed a pre-determined acceptable level. Keeping extraction to sustainable yield does not necessarily achieve this as aquifer properties, bore concentrations and individual pumping patterns vary considerably. The ASI allows quantification of spatially distributed levels of stress.

ASI is defined as the ratio of modelled drawdown for a target area relative to the target drawdown for that area that has been determined to meet a desired management strategy. The 'area' can be a model cell, spatial zone, or entire layer. The target drawdown can be selected intuitively, or by other means such as using plotted distribution of probability versus modelled drawdown for the base scenario for different planning timeframes. Using this approach, lower probability (up to 70%) target drawdown can be applied across an entire layer, intermediate probability (70 – 90%) target drawdown may be suitable for a zone or group of cells, whilst high probability (95 – 100%) target drawdown may be suitable for individual cells (Table 1.1).

Table 1.1 Target drawdowns for 10 and 25 year planning horizons for 82 MCM/yr pumping

	Target Drawdown (m)		
Probability (%)	10 Years	25 Years	Application
68	1.6	3.0	layer
90	6.0	9.7	zone
95	7.4	11.7	zone/cell
99.7	11.1	17.9	cell
100	14.8	21.3	cell

For further analysis in this case study the target drawdowns selected are at 68 percent for the layer, 95 percent for zones and 100 percent for cells. Areas where simulated drawdown is greater than the allowable (target drawdown) at any time reflects a potential violation of the management objective. These areas may be considered as potential 'hotspots' (aquifer stress zones). Resource managers can then consider options such as improved monitoring to validate predictions, restricting further development at these sites, setting upper limits for pumping, encourage trading out of these areas or explore alternative strategies for reducing the level of stress at these sites, such as targeted offset by MAR.

1.10 Spatial Analysis of ASI at 10 and 25 years

The ASI for the 10 and 25 year planning horizons are shown in Figure 1.1 and 1.2 respectively. The selection of the maximum average drawdown for the deep aquifer precludes more than one cell from exceeding an ASI of 1. In the ASI range from 0.7 to 1 where stresses are likely to be high the number of cells for the 10 year planning period is 17, whereas for the 25 year planning period there are 32 cells in the ASI range of 0.7 to 1.

A ratio <1 identifies areas where the aquifer stress is below the predefined target stress curve, and where increased groundwater pumping could be allowed. A ratio >1 indicates a potential violation of the management objective and is a prompt for reduced pumping.

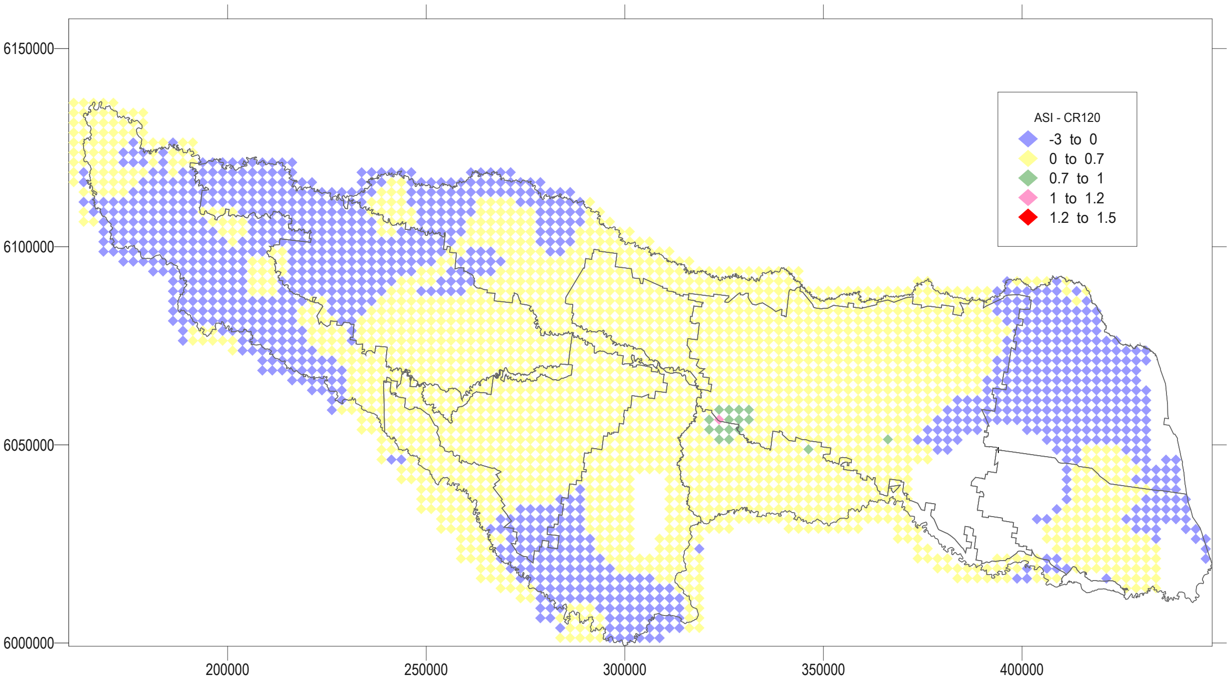

Figure 1.1 ASI for 82 MCM/yr pumping across the plan area; 10 yr scenario.

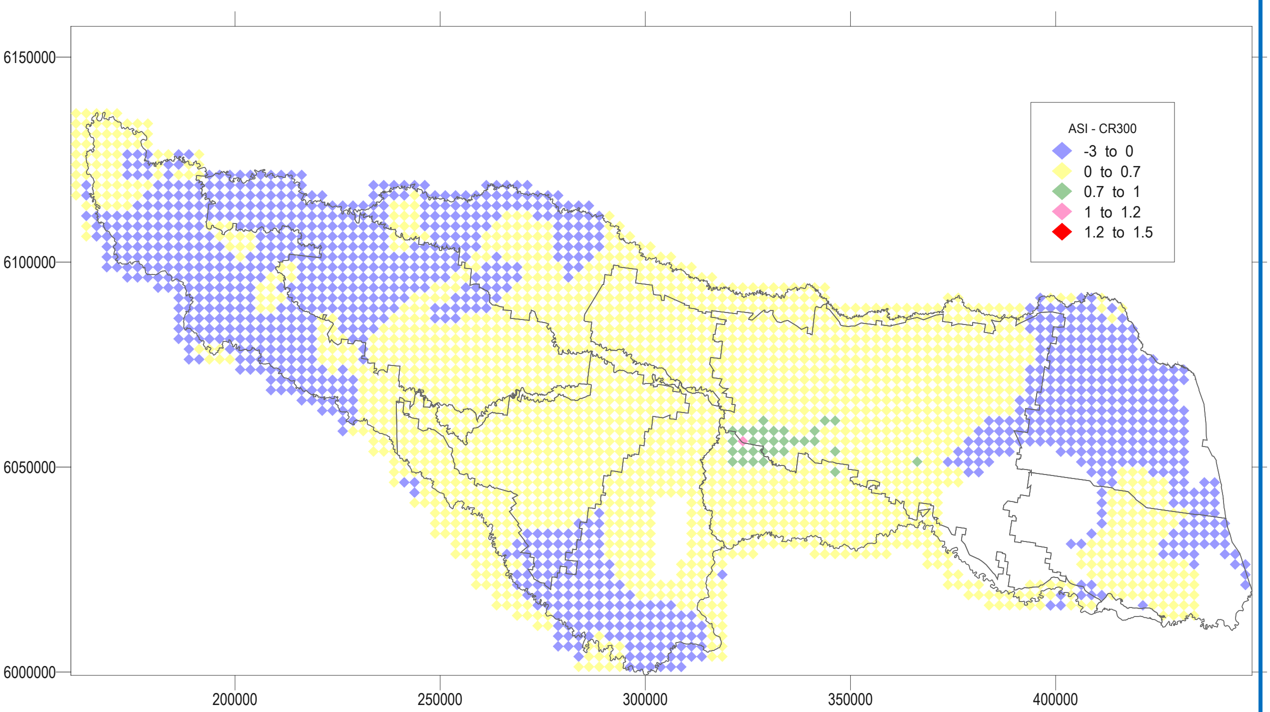

Figure 1.2 ASI for 82 MCM/yr pumping across the plan area; 25 yr scenario

The above approach can be applied with various planning timeframes and annual pumping rates, and the drawdown hotspots with an ASI>1 subject to scrutiny and consideration for changed management strategies. The use of time-varying target drawdowns is beneficial as it allows an understanding of the phased increase in the level of stress being imposed on the aquifer, and also allows for targeted drawdowns to be linked to discrete planning periods.

Figure 1.3 show the spatial distribution of ASI for the 123 MCM pumping scenario (150 percent of sustainable yield) at the end of 25 years. Compared to the 82 GL scenario there is a very large increase in cells with ASI greater than 0.7. At the end of 25 years the ASI in the range from 0.7 to 1 increases to 255 cells and there are also 95 cells with an ASI greater than 1 which are potential hotspots. Visually one can see this by an increase in the number of cells in the green range and additionally a large increase in the pink and red cells which are potential hotspots. There are also 4 cells with an ASI greater than 1.5 at the end of 10 years as well as 25 years. If the aquifer were operated for a period of time at a pumping level of 123 MCM per year than special attention must be paid to potential hotspot cells to ensure that the ASI does not exceed 1. Keeping the ASI below 1 will ensure that stresses on the aquifer are minimised and also a new equilibrium is reached gradually.

