Charles Sturt University

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Agriculture Water Environment

Assessing Groundwater Monitoring in the Southern Bari Doab and Guidance for Strengthening Groundwater Monitoring across Punjab

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Disclaimer

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Executive Summary

In many arid to semi-arid regions of the world, groundwater is regarded as one of the most significant yet limited natural resources. About 43% of the world's agricultural water requirements and 50% of drinking water needs are supplied by groundwater (FAO, 2022). Shortfalls in surface water supplies are driven by population pressures, increasing competition from different water user sectors, and a changing climate. Additionally, the drive for higher cropping intensity has largely driven irrigators to increase their reliance on groundwater to supplement surface water supplies, leading to over-extraction of groundwater resources in parts of the Southern Indus Basin. To improve our understanding of the resource, monitoring groundwater levels and quality is critical in selecting cropping patterns, drainage system design, and other agro-management practices, and gauging the impact of fertilisers and pesticides on groundwater resources. Understanding groundwater in Southern Punjab and the Indus Basin requires both spatial and temporal data on groundwater levels and water quality. Moreover, groundwater resource assessment also requires data on aquifer geometry, hydraulic properties, climate, the river and canal network, and a good knowledge of spatial and temporal pumping patterns. These data are also a rich source for developing groundwater models. Although groundwater models can and are being developed for parts of the Indus Basin, a major improvement in data quality and strategic data collection is required to develop robust models for informed decisions on planning and managing the water resource. As part of the Adapting to Salinity in the Southern Indus Basin (ASSIB) project, significant effort is being expended on developing a groundwater model covering a selected sub-region in Southern Punjab. The groundwater model covers the districts of Multan, Khanewal, Lodhran, and the lower part of Vehari, where groundwater depletion and water quality concerns are significant issues. The project aims to understand trends impacting groundwater resource availability, quantify the water balance, and undertake scenarios to assess the risk to groundwater of increasing extractions that are causing declines in groundwater over the long-term. This report provides a brief assessment of the monitoring program undertaken by the Water Resources Zone of the Punjab Irrigation Department (PID) and provides guidance for improving the monitoring of water resources.

A total of 281 observation wells have been installed by the PID. They monitor groundwater levels twice in a year during the pre- and post-monsoon seasons. Of the 281 wells, 239 were active, while 42 have been defective or inactive for the past three to seven seasons. A total of 104 observation wells were used during the analysis and they had reasonable temporal groundwater level data from 2010 to 2020. Groundwater monitoring and spatio-temporal trends in depth to water (DTW) were measured for the pre- and post-seasons of 2010, 2015, and 2020. ArcGIS was used to interpolate the DTW and estimate temporal changes in DTW. The results showed that DTW in the study area ranged from 4 m to 24 m. Shallow DTW was observed along the River Ravi and River Chenab, while high DTW was observed in Lodhran and some parts of Jalalpur, Khanewal, and Mailsi. This is to be expected as the Chenab River is the main source of surface water supplies for Southern Punjab. The groundwater levels in most parts of the study area were deeper than those in 2015. The abrupt change in DTW in 2010 was due to flooding from late July to August. Groundwater levels in most of the study area declined in 2020 compared to 2015, indicating that pumping stresses were increasing. The analysis from 2010 to 2020 showed that DTW increased in all the districts of the study area except Lodhran, where water levels rose by up to 1.6m. Our analysis showed that 58 observation wells are in areas where the rate of increase in DTW is relatively high. These observation wells are in the Jahanian, Duniapur, Mailsi, Multan, Shujabad, and Jalalpur sub-districts.

Groundwater quality in most parts of the study area is in the fresh (<0.7 dS/cm) to marginally fresh (0.7-3 dS/cm) water classes for irrigation purposes. The areas with hazardous water quality (> 3 dS/cm) were scattered. Temporal trends indicate that the area of marginal quality class increased by 7.3% in 2019 compared to 2015. Based on our analysis, we recommend existing observation wells, particularly those in critical zones where groundwater levels are depleting at a significantly high rate and in the areas where EC values are high, be fitted with CTD loggers (conductivity, temperature and depth). CTD loggers will also provide the PID with information on seasonal trends and help it develop guidelines for managing resource depletion in hotspots.

Contents

Figures

Tables

Abbreviations

ACIAR	Australian Centre for International Agricultural Research
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTD	Conductivity, Temperature and Depth (a type of logger)
DTW	Depth to Watertable
EC	Electrical conductivity (1 mS/cm= 1dS/m = 1000 µS/cm = 640 mg/l)
GWL	Groundwater Level
LBDC	Lower Bari Doab Canal
NWP	National Water Policy
PID	Punjab Irrigation Department
PWP	Punjab Water Policy
SCARP	Salinity Control and Reclamation Project

1. Introduction

Pakistan presently faces tremendous groundwater management issues as it battles to provide food security to its rapidly expanding population and manage competition for water for industry, domestic and agriculture. Pakistan must also allocate sufficient water to meet environmental requirements and maintain ecosystem functions. To adopt an integrated approach to improve water resources management, systematic monitoring of groundwater resources will play a vital role. Groundwater monitoring is essential for site investigation, risk assessment, remediation, and resource management. It offers vital data for monitoring groundwater levels and water quality dynamics specific to each site. An analysis of the present groundwater monitoring network for a selected area in the Southern Bari Doab covering the districts of Vehari, Lodhran, Multan, and Khanewal was conducted for the Adapting to Salinity in the Southern Indus Basin (ASSIB) project, which is funded by the Australian Centre for International Agricultural Research (ACIAR) and Charles Sturt University (CSU). The report is based on existing observation wells installed by the Punjab Irrigation Department (PID) in a part of Southern Punjab within the alluvium of the Indus Basin Irrigation System. The groundwater analysis focused on the depth to watertable (DTW) for the pre- and post-monsoon seasons of 2010 and 2015, as well as the pre-monsoon season of 2020. This period was selected as the project aims to develop a groundwater model using data from 2010 to 2020 and provide improved insights into the monitoring data available for model development.

1.1. Aims and Objectives

The report aims to analyse the current monitoring network installed by the Punjab Irrigation Department for a selected region of Southern Punjab. This will include an analysis of temporal variations in depth to watertable (DTW) for the pre- and post-monsoon seasons of 2010 and 2015, and pre-2020, and electrical conductivity levels for 2010, 2015, and 2019.

The analysis of water levels and water quality data from the existing network can guide some recommendations related to site-specific monitoring of observation wells. This can provide a helpful platform for improved groundwater monitoring in terms of recording water levels, water quality, and pumping wells. Selected results from the groundwater modelling study are also used for improved planning and management of groundwater data sources.

1.2. Study Area

The study area covers the southern-most part of the Bari Doab between the tail end of the Ravi River, the Chenab River in the north, and the Sutlej River along the southeast, containing four administrative districts – Multan, Khanewal, Lodhran, and Vehari. The total area under study is about 11,348 km^2. The area comprises a network of main, branch, and link canals, as shown in Figure 1. Shuttle Radar Topography Mission (SRTM) data show a flat area with a normal slope. The elevation ranges from 99 m (southwest) to 156 m (northeast) above mean sea level (m-amsl). The historical meteorological record shows that the area is in a semi-arid climate zone with an annual average rainfall of less than 250 mm/year. Because of the non-perennial canal supply system in some of the canals under the Southern Bari Doab Canal command, farmers must rely upon groundwater irrigation to fulfil their agricultural water demands. There are generally two cropping seasons in the area – Rabi (April–September) and Kharif (October–March). Wheat is the major Rabi crop, while maize, rice, and cotton are the main Kharif crops. Sugarcane is also grown as an annual crop in some areas.