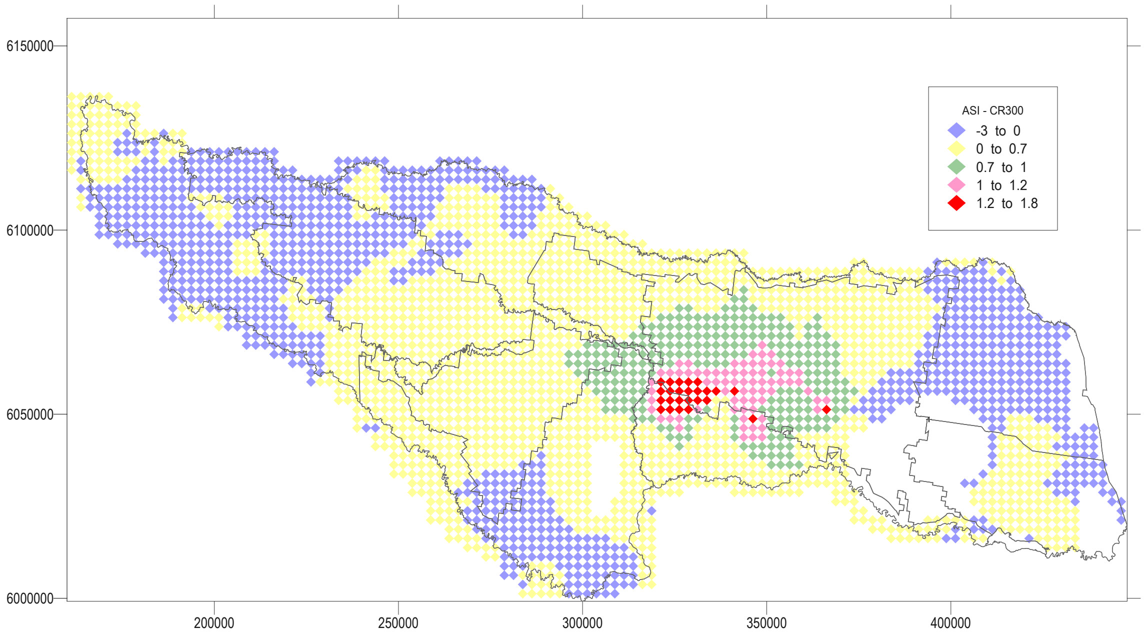

Figure 1.3 ASI at the end of 25 years for 1233 MCM/yr pumping across the plan area; 25 yr scenario

1.11 Temporal analysis of ASI for individual cells and zones

The temporal variation in ASI over a 25 year planning period is shown in Figure 1.4 for an individual cell. The drawdowns used for calculation of ASI for individual cells involved using a 12 period moving average corresponding to one year. This smooths out the annual cyclical response due to pumping and presents a smooth curve which is representative of the broad spectrum of stress being imposed on the aquifer. The ASI values for the 82 MCM pumping scenario provide the base scenario from which target drawdowns were selected. The 66 MCM scenario shows a maximum ASI of 0.7 which indicates that there is much less stress being imposed on the aquifer by this scenario. The 100 MCM curve exceeds ASI of 1 around 2015 indicating that pumping at these levels for up to 15 years may be acceptable, but beyond 15 years will induce high stress levels in the aquifer. Similarly for the 123 MCM curve the stress in the aquifer exceeds tolerable limits by 2008 and by 2020 stress is 50 percent higher than for the sustainable yield or base scenario. The impact of droughts is evident by the bulges in the ASI-82/100 curve. The drought scenario remains below an ASI of 1 indicating that the aquifer stress is within acceptable limits.

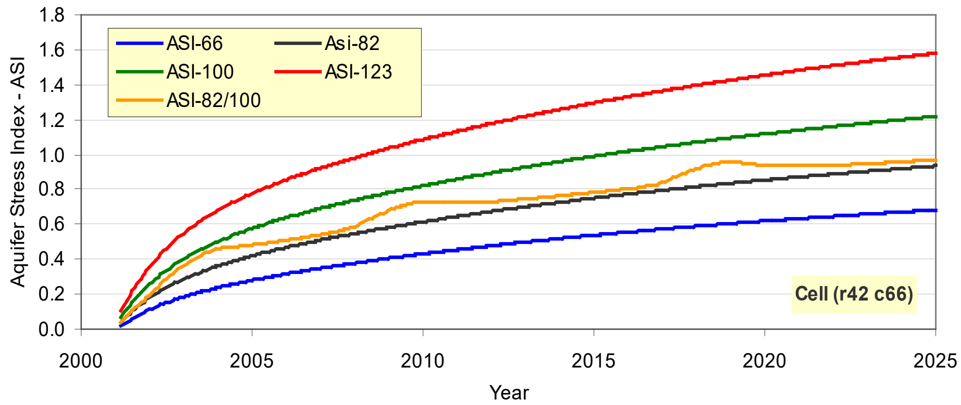

Figure 1.4 Temporal variation in ASI for an individual cell; 25 year scenario

The temporal variation in ASI over a 25 year planning period is shown in Figure 1.5 for management zone 3. The 82 MCM pumping scenario shows the maximum ASI at the end of 25 years is below 0.8 which is well below the threshold of 1. The 66 MCM curve shows the stress levels are much below the base scenario. The 100 MCM curve does not exceed ASI of 1 which indicates that the zone can withstand levels of pumping up to 100 MCM. For the 123 MCM curve the stress exceeds tolerable limits by 2016 and by 2025 stress is 20 percent higher than for the sustainable yield curve. The drought scenario remains below an ASI of 0.8 indicating that the stress is within acceptable limits.

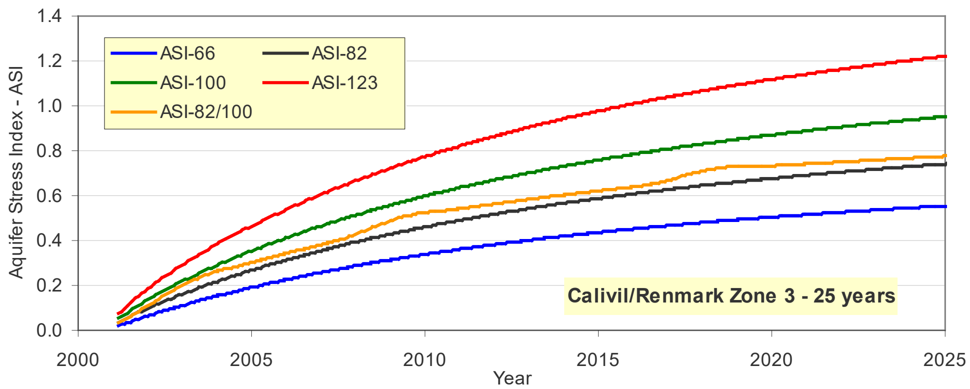

Figure 1.5 Temporal variation in ASI for an individual zone; 25 yr scenario

1.12 References

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Appendix -D: Improving groundwater management to enhance agriculture and farming livelihoods: Communications Report

This report offers a compilation of all communications material produced over the life of the project.

Extension Farmer Knowledge Products

Groundwater Booklet

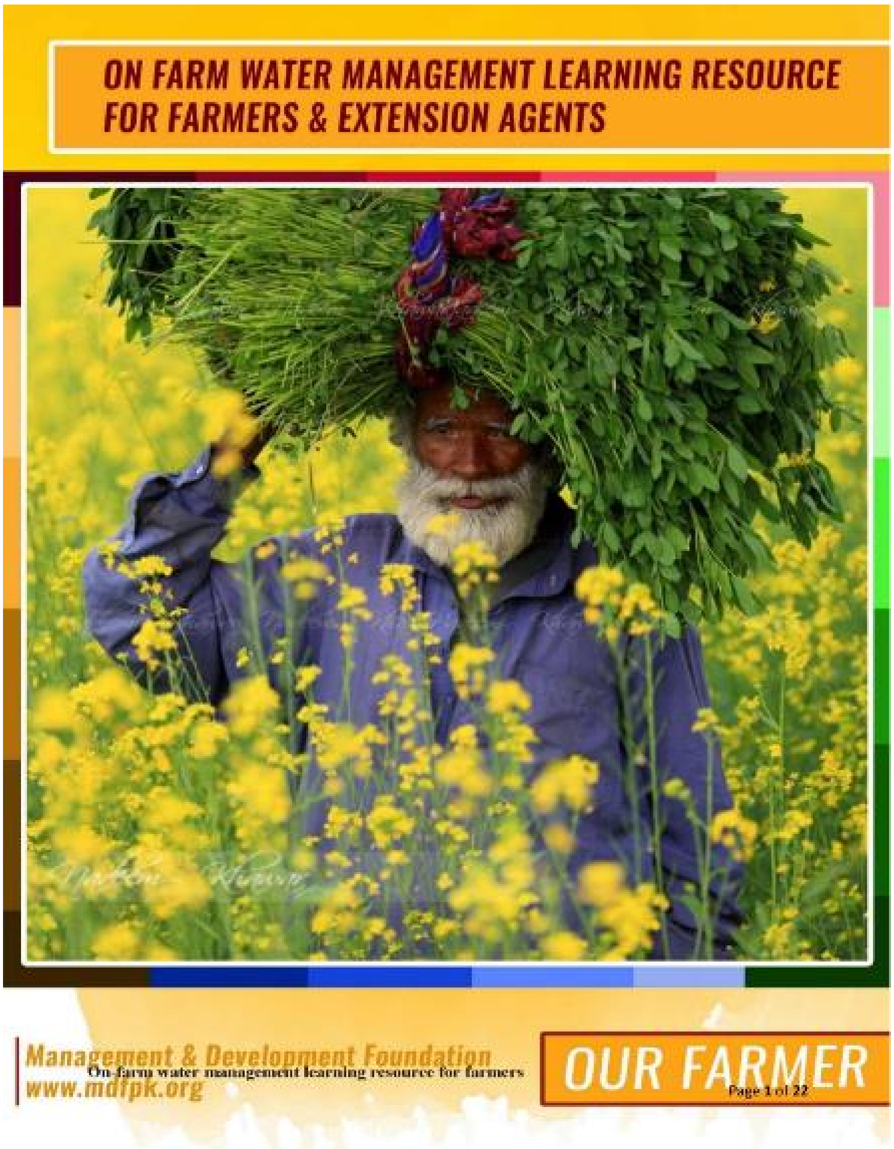
In English /Sindhi / Urdu

Groundwater booklet - Sindhi

[Groundwater booklet Urdu]

[On Farm Water Management Manual PowerPoint slides Sindhi Version]

On-Farm-Water Management booklet English version



On-Farm Water Management booklet Sindhi Version

On-Farm Water Management booklet Urdu Version

Farmer Card 1

Conjunctive Use

Charles Sturt University

FARMER CARD

Conjunctive Use of Water

Conjunctive use is the blended use of tubewell and canal water. In Pakistan, canal water used for irrigation is of better quality (low in salts) compared to groundwater which can vary from fresh to brackish to saline.