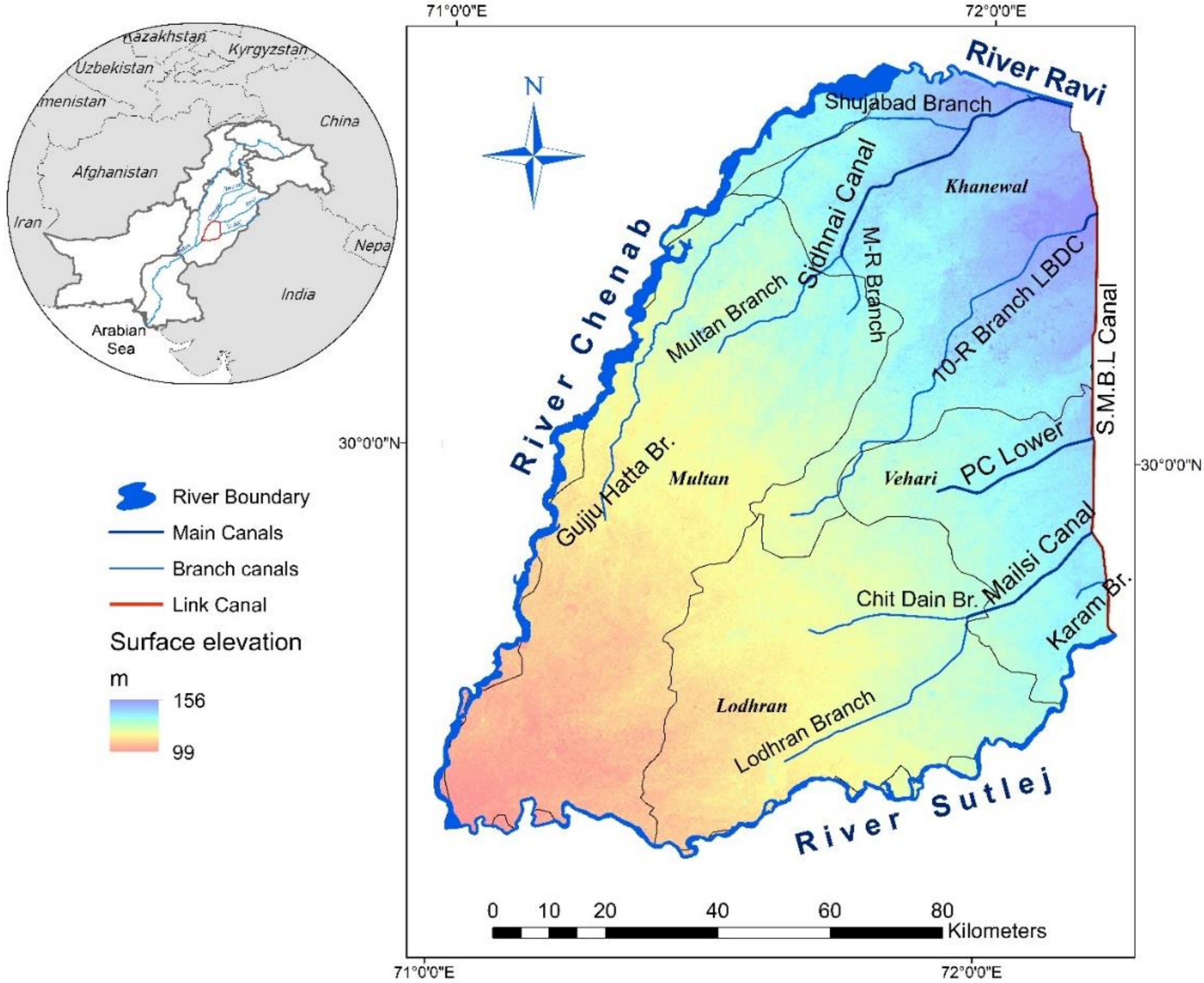


Figure 1. Southern part of Bari Doab with physiological features

2. Groundwater Monitoring Policy and Guidance

2.1. National and Punjab Water Policies

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

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

i. Aquifers are an important national resource that merits protection from pollution and unsustainable abstractions. The Indus Basin aquifer is particularly important. The NWP recognises that protecting aquifers is challenging and will require extensive knowledge transfer to groundwater users.

ii. The NWP stresses strengthening monitoring systems to determine sustainable groundwater potential and prepare groundwater budgets for sub-basins and canal commands. It emphasises measures to prevent lateral/vertical movements of saline waters into freshwater zones and advises provincial governments to enforce legislation and take regulatory measures.

iii. The policy supports the adoption of technologies for sustainable extraction of groundwater from shallow freshwater lenses overlying saline water using skimming wells.

iv. The policy recommends the transition of remaining SCARP tubewells in the public sector to the private sector, leaving the development of fresh groundwater entirely to the private sector as a local resource. However, the policy on local groundwater management is unclear, other than urging enforcement and regulatory measures to limit extractions.

v. A significant thrust of the NWP is on enhancing artificial recharge schemes where technically and economically feasible, along with priority investment for groundwater recharge schemes.

vi. The policy states that abstractions from the aquifer shall be managed sustainably to balance recharge and boundary flows, but it lacks guidance on how this is to be achieved, leaving it to provincial departments to effect change.

vii. The NWP advises that secondary salinisation due to indiscriminate groundwater abstraction shall be avoided by controlling or restricting pumping by enforcing a strict regulatory framework. However, it does not provide a framework for how 1.4 million tubewells can be regulated or how to implement regulatory measures.

viii. Protecting water resources, lakes, rivers, canals, and groundwater from pollution is a national priority.

Groundwater directives include the creation of groundwater management planning and regulatory zones. The NWP advocates a range of groundwater priorities, the first two relating to education (recognising groundwater as a resource) and monitoring. Points iii, iv, and v are focused on supply options. The NWP recommends managing the groundwater table so that it does not adversely affect crop growth or increase the risk of soil salinity and saltwater intrusion. The last two points will be difficult to implement where groundwater use is high and aquifers are showing signs of stress without significant investment in adaptation options. A regulatory framework in itself will be challenging to implement, with over 1.2 million tubewells in Punjab, and we foresee the need for a dedicated stakeholder engagement process to improve knowledge of groundwater irrigators and allow irrigators to have a voice in managing the resource.

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

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

***Punjab Water Policy*:** The Punjab Water Policy (2018) provides policy direction for the sustainable management and development of water from all sources (surface water, groundwater, and rainwater) and all sub-sectors of water use (domestic, stock water, agriculture, industry, commercial, and the environment).

The Punjab Water Policy (PWP) recognises the lack of an integrated database for water and the environment, water balance, and simulation models, the use of which could help resolve water allocation and equity issues. The PWP emphasises demand management and the adoption of remote sensing, GIS, internet, and mobile technologies.

The PWP also calls for the building of extensive knowledge databases to monitor equitable water distribution from head to tail, crop monitoring, reallocation, trading, and groundwater monitoring.

- The PWP is determined to increase surface water availability by building storage structures, including structures that store excess water during wet months, transfer excess water to water-scarce areas, and mitigate the impact of flash floods. It also focuses on the reallocation of water among different sectors and the reuse of wastewater after treatment.
- To ensure sustainable groundwater abstraction, the PWP recommends mapping and monitoring the groundwater resources as well as controlling over-abstraction in critical zones in Punjab where water levels are depleting at a significant rate. It also recommends the establishment of a Water Resources Commission that will be responsible for allocating and managing water resources.
- Domestic and industrial effluent is generally disposed of in ponds, open water channels, canals, and rivers. It seeps into the surficial aquifer and contaminates the groundwater. The extensive use of fertilisers and the application of brackish water in some areas of Punjab also affect water quality. The PWP recommends enforcing regulations in collaboration with the Environmental Protection Agency to monitor the use of fertilisers and prevent saltwater intrusion into freshwater zones.
- To manage the projected impacts of climate change on water resources, the development of large storages is recommended to provide a safety factor to cope with floods and droughts.
- Waterlogging, soil salinity, deforestation, and soil conservation are the key factors affecting land resources. Integrated management is essential for optimising water and land resources for agriculture and other uses.
- For better water and food demand management, the PWP recommends the urgency of key measures, including population rate control, increasing water productivity, adapting efficient irrigation systems, strategically revising cropping patterns, and researching the water-food-energy nexus.
- To improve water governance, the PWP advises ease of access to information related to surface and groundwater resources for water users. This plays a significant role in raising awareness, which can lead to improved water resource management at the farm level.
- Several departments have a role in land and water development and management, but coordinated action is lacking. The PWP reforms are needed to improve the planning, development, and management of water resources.

3. Methodology

The analysis was conducted on observed water levels recorded by the Punjab Irrigation Department and freely available to download from the PID website. The sorting of active and inactive observation wells was undertaken and wells with no data for the past three to six seasons (pre- and post-monsoon) were discarded. To calculate the spatio-temporal change in groundwater levels (GWL) and depth to watertable (DTW), inverse distance weighting using the ArcGIS tool was used for interpolation. Changes in DTW were determined between the pre-monsoon and post-monsoon seasons of 2010 and 2015 and the pre-monsoon season of 2020. Also, the electrical conductivity for water quality maps were created using the ArcGIS tool for pre-2015 and pre-2019.

4. Results

4.1. Active/Inactive Observation Wells

The Punjab Irrigation Department (PID) has installed about 3300 monitoring wells covering the alluvial aquifer in Punjab. The monitoring and maintenance of these observation wells is undertaken by teams of gauge readers during the pre- and post-monsoon periods. A total of 281 observation wells are in the area under study. The monitoring of depth to water was undertaken in 239 active piezometers. The remaining 42 were defective or inactive during pre-monsoon 2010 and 2020 (Figure 2). Some of the observation wells showed null readings in some years and, after that period, restarted recording water levels. Groundwater levels are monitored twice yearly – before and after the monsoon season. Details of active and inactive monitoring wells are shown in Appendix A.

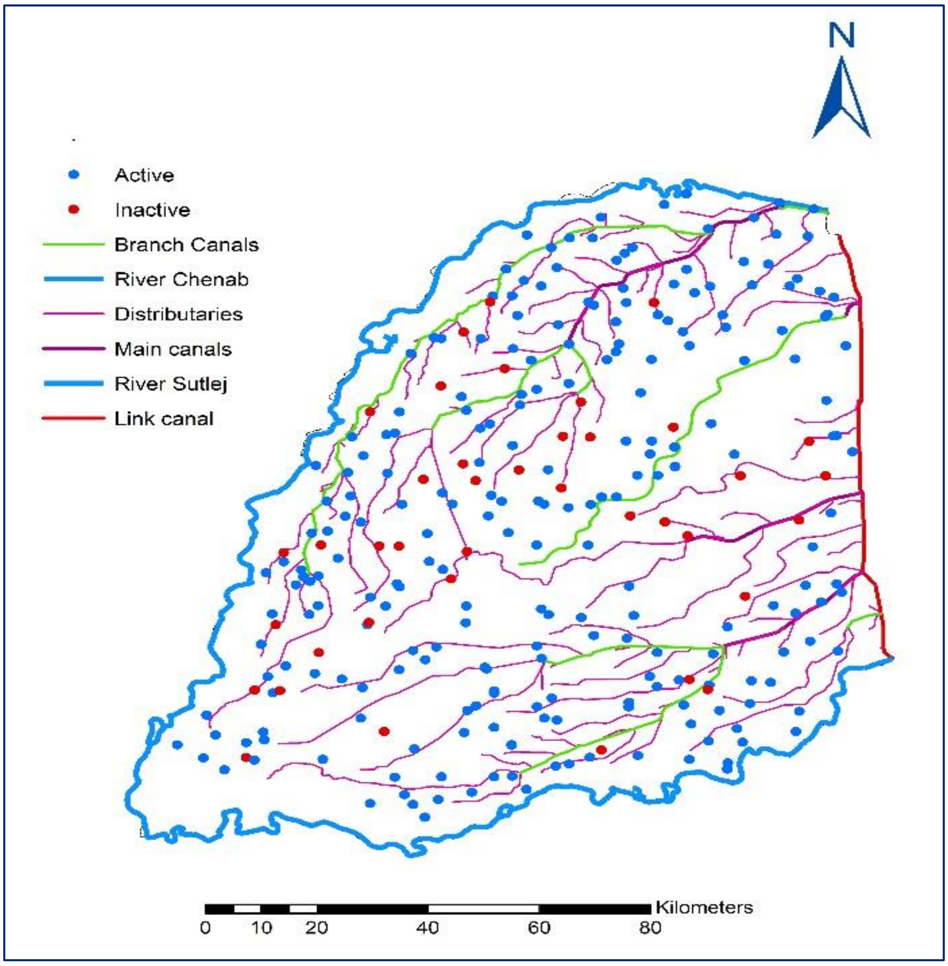
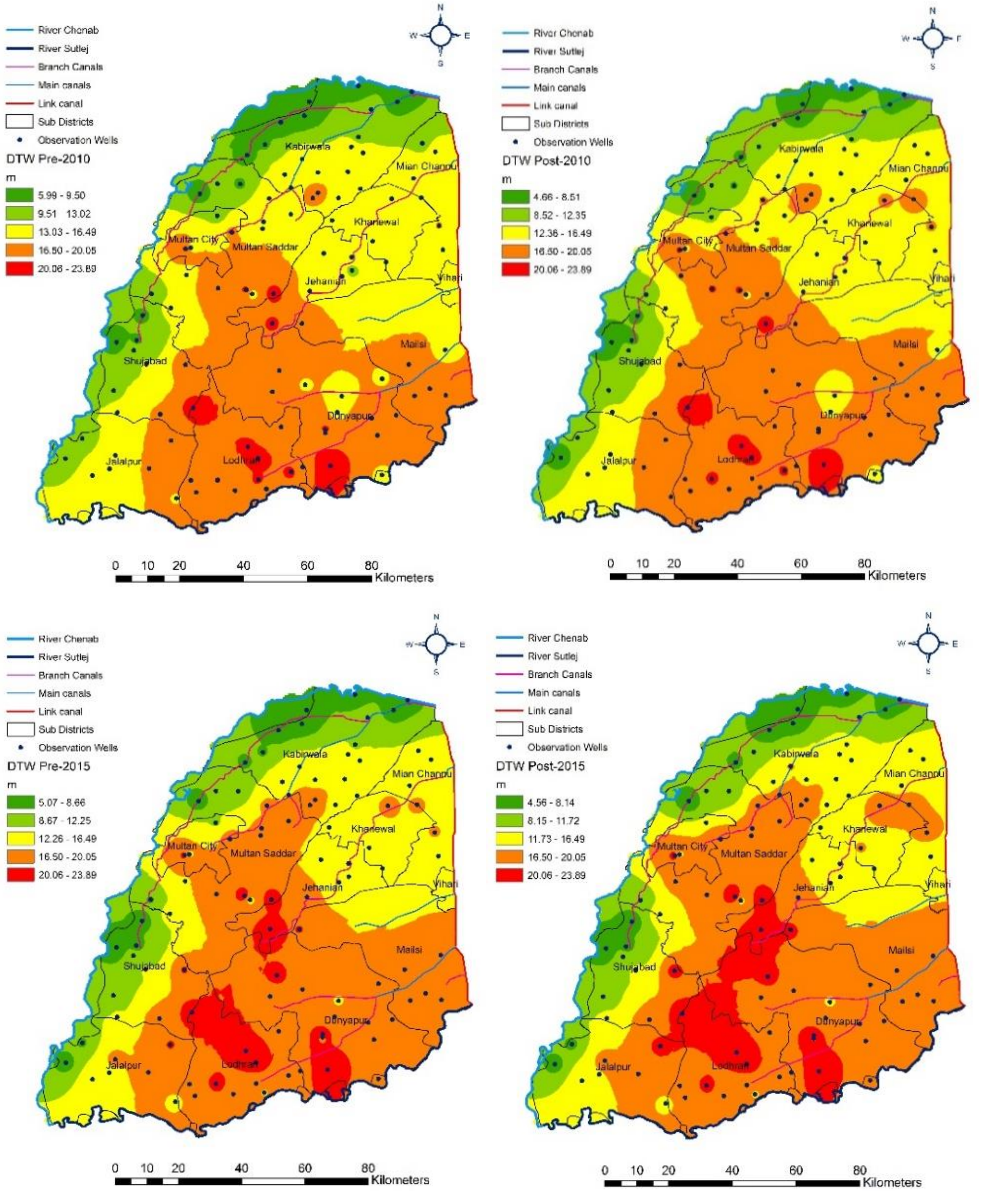