Learning Together

Charles Sturt University

FARMER CARD

For one part tubewell water use two parts of canal water 2:1 ratio

	+	 	=	Total water (conjunctive water)

The use of blended water in the right quantities minimises the build-up of salts in the crop root zone.

Different Forms of conjunctive use practised by farmers

Another form of conjunctive use practiced by farmers in Pakistan is to use tubewell water when canal water is scarce and to apply canal water for the last irrigation which helps flush out salts accumulated in the root

Some farmers at tailend of canals apply two irrigations with tubewell water and then the third irrigation with canal water to minimize build-up of salinity

Learning Together

Conjunctive Use Sindhi

Conjunctive Use Urdu

Conjunctive Use of Water

ٹیوب ویل اور نہری پانی کامشترکہ استعمال۔ پاکستان میں نہری پانی بہت اچھا ہے جس میں نمکیات بہت کم ہیں بنسبت ٹیوب ویل کے پانی کے جس میں نمکیات اور دوسری نقصا ندہ چیزیں شامل ہیں۔

For every one bucket of tubewell water use two buckets of canal water 2:1 ratio

	+	 	=	Total water (conjunctive water)

ٹیوب ویل اور نہری پانی کو صحیح مقدار میں دینے سے نمکیات کا پودرں کی جڑوں اور پودوں پر جمع ہونے والے عمل کو کم کردیتا ہے ۔

Different Forms of Conjunctive use practised by farmers

سندھ کے کاشتکار جو دریاؤں کی بیھاڑ میں رہتے ہیں وہ پہلے دو پانی ٹیوب ویل سے اور ایک پانی نہر سے دیتے ہیں جس سے بھی زمین میں نمکیات کم ہو جاتے ہیں

پاکستان کے کاشتکاروں کا ایک اور بھی طریقہ ہے وہ یہ کےپہلے دو مرتباہ ٹیوب ویل کا پانی استعمال کرتے ہیں اور آخری پانی نہر کا استعمال کرتے ہیں جس سے نمکیات و غیرہ نکل جاتے ہیں۔

Farmer Card 2

Raised beds

Charles Sturt University

FARMER CARD

Raised Bed Cropping

Raised-beds are a type of planting crops in which furrows – long, narrow trenches made in the ground by a plough – are widely spaced and crops are planted on raised strips. The width of the strips is determined to ensure homogeneous adequate water distribution into the soil profile to meet crop water requirements.

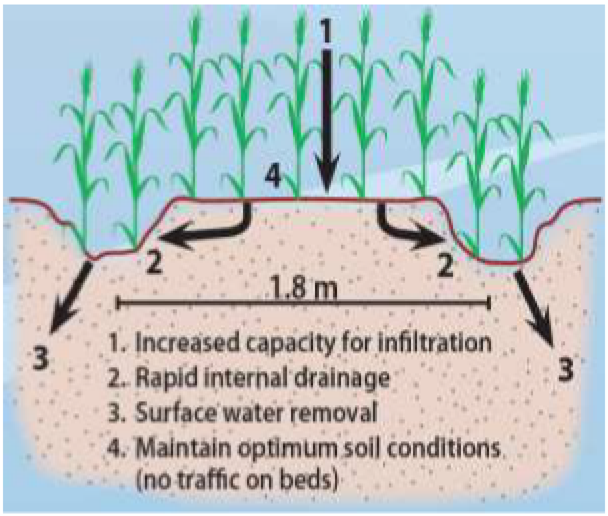
Learning together

Charles Sturt University

FARMER CARD

Crops best suited for raised beds: carrot, potato, cassava, peppers, tomatoes, lettuce, spinach, and even wheat and maize can also grow by this method.

Crop fertilising: The raised bed system greatly improves all-weather access to waterlogged sites. This improves the opportunity for growers to apply mid-season fertiliser. On raised beds, it is important to apply fertiliser precisely on the sown rows of crop on the beds, and to minimise fertiliser in the furrows.



Environmental benefits of raised bed farming include a reduction in soil salinity, soil and water pollution, water logging, and drainage water.

Learning together

Raised beds Sindhi

ڪرن تي پوکي

پاڪستان خاص ڪري سنڌ جا آبادگار پنهنجي فصلن کي هفتي ۾ هڪ دفعو ضرور پاڻي ڏين ٿا، تنهنڪري پاڻي جو مقدار انهن جي سڄي فصل تائين پهچڻ لاءِ موجود نه هوندو آهي ، تنهن لاءِ هو آبپاشي جي ٻين طريقن يعني ٽيوبويل يا مينهن تي ڀروسو رکن ٿا. هتي فصلن کي پاڻي سان ٻوڙڻ يا فصلن ۾ پاڻي وافر مقدار ۾ ڇڏي ڏيڻ وارو طريقو ڪار جي رسم هلندڙ آهي ، جنهن سان 30 کان 50 سيڪڙو پاڻي وڌيڪ استعمال ٿئي ٿو اهو پڻ مشاهدو ڪيو ويو آهي ته گذريل ڪيترن ئي سالن کان فصل سخت متاثر ٿي رهيا آهن. پاڻي جي کوٽ جي ڪري آبادگار غير يقيني واري صورتحال ۾جتي پاڻي موجود آهي اتي فصلن کي ضرورت کان وڌيڪ پاڻي ڏين ٿا ، جنهن جي ڪري فصلن جو فائدي جي بجاءِ نقصان ٿئي ٿو. پاڻي جي موجودگي ڏينهون ڏينهن گهٽجي رهي آهي ان لاءِ پاڻي کي بچائڻ جي طريقي ڪارگر استعمال ڪرڻ جي ضرورت آهي . ڪرن تي فصل ڪاهي نالي جي ذريعي ان کي پاڻي ڏيڻ آبپاشي جو تسلي بخش طريقو آهي جنهن سان پاڻي جو گهٽ استعمال ٿئي ٿو. پاڻي جي کوٽ جي ڪري آمريڪا ۽ انڊيا پنهنجي زرعي نظام کي ڪرن تي تبديل ڪيو آهي پر ان جي بر عڪس سنڌ جي تمام ٿورن ابادگارن اهو عمل ڪيو آهي جن ۾ نواز آباد فارم ۽ عاصم زرعي فارم شامل آهن جيڪي ٽنڊوالهيارضلعي ۾ آهن اهي پاڻي کي مناسب مقدار ۾ استعمال ڪري ٻين فصلن لاءِ به پاڻي بچائن ٿا

- . آبپاشي ۾ سڌارو ۽ غذائي بندوبست
- . پاڻي جي بچت
- . فصل جي سٺي پيهڪ يا اپت

- . ٻج جو گهٽ استعمال
- . سم ۾ گهٽتائي

ڪرن تي فصل ڪاهڻ سان پاڻي جي ورهاست ۾ سڌارو اچي ٿو، آبپاشي لاءِ پاڻي جي ضرورت گهٽ پوي ٿي، ان طريقي سان انڊيا چانور ۽* ڪڻڪ جا فصل ڪاهي پاڻي کي بچائڻ ۾ مهارت حاصل ڪئي آهي. پاڪستان جي صوبي پنجاب ۾ ڪڻڪ ۾ چانور جو فصل في ايڪڙ 29 مڻ پيداوار ڏيندو هيو پوکرن تي پوکائي کان پوءِ پيداوار وڌي 35 مڻ في ايڪر ٿي، جنهن سان 17 سيڪڙو پيداوار ۾ اضافو ٿيو، 30 کان 35 سيڪڙو پاڻي جي بچت ٿي.ان مان اهو ثابت ٿئي ٿو ته اسين ڪرن ته فصل ڪاهي وڌ کان وڌ فائدو حاصل ڪري سگهون ٿا. پاڻي تي تحقيقاتي اداري فيصاآباد ،زرعي يونيورسٽي ڪرن تي پوکي ڪندڙ آبادگارن لاءِ 90سينٽي ميٽر تي ڇيڻ قطارن جو نظام متعارف ڪرايو آهي ، جنهن جي نتيجي ۾ 40 سيڪڙو پاڻي جي بچت ٿئي ٿي، ۽ فصلن جي پيداوار ۾ 18 سيڪڙو تائين اضافو ٿئي ٿو .