Figure 2. Location of active and inactive observation wells in the study area

4.2. Analysis of Temporal Variation in DTW

In pre- and post-2015, DTW ranged between 4.56 m and 12.25 m. Along the Ravi and Chenab Rivers, the areas represented with dark and light green are where water levels are relatively close to the surface. Areas where DTW ranges between 12.26 m and 16.49 m are represented by yellow, and the areas where DTW is relatively high are represented by brown and red. These areas are typically found around Jahanian, Duniapur, Lodhran, and Mailsi sub-districts.

During pre-2020, the change in DTW, represented by dark and light green, ranges between 5.6 m and 14.2 m, mostly along the Ravi and Chenab Rivers. The DTW ranges from 14.2 m to 16.8 m, represented by yellow, and covers the northeast and a section between the areas where DTW is shallow (dark green, along the Chenab River) and where it is relatively deep (brown). Also, the area with high DTW, represented by brown and red, increased in parts of the Multan, Jahanian, Duniapur, Lodhran, and Mailsi sub-districts (Figure 3). These are areas where groundwater stresses are increasing due to declining water levels.



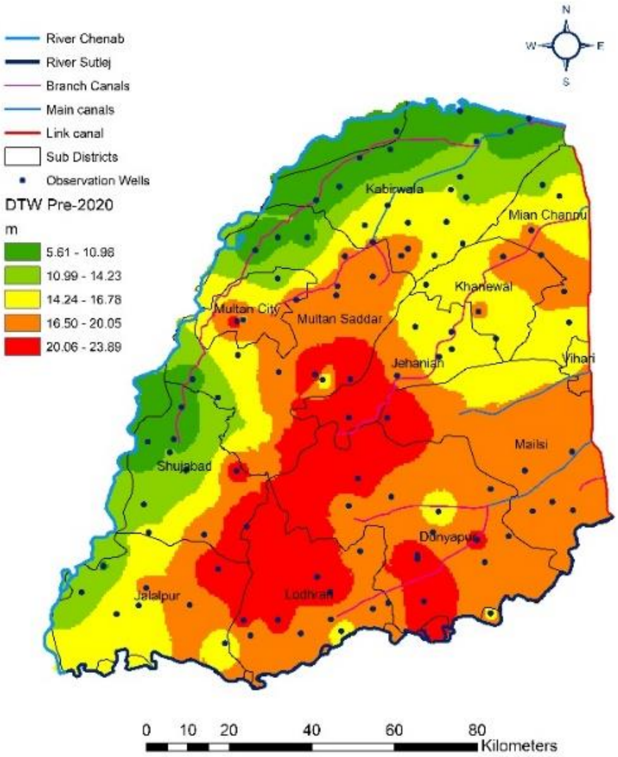


Figure 3. Spatio-temporal variation in DTW for pre and post 2010, 2015 and 2020

4.3. Spatio-temporal Change in DTW under Different Classes (Pre-2010 to Pre-2015)

Analyses of DTW level changes are shown in Figures 4 to 7, where negative values indicate areas where water levels have risen, and positive values represent a decline in water levels. We found DTW levels had increased by >1 m along the Ravi and Chenab Rivers, which is represented by dark green in Figure 4. Faded green areas show where water levels have risen by 0.88 m to 1 m, which extended for some distance along the Ravi and Chenab Rivers. Areas in yellow show where water levels have risen by 0.1–0.89 m; they are largely confined to the northeast and surround the areas where water levels have declined. The brown areas are where water levels have declined by 0.1–0.27 m, and the red areas are where water levels have declined by more than 0.28 m (Figure 4). The areas where water levels declined between 2010 and 2015 increased significantly from 4,864 to 6,051 km^2 (Table 1). A major reason behind the adoption of only two classes (Class 4 and 5) is that the focus of the report is to highlight areas where DTW is increasing.

Table 1. Percent DTW area change during 2010, 2015 and 2020

Class	1990 area (%)	2000 area (%)	2010 area (%)	2020 area (%)
1	-1	25	83	80
2	-2	-16	-14	-16
3	-24	-28	-17	-37
4	15	10	-18	-5
5	143	269	149	508

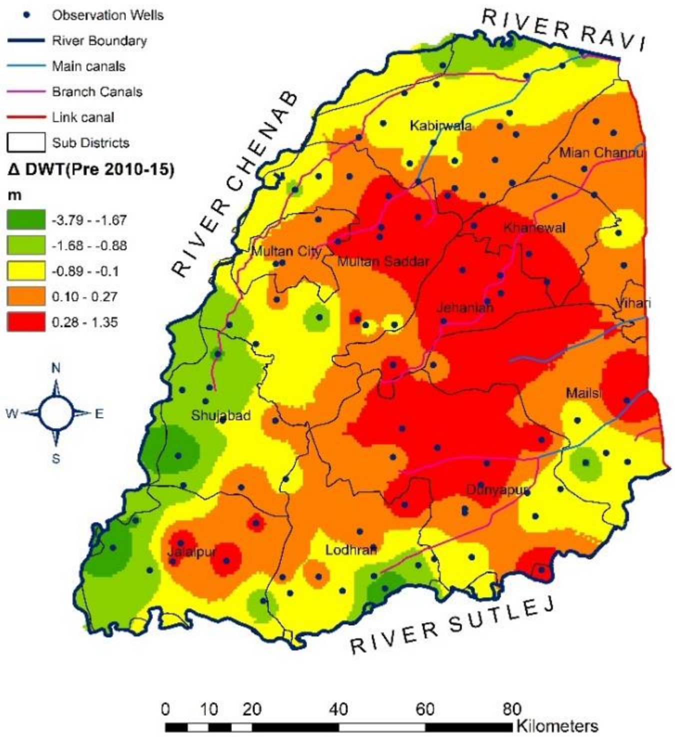


Figure 4. Spatio-temporal change in DTW (pre-2010 to pre-2015)

4.4. Spatio-temporal Change in DTW (Post-2010 to Post-2015)

From post-2010 to post-2015, the DTW decreased by more than 1.3 m in the areas represented by dark green. Faded green represents the area where the DTW decreased, ranging from 0.62 to 1.3 m. The decline in DTW, representing a rise in river water levels, may be due to the heavy floods during the 2010 monsoon. Areas represented by yellow show a decrease in DTW ranges (0.1–0.63 m). Also, increasing DTW ranging from 0.1 to 0.42 m was represented with brown, while DTW increased by more than 0.43 m in the area represented by red (Figure 5). The area under high DTW (Class 4 and 5) was 4,942 km^2 and 312 km^2 in post-2010. This increased to 5,479 km^2 and 1,152 km^2 post-2015. The area under high DTW (Class 4 and 5) increased by 11% and 269%, respectively (Table 1).

4.5. Spatio-temporal Change in DTW (Pre-2015 to Pre-2020)

From pre-2015 to pre-2020, the DTW decreased by 0.1 m in the pockets represented by dark green. An increase in the DTW was observed in most parts of the study area, ranging from 0.1 m to 0.9 m and represented by light green. The area in yellow represents an increase in DTW ranging from 0.92 m to 1.55 m. Also, a significant increase in DTW was observed, ranging from 1.56 m to 2.52 m, and greater than 2.53 m in the areas represented by brown and red, respectively (Figure 6). The area under high DTW Class 4 was 5,246 km^2, which decreased to 4,298 km^2 (an 18% decline in area), while the area under Class 5 was 806 km^2 in pre-2015 and increased to 2,011 km^2 during pre-2015 (a 149% rise in area).

4.6. Spatio-temporal Change in DTW (Pre-2010 to Pre-2020)

From pre-2010 to pre-2020, water levels rose by more than 0.91 m along the middle reach of the Sutlej River, represented by the dark green in Figure 7. The faded green represents the area where the water level rose between 0.92 m and 0.1 m along parts of the Ravi, Chenab and Sutlej Rivers. A rise in water levels from 0.1 m to 0.74 m was observed, represented by yellow. Also, a significant decrease in water levels was observed, ranging from 0.75 to 1.51 m, and more than 1.52 m represented in Figure 7 by brown and red, respectively.

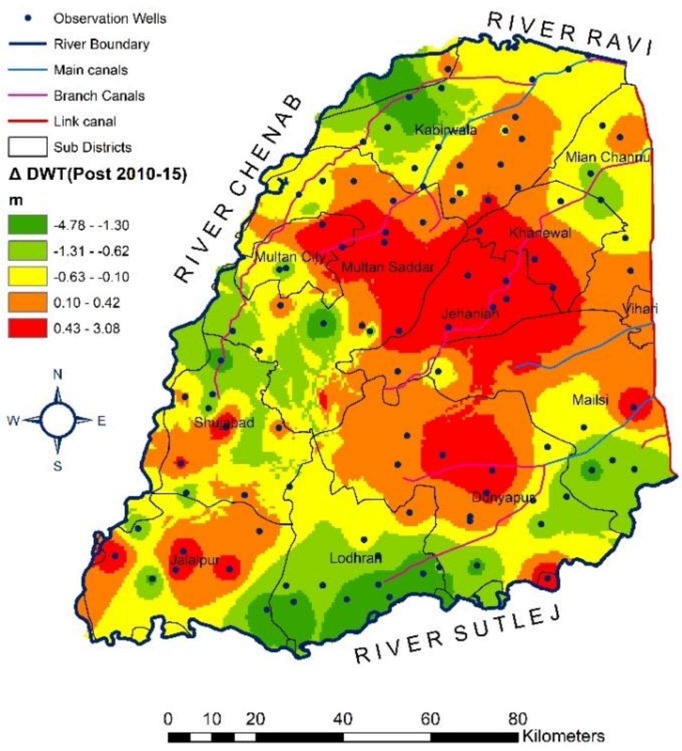


Figure 5. Spatio-temporal change in DTW (post-2010 to post-2015)

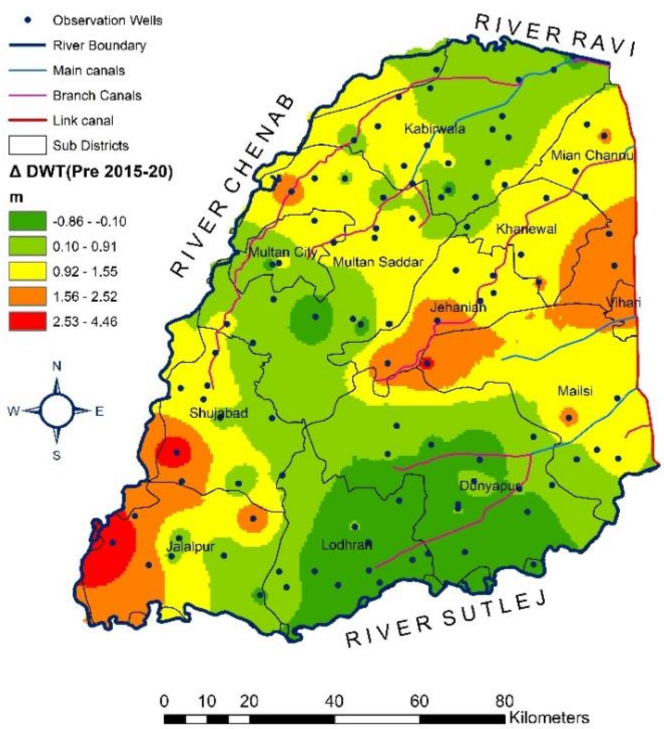


Figure 6. Spatio-temporal change in DTW (pre-2015 to pre-2020)

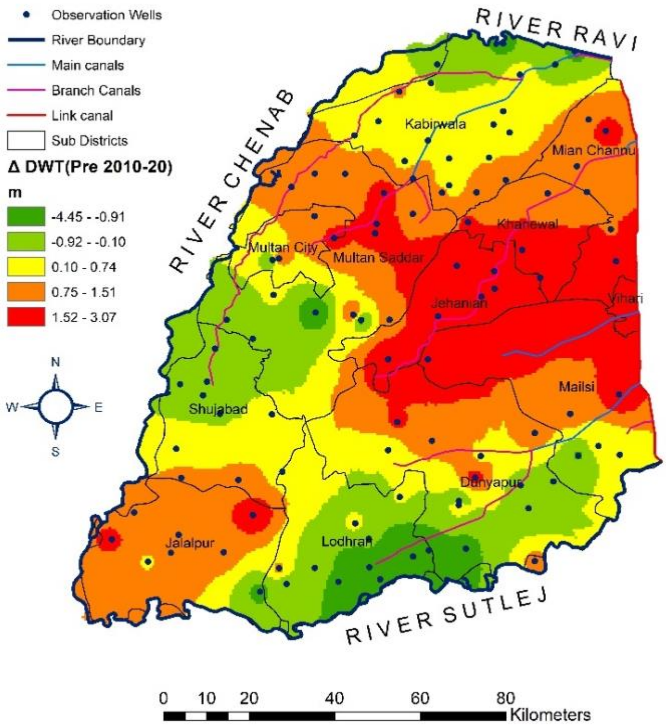


Figure 7. Spatio-temporal change in DTW (pre-2010 to pre-2020)

The area under high DTW class 4 was 4,533 km^2, which decreased to 4,298 km^2 (a 5% decline in area), while the area under class 5 was 331 km^2 in pre-2015, which increased to 2,011 km^2 during pre-2015 (a more than 500% rise in area).

4.7. Spatio-temporal Variation in Average DTW in Sub-districts

Average DTW was calculated for the sub-zones for the 2010, 2015, and 2020 seasons by taking the average DTW values of all observation wells in each sub-district. Variation in average DTW for each sub-districts has been ploted in Figure 8.