Raised beds Urdu

Charles Sturt University

FARMER CARD

ACIAR

کیری کاٹے

کیاریوں کے ذریعے فصل لگا نے کے لئے لمبی نالیاں ایک ہی مفاصلے سے زمین کے اوپر ہل سے لگائی جاتی ہیں - پودے ان ابھری ہوئی پٹڑیوں پر لگائے جاتے ہیں جبکہ کیاریوں کا مفاصلہ ایک جیسا ہونا چاہئے جس سے پانی کی لیکساں مقدار دینے میں مدد ملتی ہے جس سے فصل میں پانی کی ضرروت بھی پوری ہوتی ہے۔

Charles Sturt University

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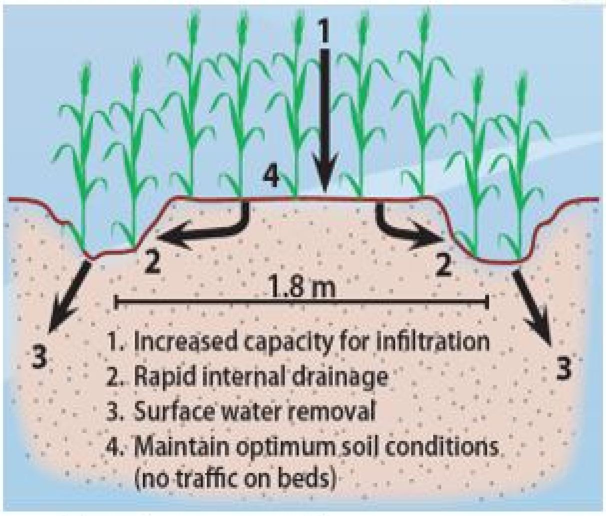
کیری کے لئے سب سے بہتر اور مناسب فصلیں: گاجر، آلو،اروی، مرچ، ٹماٹر،سلاد پتہ ، پالک، اور یہاں تک کہ گندم اور مکئی بھی اس طریقہ کار سے اگائے جاسکتے ہیں ۔

فصلوں کی کھاد :کیاریوں والا طریقہ کار ہر موسم میں پانی کی بہترفراھمی میں مدر دیتا ہے اس سے آبادگار کو ہر موسم کے بیچ میں بھی کھاد دینے کے لئے اچھا موقع ملتا ہے ۔اس سے نالیوں پر کھاد چھڑکنے سے کھاد کا استعمال کم سے کم ہوجاتا ہے۔



کیری کاشتکاری کے ماحولیاتی فوائد میں مٹی کی آبادی، مٹی اور پانی کی آلودگی، پانی سے بچنے، اور نکاسی آب کے پانی میں کمی شامل ہے

Farmer Card 3

Salinity Crops

Charles Sturt University

FARMER CARD

ACIAR

Salinity of your groundwater

When the salt content of groundwater reaches certain thresholds it becomes unsuitable for some uses. Saline water can damage soil, be unpalatable to drink and affect the growth of crops and pasture.

The table shows how increasing salinity of irrigation water reduces the potential yield of different crops.

How salinity impacts crop yields

Decrease in yield potential & crop tolerance with increasing EC	0%	10%	25%	50%	100%
EC (mS/cm) ------>	ECw	ECw	ECw	ECw	ECw
FIELD CROPS	5.3	6.7	8.7	12	19
Barley	5.1	6.4	8.4	12	18
Cotton	4	4.9	6.3	8.7	13
Wheat	2.1	2.4	2.7	3.3	4.4
Groundnut (Peanut)	2	2.6	3.4	4.8	7.6
Rice (paddy)	1.1	2.3	4	6.8	12
Sugarcane	1.1	1.7	2.5	3.9	6.7
Note: For guidance only. Absolute tolerances vary depending upon climate, soil conditions and cultural practices.					

Barley and cotton are more salt tolerant than maize or sugarcane. So if you are using groundwater where salinity levels are high then you may want to consider a suitable crop to grow. To get maximum yield from your crops you should minimise using water of high salinity, and where possible use surface and groundwater conjunctively to minimise the risk of salinity build up in your root zone.

Learning Together

Charles Sturt University

FARMER CARD

ACIAR

Impact of Salinity

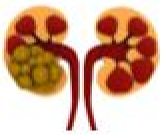
Environmental

- Increased ponding and flooding of water
- Increased exposure of bare earth
- Reductions in landscape plant cover
- Increased water salinity

- Increase in wind-borne dust related respiratory illness

Agricultural/Economic

- Reduction in area of fertile land
- Loss of local irrigation and drinking water supplies
- Reduced agricultural production
- Loss of income
- Accumulation of pesticides and chemicals in water logged areas



- Increase in mental and physical stress related to socio-economic changes
- Drinking water with high salinity can lead to health problems such as blood pressure, headaches, seizures and kidney failures.

Learning Together

Salinity Crops Sindhi

Charles Sturt University

ACIAR

Salinity of your groundwater

زميني پاڻي ۾ جڏهن نمڪيات جي مقدار وڌندي آهي ته اهو پاڻي نه پيئڻ جي لائق رهندو آهي نه ئي زراعت جي.

How salinity impacts crop yields

Decrease in yield potential with increasing	100%	90%	75%	50%	0%
EC (mS/cm) ------>	ECw	ECw	ECw	ECw	ECw
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مٿي ڏنل ٽيبل ٻڌائي ٿي ته لوڻياٺ وارو پاڻي ڪهڙي طرح پيداوار کي گهٽ ڪري ٿو. گندم ۽ ڪپهه بنسبت مڪئي ۽ ڪمند جي گهڻي نمڪيات واري پاڻي کي برداشت ڪري سگهن ٿا. انهي لاءِ جنهن زمين ۾ سم ۽ ڪلر هجي ان زمين تي اهڙن فصلن جي پيداوار ڪجي جيڪي زمين تي پيداوار ڪري سگهن. ۽ پيو ان حالات ۾ نهر ۽ ٽيوب ويل جي پاڻي کي گڏ استعمال ڪرڻ گهرجي.

I

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نمڪين پاڻي جا اثرات

ماحولياتي

تالاب ۽ ٻوڏ جي پاڻي ۾ واڌارو

گهڻي زمين جو غير آباد رهڻ

فصلن جي پوک جو گهٽجڻ

پاڻي جو استعمال جي قابل نه هجڻ

مٽي واري هوائن جي ڪري ساهه جي سرشتي جي بيمارين جو وڌڻ

زرعي/معاشي

زرخيز زمين جي ڪمي
نهري پاڻي ۽ پيئڻ جي پاڻي ۾ ڪمي
زرعي پيداوار ۾ ڪمي
آمدني ۾ ڪمي
پيئڻ پاڻي تي جيئت مار ۽ زهريلين دوائون چڙهڪڻ

آمدني ۾ ڪمي جي ڪري نفسياتي دٻاءُ ۽ ان سان متعلق بيمارين ٿي ويندين اهن. مثال طور: بلڊ پريشر، مٽي جو سور، گردن جي بيماري

نمڪيات وارو پاڻي صحت جي لاءِ نقصانڪاري آهي

Salinity Crops Urdu

Charles Sturt University

ACIAR

Salinity of your groundwater

زیر زمین پانی میں جب نمکیات کی مقدار زیادہ
ہوجائے تو وہ پانی نہ تو پینے کے لائق رہتاہے
اور نہ کاشتکاری کے۔

How salinity impacts crop yields

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اوپردی گئی ٹیبل بتاتی ہے کہ کس طرح نمکیات والا پانی پیدائش
کو کم کرتا ہےجو اور کپاس بنسبت گنے اورمکئ کے زیادہ
نمکیات والے پانی کو برداشت کرتےہیں اس لئے ایسی زمین
جس میں کلر ہے اس میں ایسے فصل لگانےچاہئیے جو اس
زمین میں بہتر پیداوار دےسکے۔ او ر دوسرا اگر ممکن ہو تو
ان حالات میں ٹیوب ویل اور نہری پانی کا مشترکہ استعمال
کرنا چاہئے

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نمکین پانی کے اثرات

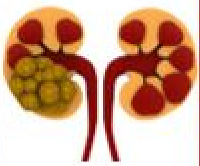
ماحولیات

تالاب اور سیلاب کے پانی میں زیادتی
زیادہ زمین کا غیرآباد رہنا
فصلوں کی کاشت کا کم ہونا
پانی کا قابل استعمال نہ رھنا

مٹی والی ہواؤ ں سے سانس کے سرشتے
کی بیماریوں کا بڑھ جانا

زرعی/معاشی

زرخیز زمین کی کمی
نہری پانی اور پینے کے پانی میں کمی
زرعی پیداوار میں کمی
آمدنی میں نمایاں کمی
کھڑے پانی میں جیت مار ادویات اور دوسرے
زھریلی مادوں کی زیادتی



آمدنی میں کمی کی وجہ
سےنفسیاتی دبا ؤ اور اس سے
متعلق بیماریاں ہوجاتی ہے
نمکیات والا پانی صحت کے لئے
نقصان دہ ہے مثال طور:
بلڈپریشر، سر درد، گردوں کے،

Farmer Card 4

Salinity and Health

Charles Sturt University

FARMER CARD

ACIAR

Salinity of your groundwater

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Learning Together

Charles Sturt University

FARMER CARD

ACIAR

Drinking Water and Health

For drinking water, you have to be more careful, the Pakistan Water Quality standard for drinking water is (1000 mg/l or 1550 µS/cm). Drinking water with high salinity can lead to health problems such as blood pressure, headaches, seizures and kidney failures.

Testing the quality of your drinking water is important for your families' health. You can get your Tubewell water tested from PCRWR laboratories (cost Rs 200/-). This will tell you if your tubewell water is safe to drink – it will give you peace of mind to know that the water you drink is safe for your children and you.

The salinity of groundwater and canal water can be tested using an EC meter. The EC meter measures the electrical conductivity of water. As the salts in the water become higher the EC value also becomes higher.

- Take a sample of water from your tubewell in a clean bottle.
- Switch on the EC meter and put the EC meter in the bottle.
- If the EC meter reads below 1550 the salinity of the water meets the guidelines for drinking. Note: there may be other contaminants in the water such as arsenic or pathogens. Checking the quality of the water source every year will help you keep your family healthy and safe.