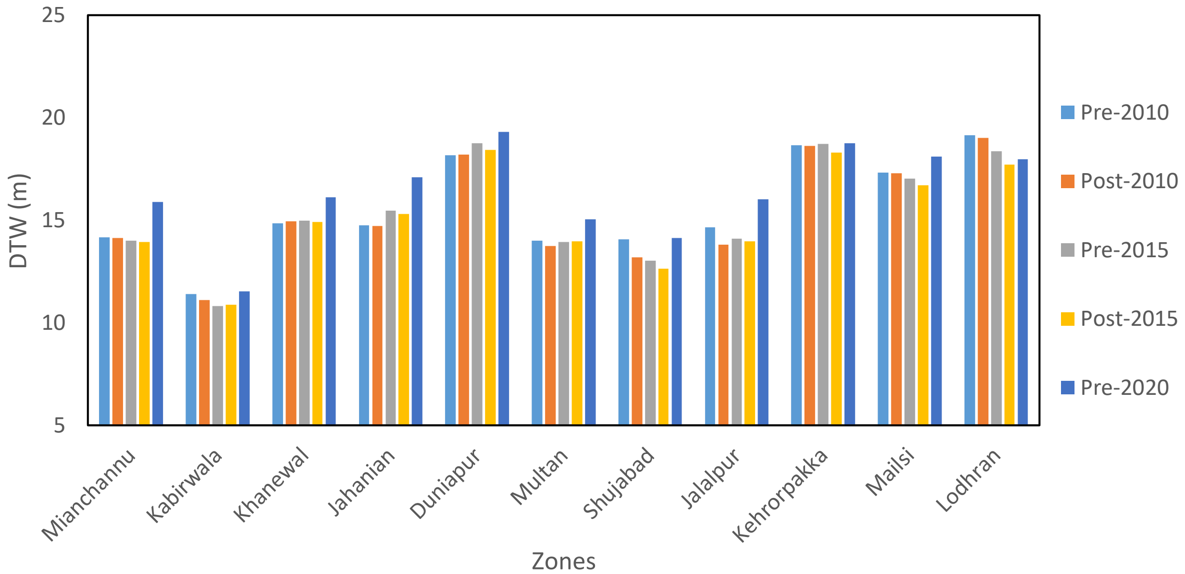


Figure 8. Average change in DTW for sub-zones located in the study area

5. Discussion

5.1. Monitoring of Wells from 2010 to 2020

The Punjab Irrigation Department (PID) monitors the observation wells twice yearly – before and after the monsoon season. There are a total of 281 observation wells located in the study area. The data shows that monitoring was not regular from 2010 to 2020. Of the 281 observation wells, 214 were monitored during 2010, and the number of wells monitored each season decreased gradually from 2010 to 2020. During the pre-2020 season, the DTW of only 20 observation wells was recorded. During post-2016, pre-2017, post-2018, and pre-2020, the DTW of less than 50 observation wells was recorded. The number of wells monitored from 2010 to 2020 is shown in Figure 9. Out of the total 104 observation wells used in the DTW analysis, 58 were in the zones where DTW and DTW depletion rates are significantly high. The location of these wells is shown in Appendix A.

The PID has made a considerable investment in the monitoring infrastructure; however, the infrastructure does not realise its full potential. This will require assessing how monitoring wells are designed and constructed so that the Government of Punjab gets better value for its investment in groundwater monitoring. Besides improving the design and construction, an improved monitoring strategy is also required, where monitoring wells in areas showing declines in water levels and water quality are prioritised and instrumented with depth and EC loggers. This will provide the PID with improved data monitoring of hotspots and information for raising community awareness about the rate of decline in water levels and changes in water quality, which could affect agricultural production.

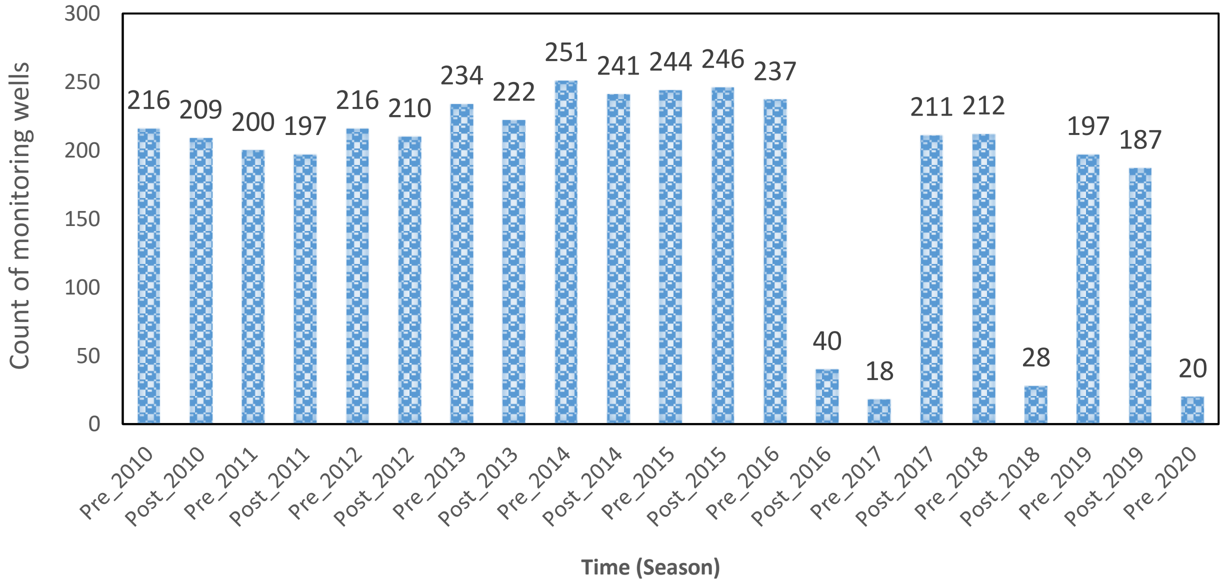


Figure 9. Number of wells monitored during 2010–2020 in the study area

5.2. Number of Tubewells from 2010 to 2020

The main reason for the increasing depth to water in the area is the rise in the number of tubewells with each passing year, as canal supplies are insufficient to meet the demand of the agriculture sector. The number of tubewells for 2010 and 2020, as documented by the Punjab Bureau of Statistics, was 44,687 and 52,782, respectively (Figure 10). This increasing trend in the number of tubewells will likely accelerate declines in water levels with associated impacts on water quality for groundwater irrigation. Also, as the water levels are depleted, groundwater pumping costs for irrigation will increase. We have undertaken scenarios that show the increasing trend in tubewells, particularly under climate change scenarios SSP2-4.5 and SSP4-8.5, will result in the dewatering of substantial areas of the top layer of the aquifer, which will result in the denial of access to groundwater for smallholder farmers who may not have the resources to deepen wells or invest in submersible pumps – posing a risk to food security in Southern Punjab (Raheem et al., 2024).