PCRWR - Water Testing Laboratory

Learning Together

Salinity and Health Sindhi

Salinity and health Urdu

Charles Sturt University

Salinity of your groundwater When

زیر زمین پانی میں جب نمکیات کی مقدار بڑھ جائے تو وہ پانی نہ تو پینے کے لائق رہتا ہے اور نہ کاشتکاری کے۔

How salinity impacts crop yields

Decrease in yield potential with increasing	100%	90%	75%	50%	0%
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اوپر دی گئی ٹیبل بتاتی ہے کہ کس طرح نمکیات والا پانی پیداوار کو کم کرتا ہے جو اور کپاس بنسبت گنے اور مکئی کے زیادہ نمکیات والے پانی کو برداشت کرتے ہیں اس لئے ایسی زمین جس میں کلر ہے اس میں ایسے فصل لگانے چاہیے جو اس زمین میں بہتر پیداوار دے سکے۔ اور دوسرا اگر ممکن ہو تو ان حالات میں ٹیوب ویل اور نہری پانی کا مشترکہ استعمال کرنا چاہئے۔

PCRWR - Water Testing Laboratory Address

Charles Sturt University

Drinking Water For Health

انسانی زندگی کے لئے صاف پانی کا استعمال بہت اہم ہے

پاکستان میں پینے کے پانی کی چکاس کے ادارے کے مطابق

اس میں نمکیات (1000mg/ 1550 uS/cm) سے زیادہ نہیں ہونی چاہیے اس سے

زیادہ ہونے پر سر درد، بلڈ پریشر، گردوں کی بیماریاں وغیرہ

ہونے کے خدشات ہیں

PCRWR - Water Testing Laboratory Address

اپنے ٹیوب ویل کے پانی سے کچھ پانی ایک صاف برتن میں ڈالیں۔ میٹر کا سوئچ آن کریں اور میٹر کو بوتل یا برتن کے اندر ڈالیں۔ اگر مقدار ۱۵۵۰ سے کم ہو تو پانی استعمال کے لائق ہے۔ ایسے ٹیوب ویل کے پانی کو سال میں ایک مرتبہ ضرور چیک کروائیں۔

پانی کی چکاس: پانی کی شفافیت پینے والے پانی کے لئے بہت اہم ہے۔ اس لئے اپنے خاندان کی صحت کے لئے اپنے ٹیوب ویل کے پانی کو (PCRWR) سے دو سو روپے فیس دے کر چکاس کروائیں جس سے آپ کو جانکاری ہو گی کہ آپ کے ٹیوب ویل کا پانی استعمال کے لئے مناسب ہے یا نہیں۔ پانی میں نمکیات کی چکاس کے لئے جو آلا استعمال ہوتا ہے

اس کو (EC) میٹر کہتے ہیں۔ یہ آلا برقی رو سے پانی میں نمکیات کی موجودگی اور اس کی مقدار کو ظاہر کرتا ہے

Farmer Card 5 – Water Logging

Charles Sturt University

FARMER CARD

ACIAR

Waterlogging causes and Preventive Measures

The rise of the watertable to the surface level is called waterlogging and the appearance of salty patches is called salinity. Salts in the soil also rise to the surface with the watertable. When the soil profile is saturated and water appears on the surface and evaporates resulting in salt deposits on the soil surface.

Learning Together

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Waterlogging and salinization are major impediments to the sustainability of irrigated lands and livelihoods of farmers, especially smallholder farmers, in the affected areas of the Indus Basin.

Causes of Waterlogging:

- Inadequate drainage of overland run-off increases the rate of percolation and in turn helps in raising the water table.
- Seepage of water from earthen canals also adds significant quantity of water to the underground reservoir continuously.
- Sometimes subsoil does not permit free flow of subsoil water which may accentuate the process of raising the water table.
- Irrigation water is used to flood the fields. If it is used in excess, it may help appreciably in raising the water table.

Preventive Measures:

- Improving irrigation efficiency by applying the right amount of water for crop needs
- Lowering groundwater levels through deep tubewells
- Leaching of salts by excess irrigation
- Drainage of water from waterlogged areas
- Application of chemical amendments (e.g. gypsum, acids, organic matter)
- Lining of channels in waterlogged areas.

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Farmer Card Water Logging Sindhi

Charles Sturt University

ACIAR

آبادگار ڪارڊ

سم ٿيڻ جا سبب ۽ بچاءَ جا طريقا

زمين جي سطح تي پاڻيءَ جي چڙهي اچڻ کي سم چئجي ٿو ۽ زمين جي مٿان لوڻن جي ٽڪن جي ظاهر ٿيڻ کي ڪلر چئجي ٿو. سم ٿيڻ جي ڪري زمين جي اندران لوڻ/ڪلر مٿي چڙهي اچي ٿو. جڏهن زمين جي سطح تائين سم چڙهي اچي ٿي ۽ سم جو زمين جي مٿان وارو پاڻي اس ۽ هوا ۾ اڏامڻ لڳي ٿو ته ان جي نتيجي ۾ لوڻ/ڪلر زمين جي مٿان ظاهر ٿئي ٿو.

سنڌو نديءَ جي متاثره علائقي ۾ آبپاشيءَ وارين زمينن، آبادگارن جي روزگار ۽ خاص طور تي ننڍن آبادگارن جي پائداريءَ ۾ سم ۽ ڪلر مُکيه رڪاوٽون آهن.

Learning Together

MDF

Charles Sturt University

آبادگار ڪارڊ

سم جا ڪارڻ

* سم جي نيڪال جو مناسب بندوبست نه هئڻ، جنهن جي نتيجي ۾ پاڻي زمين ۾ جمع ٿيندو رهي ٿو ۽ سم کي وڌائي ٿو.
* ڪچن ڪينالن مان پاڻي زمين اندر سمندو رهي ٿو ۽ اُهو ڪافي مقدار ۾ زمين جي اندر لڳاتار جمع ٿيندو رهي ٿو.
* ڪڏهن ڪڏهن زمين جو اندريون تهه پاڻيءَ جي وهڪري ۾ رڪاوٽ بڻجي ٿو، جنهن جي نتيجي ۾ به سم ظاهر ٿئي ٿي.
* ٻوڏ واري طريقي سان فصلن کي پاڻي ڏيڻ دوران گهڻو پاڻي ڏيڻ جي ڪري به سم وڌي ٿي.

سم کان احتياط

* فصلن جي گُهرج مطابق مناسب پاڻي ڏجي.
* جَرَ جي پاڻيءَ کي اونهن ٽيوب ويلن هلائڻ ذريعي گهٽائجي.
* گهڻو پاڻي ڏني لوڙن کي ڳاري زمين اندر موڪلجي.
* سم وارن علائقن ۾ سم نالن جو بندوبست ڪجي.
* جپسم، تيزاب، نامياتي مادي وغيره جو استعمال.
* سم وارن علائقن ۾ ڪينالن کي پڪو ڪرڻ.

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Farmer Card Water Logging Urdu

آباد گار کارڈ

سیم ہونے کے سبب اور بچاو کے طریقے

ہیں

سیم ہونے کی وجہہ سے زمین کے اندر نمکیات /کلر اوپر چڑھ اتا ہے۔ جب زمین کی سطح تک سیم اجاتا ہے اور اوپر والا پانی دھوپ اور ھوا میں اڑنے لگتا ہے تو اس کے نتیجے میں نمکیات /کلر زمین کی سطح پر ظاھر ہوتا ہے۔

دریائے سندہ کے متاثرہ علاقوں میں آبپاشی والی زمینوں ، کاشتکاروں کے روزگار اور خاص طور پے چھوٹے کاشتکار کی پائداری میں سیم اور کلر سکیہ رکاوٹیں ہیں۔

سیم کی وجوہات

- سیم کی نکاسی کا مناسب ذریعا نہ ہونا، جس کی وجہ سے پانی زمین پے جمع ہوتا رہتا ہے اور سیم بڑہتا ہے
- کچے کینالوں میں سے پانی سیم ہوتا رہتا ہے اور کافی مقدار میں زمین کے اندر مسلسل جمع ہوتا رہتا ہے۔
- کبھی کبھی زمین کے اندرونی حصہ پانی کے بہاءو میں رکاوٹ بنتا ہے، جس وجھہ سے بھی سیم ظاہر ہوتا ہے۔
- سیلاب کی سورتحال میں زمینوں کو زیادہ پانی دےنے کی وجھہ سے بھی سیم بڑہتا ہے۔

سیم سے احطیاط

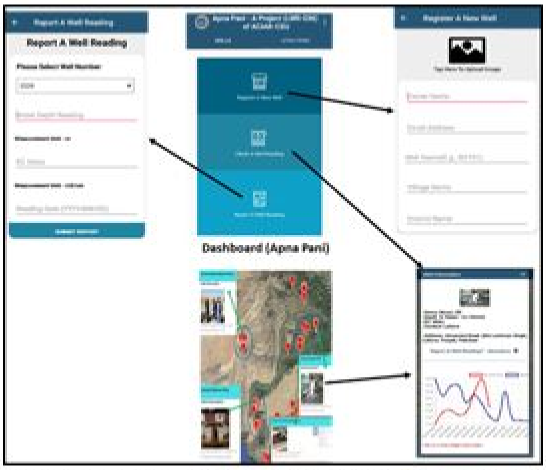
- کھیتوں کو ضرورت کے مطابق پانی دیا جائے۔
- سیم کے پانی کو گہرے ٹیوب ویل چلانے سے کم کیا جا سکتا ہے۔
- زیادہ پانی میں نمک پگلا کر زمین میں دیا جائے،
- سیم زدہ علاقے میں سیم نالوں کا مناسب بندوبست کیا جائے۔
- جپسم، تیزاب، نمباتی مادوں کا استعمال۔
- سیم زدہ علاقوں میں کینالوں کو پکا کیا جائے۔

Farmer Card Apna Pani /Apna Farm

Charles Sturt University

APNA PANI

ACIAR



Through this project, we are offering a mobile application Apna Pani with two modules (Wells and Apna Farm) and a web application to the stakeholder communities.