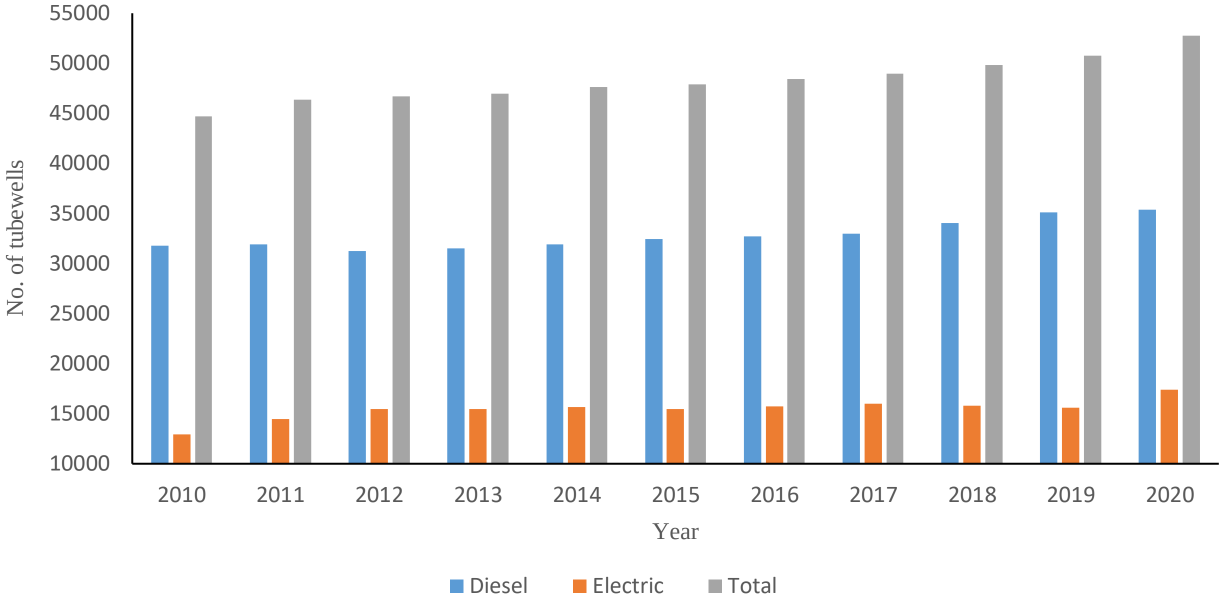


Figure 10. Number of tubewells in the study area

5.3. Spatio-temporal Variation in Electrical Conductivity of Groundwater

Electrical conductivity (EC) generally indicates the level of dissolved salts in the water. In the study area, the number of tubewells monitored during pre-2010, 2015, and 2019 was 432, 525, and 632. Also, the location of monitoring wells from 2003 to 2013 differs from those monitored after 2013. This is why the spatial pattern of EC during 2010 differs from that of 2015 onwards. At some locations, water quality sample leakage occurred before measuring the water quality. In addition, some of the outliers were also removed before interpolating the data. The area is divided into three classes – relatively fresh, marginal, and hazardous. Standard ranges for irrigation water are shown in Table 2. The extent of the area under fresh, marginal, and hazardous classes was 7,829.8, 3,362.9, and 152.7 km^2, respectively, during pre-2010. The area under the marginal water quality class increased to 1,217.2 km^2 (7% increase) in 2019 from 1,134.7 km^2 in 2015 (Table 3). The water quality area under the fresh and hazardous classes was almost intact – no significant change occurred (Figure 11). We have compared the temporal change in the EC between 2015 and 2020, as the location of monitoring was the same during this period. Irrigation water quality ranges based on EC are shown in Table 2.

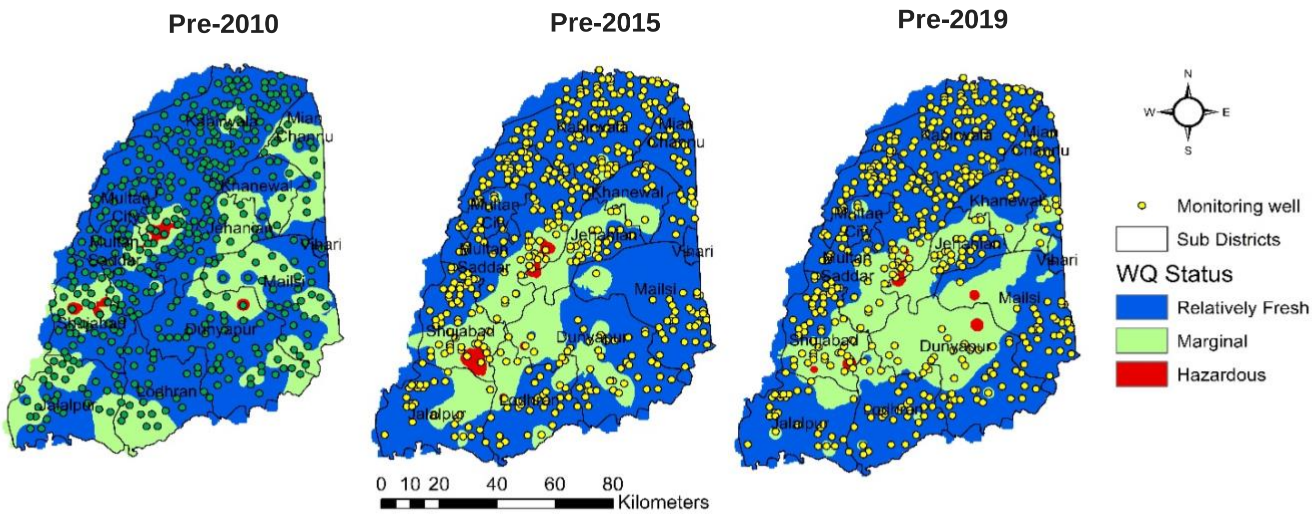


Figure 11. Spatio-temporal variation in EC value during pre-2010, 2015 and 2019

Table 2. Standard ranges of irrigation water based on EC set by CSIRO

		Degree of restriction on use		
Parameter	Unit	None	Slight to moderate	Severe
EC	**(dS/m)**	**< 0.7**	**0.7–3**	**>3**

Table 3. The areas with EC under various water quality classes during pre-2010, 2015 and 2019 in the study area

Class	EC (dS/m)	Area (km^2)			2015 to 2019 change (%)
		Pre-2010	Pre-2015	Pre-2019	
Relatively fresh	<1.5	7,829.8	10,140.5	10,058.5	-0.8
Marginal	1.6–4	3,362.9	1,134.7	1,217.2	7.3
Hazardous	>4	152.7	70.2	69.7	-0.7

The area with marginal quality groundwater has increased from 1,134.7 km^2 to 1,217.2 km^2, which suggests farmers in an additional 8,250 ha are now pumping marginal quality groundwater. This increases salt loading and will have consequences on land productivity over the long term. Farmers in the sub-districts of Khanewal, Jahanian, Mailsi, and Shujabad rely on groundwater of marginal quality for irrigation. The extent of the area under marginal and hazardous quality groundwater depends on the groundwater pumping stressors in the area.

5.4. Groundwater Monitoring for Informed Decision-making

Leveraging groundwater monitoring data helps influence important decision-making regarding groundwater extraction, aquifer recharge, and water quality improvement. Tubewell abstraction in deep watertable areas further exploits groundwater resources in the area. Long-term monitoring trends also help to decide the number of pumping wells and their monitoring, recharging sources, management, and the revision of existing cropping patterns and allocation of canal supplies. Monitoring data from several hundred wells can also be used to rationalise the monitoring network. Over-exploitation of groundwater pumping is directly linked to the water quality. In the Indus Basin, water quality declines with depth, which indicates that as water levels are drawn down, the water quality is likely to decline further. Monitoring also provides valuable information for locating vulnerable water quality zones in the area. Groundwater monitoring may also help decide and design drain installation for shallow watertable zones.

In Southern Punjab, the watertable is quite deep, and most of the canals in this area are non-perennial canal systems. Canal supplies do not fulfil the crop water requirements in dry months, and farmers must shift their agricultural water demand to groundwater. Groundwater monitoring is a key element for guiding sustainable groundwater pumping, the reallocation of canal supplies, revising the cropping pattern in the area, and tracing the water quality contaminant sources and their reclamation. A detailed literature review in context of groundwater monitoring techniques and guidelines is provided in Appendix B.

6. Recommendations for Improving Groundwater Monitoring in Punjab

To date, the monitoring, mapping, and modelling of groundwater resource use have largely been ignored. However, the National and Provincial Water Policies have a renewed focus on improving the monitoring and management of groundwater as it contributes about 50% of the irrigation water used for agricultural production. Moreover, groundwater is an important resource for domestic and industrial uses. The Punjab Irrigation Department (PID) is monitoring about 3300 observation wells for depth to watertable and 4000 tubewells for groundwater quality with biannual monitoring frequency. Despite these numbers, a considerable area is still not under the monitoring network largely due to one-third or more of the monitoring bores becoming inactive as water levels have decreased beyond the depth of the bore or the bore has collapsed or been damaged. The monitoring data quality is somewhat compromised because some bores become non-functional with time and many do not provide continuous time series data. Recently, the PID installed CTD loggers that will provide time series monitoring data at 12-hour intervals. Data from CTD loggers can be used to monitor intra-seasonal changes in groundwater levels and water quality.

The monitoring of groundwater plays an important role in improving management and governance. For this purpose, the PID is installing about 2000 new piezometers to fill the gaps, replace the dead points, and cover the non-canal commanded areas of the province. This will strengthen the monitoring framework for resource assessment. Also, the Irrigation Research Institute (IRI) of the PID is installing about 50 data loggers for experimental research for real-time groundwater data acquisition. These data loggers will be used to strengthen research programs underway within the IRI.

A comprehensive trend analysis of watertable fluctuations and water quality should be done by dividing the area into zones based on canal commands and doab level. Analyses of existing data is required to check whether monitoring in previous years was consistent. If the monitoring was inconsistent, the defective and inactive monitoring wells must be identified, rehabilitated, or replaced with new bores.