Web and mobile applications for Improving groundwater management to enhance agriculture and farming livelihoods in Pakistan- LWR-036

Charles Sturt University

APNA PANI

ACIAR

Record the well information (Owner Name, Location, and Custom name for each entry)

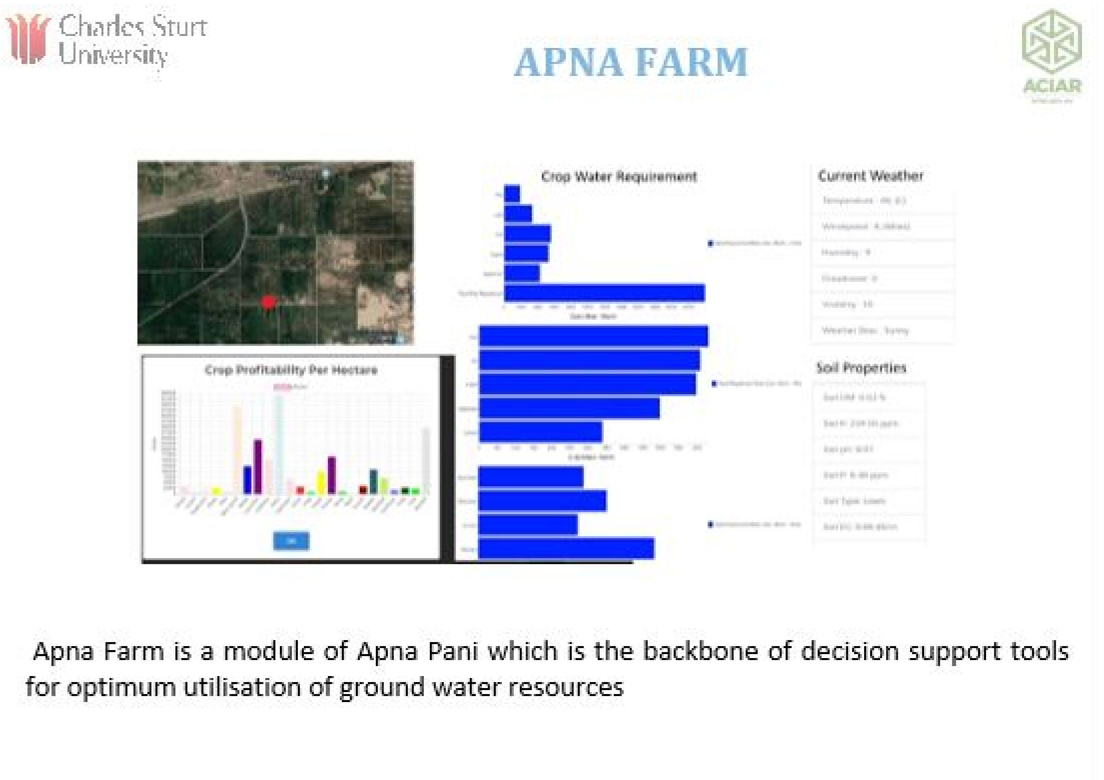
Report a well reading on daily basis, each of the reading will have well name or Well ID, EC or Depth to Water

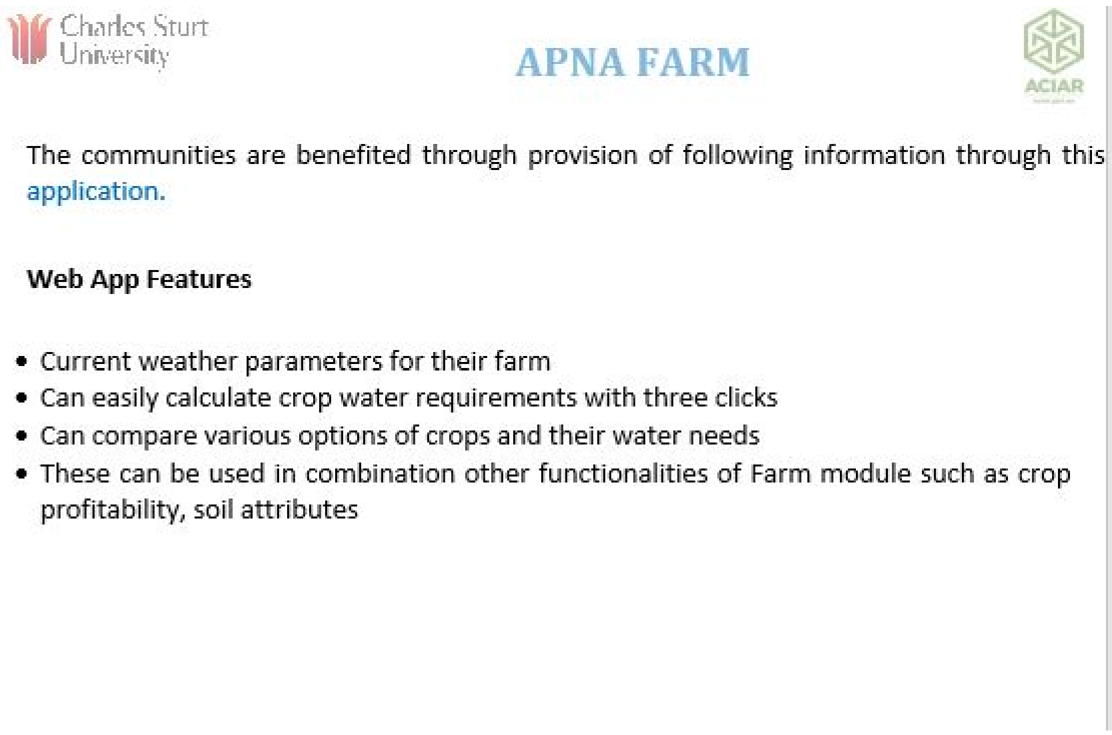
Check all the wells and their readings on graphs

Export data as CSV.

Import data from CSV.

Web and mobile applications for Improving groundwater management to enhance agriculture and farming livelihoods in Pakistan- LWR-036





The communities are benefited through provision of following information through this application.

Farmer Card RAPS

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FARMER CARD

RAPS - Punjab

RAPS (Representative Agricultural Pathways) undertaken in the stakeholder forums adopted three interventions with farmers in Sahiwal and Okara districts. These included:

- Promoting the cultivation of low delta crops
- Use of water saving technologies
- Improving soil health by using organic material

Promoting cultivation of low delta crops: To achieve these objectives, the team engaged with farmers in 11L to shift from high delta crops to low delta crops. Initially, smallholder farmers undertook trials for the following crops in 2020:

- 2 acres of sunflower crop
- 8 acres of mung bean

Both crops are being promoted by the Government of Pakistan because of the excessively high cost of imports associated with edible oil and pulses. The sunflower crop at vegetative growth stage and the crop stand was excellent. The mung bean crop had also grown very well and results were very encouraging. Replacing maize with mung beans saves 60-70 percent of water. The cost of production of mung beans is low while return on per rupee investment is 25% higher as compared to maize. It takes only 90 days to harvest and farmers are able sell the produce got money at the spot.

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In the next season trials were also undertaken for garlic which is a cash crop and also saves water. It requires 50% less water as compared to sugarcane. Garlic will also be planted in the coming season. Similarly sesame crop is being promoted, which requires only 3-4 irrigations and will be planted after wheat harvest.

Use of water saving technologies: Use of water saving methods such as bed and furrow cultivation was promoted for planting sunflower, mung bean and other low delta crops. Before planting these crops the land was laser levelled which decreases irrigation time and allows more even irrigation applications.

Improving soil health through the use of organic matter: Farmers in the stakeholder forum have agreed to adopt interventions that promote sustainable agriculture and to improve soil health by incorporating crop residues. Incorporating organic matter improves soil texture and soil fertility. This process begins after harvesting by using the stubble and residue as manure.

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Impact on livelihoods: The results of economic analysis confirmed that trials undertaken by farmers with sunflower, mung bean, and other low delta crops resulted in improved economic returns i.e. 33 % high net farm returns when wheat is replaced by sunflower and had a positive impact on poverty reduction i.e. 24 % reduction among small farmers.

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Farmer Cards Socioeconomics

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Low Delta crops

Each crop requires a certain amount of water after a certain fixed interval of time, throughout its period of growth. The depth of water required every time, generally varies from 5 to 10 cm depending upon the crop. The total depth of water (in cm) required by a crop to reach maturity is called its delta. Every crop requires a certain amount of water at certain intervals throughout its period of growth. The time interval between consecutive watering is called frequency of irrigation or Rotation period. The rotation period can also vary in the range of 6 to 15 days depending on the crop. In Pakistan, farmers are encouraged to grow low delta crops. In delta cropping system, soil salinity varies based on surface water quality, depth to and quality of the groundwater, irrigation methods and volume of rainfall

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Economic, technical and water use efficiency.

The growing imbalance between water supply and demand has already led to water shortages in Pakistan. The key issues faced in the Indus Basin include lack of equity in water distribution, deferred maintenance and low productivity. The economy and society of Pakistan is challenged by the crisis of governance, which is termed as a major obstacle to the attainment of broader objectives of sustainable development. Currently, only a small proportion of the surface run-off during the rainy season is harvested in dams and other mini-structures. The farmers should participate and play their role in operation and maintenance of irrigation and drainage networks to optimize returns from this scarce input. Necessary legislations have been issued in this context in each province. The representatives nominated at watercourse level shall represent their respective areas to ensure efficient use of water.

Economics of Sunflower and Moong beans

The common sunflower and moong beans are highly valuable from an economic point of view. The sunflower leaves are used as fodder, the flower yield a yellow dye, and the seeds contain oil and are used in food. Some sunflower species are cultivated as ornamentals for their spectacular size and flower heads, and for their edible seeds. The sweet yellow oil obtained by the compression of seeds is considered equal to olive and almond oil. Sunflower oil cake is used for stock and poultry feeding. This oil is also used in soap, paints and as lubricants. The seeds maybe eaten dried, roasted or ground into nut butter and are common in birdseed mixes.

Moong bean is an important pulse and is consumed all over the world. A moong bean is a short duration crop; it can fit in as a cash crop between major cropping seasons. It provides grain for human consumption and as well as the plant fix nitrogen to the soil. Moong bean is gaining popularity among framers for cultivation. Moong bean farmer receives high return on its investment. The co-efficient of farmer education and experience have significant positive effect on efficiency of moong bean.

Water productivity of major crops

Crop water productivity is a quantitative term used to define the relationship between crop produced and the amount of water involved in crop production. It is a useful indicator for quantifying the impact of irrigation scheduling decisions with regard to water management. Crop water productivity were computed in terms of crop water use, water applied, and economic returns. Bed planting and drip irrigation, being a proven technology that can increase crop yields and save irrigation water to improve water productivity. Three major crops including wheat, cotton and rice in cropping has been grown indifferent zones of Punjab. Wheat sown on bed has shown significant better results. Cotton also showed significantly better performance, when compared with conventional sowing. Moreover, bed planting produced more rice grains. The key principles for improving water productivity at field, farm and basin level, which apply regardless of whether the crop is grown under rain fed or irrigated conditions, are:

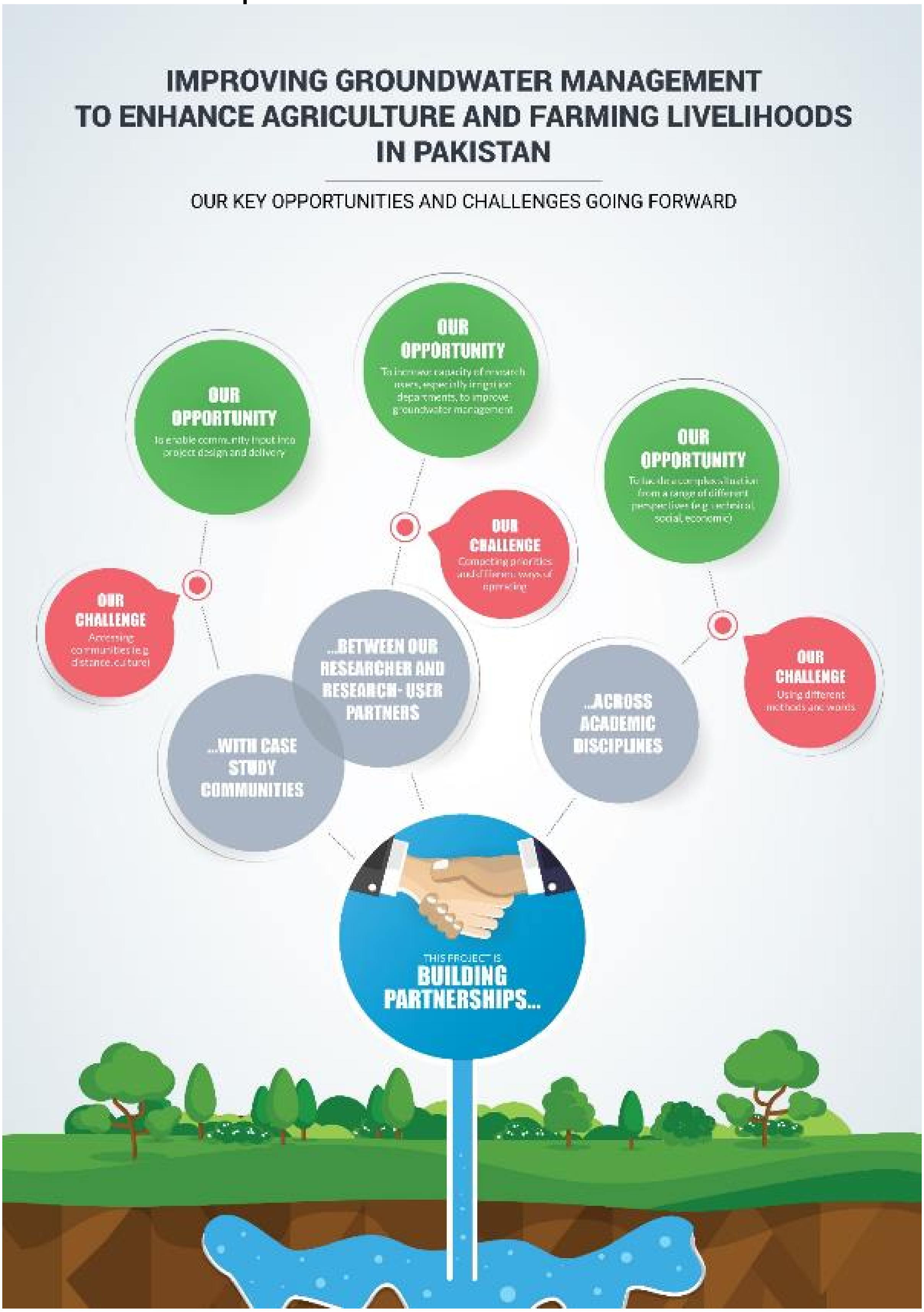
(i) Increase the marketable yield of the crop for each unit of water transpired by it;
(ii) Reduce all outflows (e.g. drainage, seepage and percolation), including evaporative outflows other than the crop stomata transpiration; and
(iii) Increase the effective use of rainfall, stored water, and water of marginal quality

Socio-economic factors affecting GW management

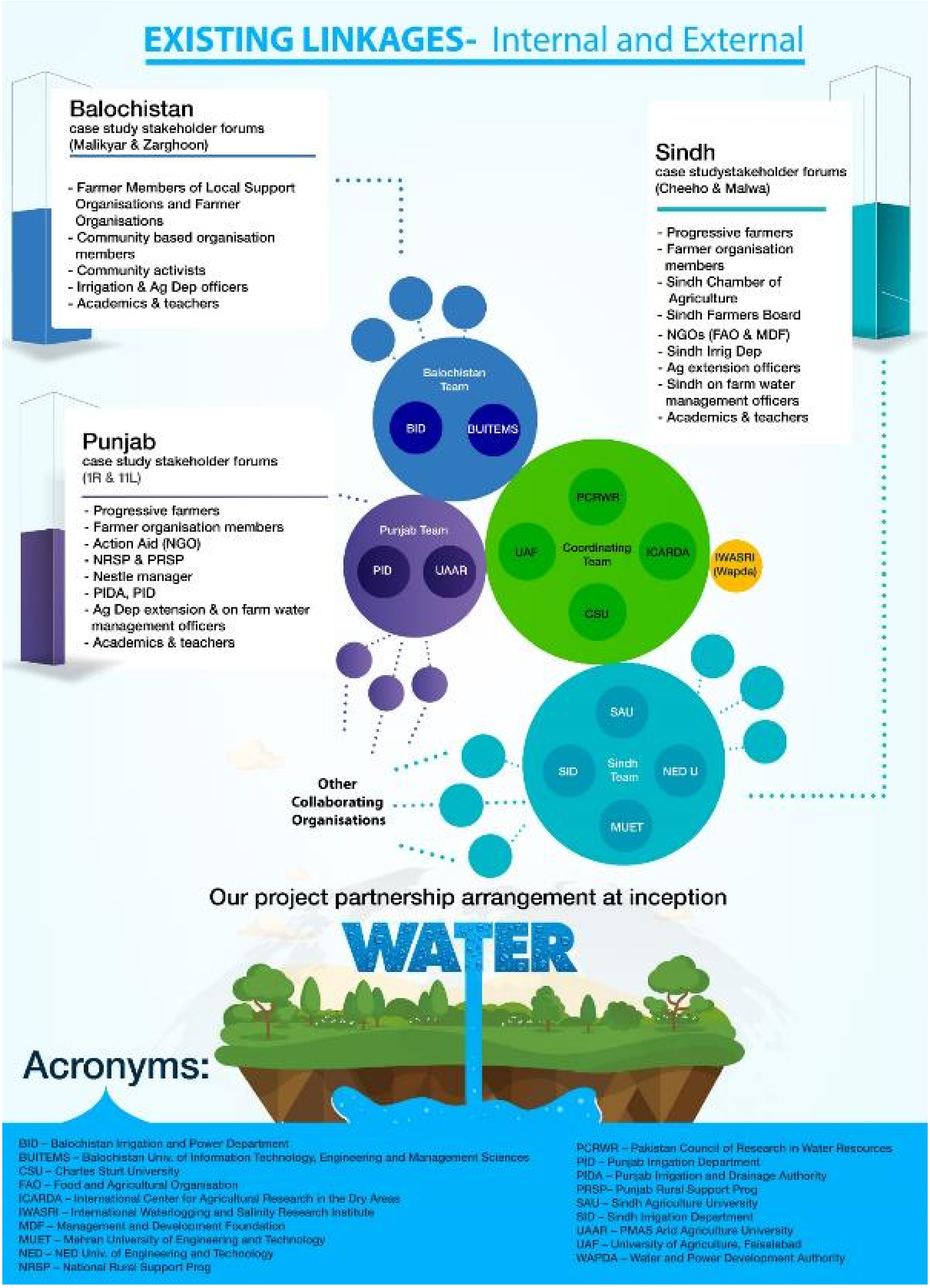
Groundwater has gradually acquired a vital role in the development of agricultural and rural economy in Pakistan. Excessive lowering of the water tables is making the pumping more expensive and wells are going out of production. Lack of information on groundwater use and its socio-economic and ecological impacts is one of the main issue regarding groundwater management. More than 60 percent farmers in Punjab use groundwater as a supplemental source to augment canal water supplies. This clearly indicates that without groundwater availability not only Punjab but also the entire country could face serious food shortages

Posters

Poster 1 - Partnerships



Poster 2 – Linkages and Stakeholder Forums



Poster 3 – photo exhibition

COLLABORATING TO STRENGTHEN RESEARCH

Setting up the new groundwater modelling data loggers in the field is Dr Jay Punthakey (CSU) with Naveed Iqbal (PCRWR); Saleem Akhtar (PID) and Khuram Ejaz (PCRWR). The data logger is being set up in the grounds of a boys' school in the Punjab 11L case study.

The Malwa distributary case study community, including progressive farmer Nazo Dharejo (second from right), discussing data loggers to be set up in their area with the Sindh groundwater modelling team

LISTENING

Listening to farmer, and husband of Nazo Dharejo (Malwa distributary case study, Nawabshah District, Sindh), are Dr Jay Punthakey and members of the Sindh groundwater modelling team.

As part of all of our participatory rural appraisals with potential case study communities, we arranged separate sessions to listen to and learn from women and their families.

SUSTAINING THROUGH PARTNERSHIP

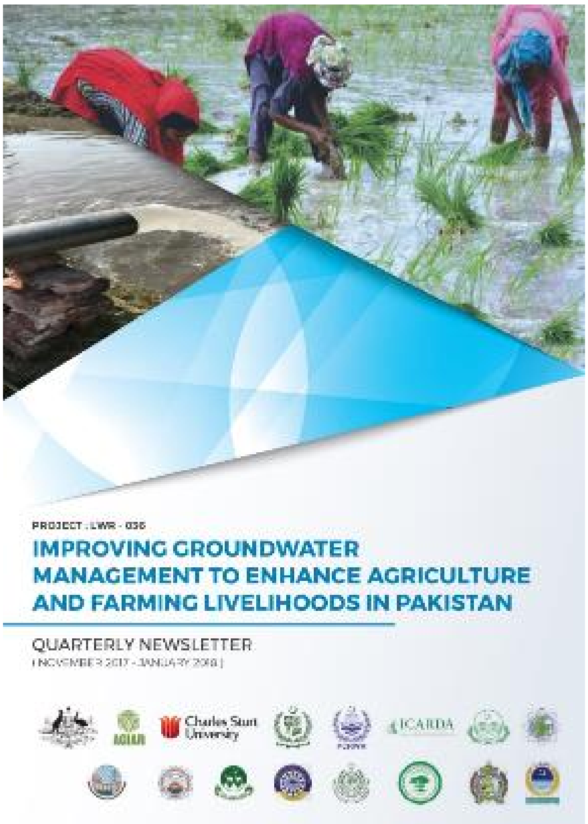
Our Balochistan team members interacting with community stakeholders to establish partnership arrangements

Helping to provide GIS training to Abdur Razzaq Khilji (BID, far left) is Kanza Javed (PCRWR) with Farooq Ahmed and Muhammad Syed in the background. As a result of this sharing of expertise, Khilji was proud to announce he had produced his own maps for his reports.

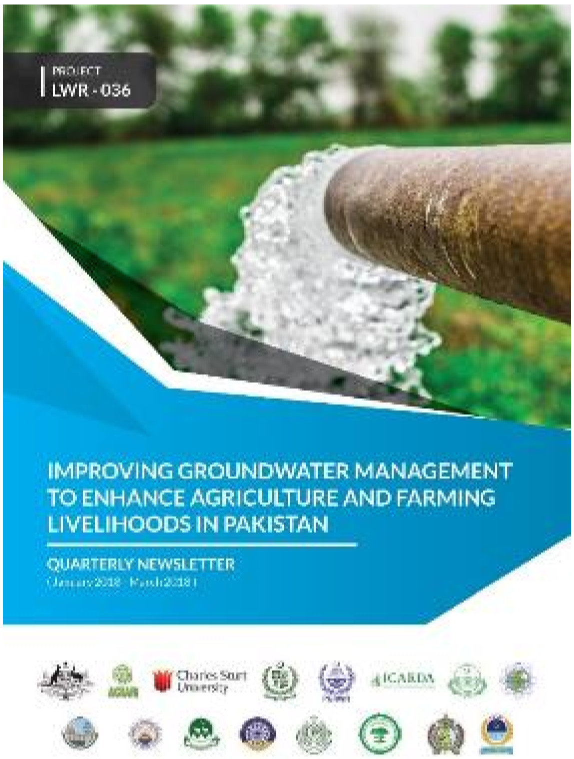
Poster 4 Collaborating to Strengthen Research

Newsletters

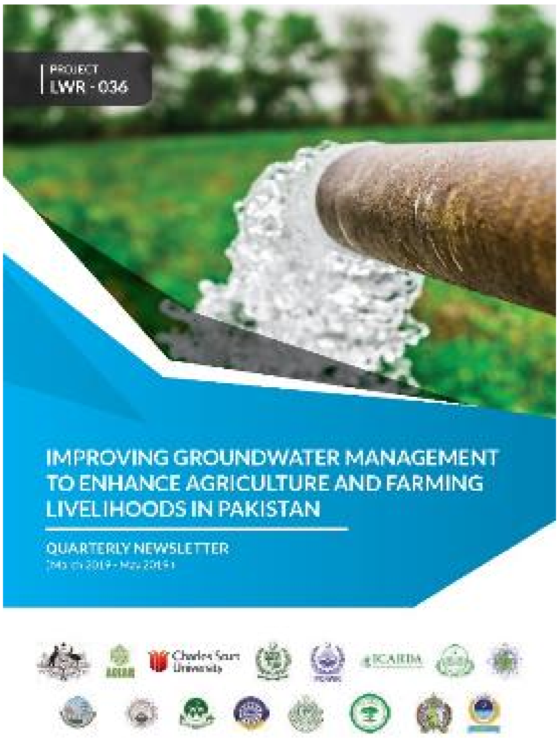
Newsletter No 1 – November 2017 – January 2018



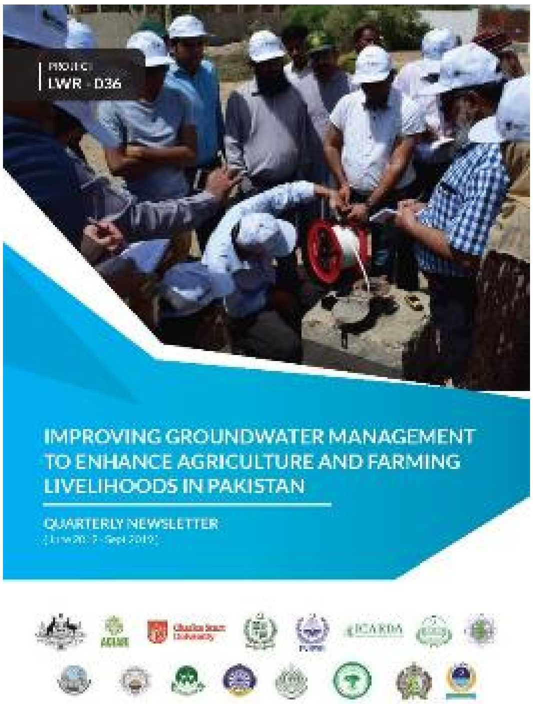
Newsletter No2 – January 2018 – March 2018



[Newsletter No3 – March 2019 - May 2019]



[Newsletter No 4 June 2019 – September 2019]



Videos

https://youtu.be/kPf_DZ183M8

https://youtu.be/mavUzjQ1zwo

Videos – Apna Pani and Apna Farm

News broadcast and farmer interviews on the Apna Pani and Apna Farm Training Session for Farmers and Youth Community at 11.L Chicawatni on 5 -6 August 2020. This training was conducted as part of the LWR-036 - Improving Groundwater Management to Enhance Agriculture and Farming Livelihoods in Pakistan.

https://youtu.be/Ipq4rx4zytk

Farmer interviews

https://youtu.be/4LO8XHm7rUg

https://youtu.be/d19SOSMAyPk

https://youtu.be/A1ATjTrXkfE

https://youtu.be/2ZeyQ9LztV8

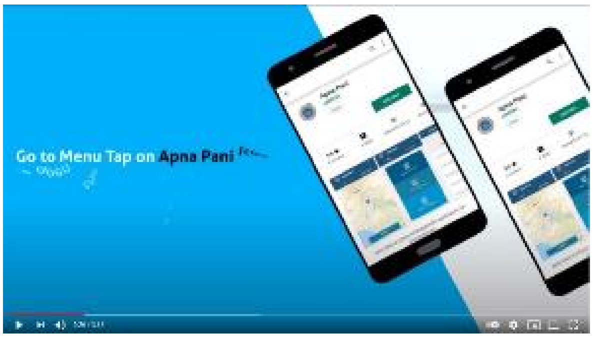
https://youtu.be/vHgz_4KCUt4

https://youtu.be/4ulnkI7o6mU

Mehran TV news story on Dr Tehmina Mangan and the Groundwater Stakeholder Workshop April 5, 2021

https://youtu.be/XJhHYFFumZk

Apna Pani App instructions- English version



https://youtu.be/I8Tb3FMc33Y

Apna Pani App instructions - Urdu Version

https://youtu.be/N9c8vLMRyJ0

SBS Urdu Australian TV News story

09/07/2019

"Water is not a free resource" – Pakistan water researchers aim to implement learnings from Australia back home

https://www.sbs.com.au/language/english/water-is-not-a-free-resource-pakistan-water-researchers-aim-to-implement-learnings-from-australia-back-home

SBS News story Urdu Radio

26/08/2020

https://www.sbs.com.au/language/english/terrific-tool-the-australian-app-that-could-be-a-game-changer-for-farmers-in-pakistan