We recommend that the Water Resources Zone begins a program of instrumenting monitoring bores with CTD loggers to monitor time-series groundwater levels at daily or 12-hour intervals, compared to recording only two readings for a year. This extra monitoring is required to understand intra-seasonal trends. The manual recording of groundwater level readings is difficult considering that the monitoring network in Punjab is extensive, and two readings in a year do not provide adequate information for the sustainable management of groundwater reserves. As the capacity to model groundwater is continuously improving in Punjab, the increased frequency of monitoring that can be accomplished with loggers will allow for calibrating and verifying a valuable data source model.

The installation of CTD loggers should preferably be done in the canal commands where water level depletion is significantly high. These areas include the canal commands of 10-R LBDC, Pakpattan Canal Lower, Mailsi Canal, Lodhran branch, and Chit Dain branch, and the areas with high EC values, which include Jahanian, Duniapur, Shujabad along the Chenab River, and Jalalpur at the tail of the Gujju Hatta branch canal.

The construction details of each new piezometer need to be logged, and a competent professional must document a detailed record of bore logs during drilling. This will yield a valuable dataset for understanding the hydraulic properties of the aquifer, which will also support other activities, such as groundwater modelling and managed aquifer recharge site investigations.

Developing an annual groundwater status in terms of data and mapping for each canal command and non-canal command is important for the awareness of water users. Sustainable groundwater management will require co-developing appropriate adaptation strategies with communities to develop an improved understanding of groundwater in their area by keeping their needs and problems in sight. The development of strategies to reduce the rate of groundwater and water quality decline will involve extensive community engagement and building community capacity to manage change.

Mapping sources of pollution from industry and the disposal of untreated sewage directly into water bodies will help regulators identify sources of pollution. Strengthening regulations to prevent untreated sewage and industrial waste disposal into canals will improve water quality for downstream users and minimise the risk of pollution of shallow groundwater sources near canals.

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Note: Includes references cited in Appendix B

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Appendix A

Table 4. Active and inactive observation wells located in the study area

Sr. No.	Status	Longitude	Latitude	Easting_LC	Northing_L	Disty__Min	Tehsil
1	Active	71.60	30.41	689100.88	3089085.33	Khudda Bux	Kabirwala
2	Active	71.62	30.46	694858.42	3090917.67	Khudda Bux	Kabirwala
3	Active	71.63	29.96	639474.15	3093176.24	10-R	Jahania
4	Active	71.63	30.41	689294.12	3092067.58	Mattital	Kabirwala
5	Active	71.64	30.38	685170.20	3093035.69	Kukkarhatta	Kabirwala
6	Active	71.65	30.44	692555.70	3093796.54	Mattital	Kabirwala
7	Active	71.67	29.94	637069.79	3097629.50	10-R	Jahania
8	Active	71.67	29.94	637071.65	3097683.51	10-R	Jahania
9	Active	71.68	30.43	691510.11	3096527.64	Kukkarhatta	Kabirwala
10	Active	71.71	30.47	695438.29	3098819.31	Chatur Garh	Kabirwala
11	Active	71.71	30.36	683451.42	3099449.55	Mungan wala	Kabirwala
12	Active	71.73	30.01	645087.77	3102365.91	10-R	Jahania
13	Active	71.73	30.52	701718.29	3100546.05	Mattital	Kabirwala
14	Active	71.69	30.02	645674.04	3098546.96	10-R	Jahania
15	Active	71.76	30.40	688413.31	3103974.57	Mungawala	Kabirwala
16	Active	71.76	30.02	645856.71	3105823.17	10-R	Jahania
17	Active	71.76	30.52	701874.68	3104113.21	Chowki Narool	Kabirwala
18	Active	71.77	30.40	687734.99	3104825.86	Chawan	Kabirwala
19	Active	71.78	30.56	706256.41	3105237.10	Shah Din	Kabirwala
20	Active	71.78	30.03	647484.44	3107454.02	10-R	Jahania
21	Active	71.79	30.29	676366.01	3107258.41	Hans	Kabirwala
22	Active	71.80	30.36	684381.63	3108388.61	Chawan	Kabirwala
23	Active	71.80	30.03	647566.30	3109755.87	10-R	Jahania
24	Active	71.80	30.48	697333.65	3108033.16	Kotli Bhutta	Kabirwala
25	Active	71.81	30.32	679754.21	3109007.60	Chawan	Kabirwala
26	Active	71.81	30.43	691465.46	3109256.97	Kabirwala	Kabirwala
27	Active	71.82	30.14	659371.04	3110833.19	10-R	Jahania
28	Active	71.82	30.40	688498.85	3109843.57	Chawan	Kabirwala
29	Active	71.83	30.51	700096.32	3110361.01	Hashmat Mirali	Kabirwala
30	Active	71.84	30.07	652236.79	3112857.32	10-R	Jahania
31	Active	71.84	30.23	669633.00	3112738.49	10-R	Khanewal
32	Active	71.86	30.11	656829.44	3114672.83	10-R	Jahania
33	Active	71.86	30.29	676676.93	3114195.11	Shamkot	Khanewal
34	Active	71.86	30.14	659515.49	3114843.53	10-R	Khanewal
35	Inactive	71.86	30.40	688653.51	3114135.23	Kabirwala	Kabirwala
36	Active	71.87	30.38	686092.77	3114842.24	Kabirwala	Kabirwala
37	Active	71.87	30.07	652352.83	3116067.25	10-R	Jahania
38	Active	71.88	30.59	709284.75	3114986.04	Fazil Shah	Kabirwala
39	Active	71.89	30.37	684887.99	3116434.62	Kabirwala	Kabirwala

40	Inactive	71.90	30.16	662559.02	3118105.16	10-R	Jahania
41	Active	71.90	30.44	692641.00	3117085.63	Mast pur	Kabirwala
42	Active	71.90	30.13	658413.54	3118443.62	10-R	Jahania
43	Active	71.90	30.09	654295.11	3118675.18	10-R	Jahania
44	Active	71.90	30.09	654264.11	3118676.32	10-R	Jahania
45	Active	71.91	30.35	682667.63	3118866.46	Venoi	Khanewal
46	Active	71.92	30.61	711623.32	3118309.42	Fazil Shah	Kabirwala
47	Active	71.92	30.46	695818.82	3118916.93	Bilawalpur	Kabirwala
48	Active	71.92	30.32	679753.04	3120015.02	Nanak pur	Khanewal
49	Active	71.93	30.42	690912.85	3120351.92	Venoi	Kabirwala
50	Active	71.95	30.54	704460.42	3121957.64	Fazil Shah	Kabirwala
51	Active	71.95	30.43	692385.42	3122699.21	Venoi	Kabirwala
52	Active	71.96	30.17	663544.09	3123929.07	10-R	Jahania
53	Active	71.97	30.38	686430.68	3124868.47	Abdul Hakeem	Khanewal
54	Active	71.98	30.35	683867.67	3125498.61	Abdul Hakeem	Kabirwala
55	Active	71.99	30.11	657221.06	3127805.55	10-R	Jahania
56	Active	72.01	30.48	697748.17	3127754.20	Hittar	Kabirwala
57	Active	72.01	30.29	676961.02	3128588.96	10-R	Khanewal
58	Active	72.01	30.29	676961.02	3128588.96	10-R	Khanewal
59	Active	72.02	30.43	692905.44	3129189.97	Abdul Hakeem	Khanewal
60	Active	72.03	30.56	707094.23	3128974.97	Fazil Shah	Kabirwala
61	Active	72.05	30.47	697368.58	3131555.58	Kot Abdullah	Kabirwala
62	Active	72.06	30.53	703719.59	3132567.65	Allah Hoo	Kabirwala
63	Active	72.07	30.59	710377.75	3132739.74	Fazil Shah	Kabirwala
64	Active	72.07	30.35	683520.59	3134245.02	10-R	Khanewal
65	Active	72.07	30.35	683520.59	3134245.02	10-R	Jahania
66	Active	72.08	30.43	692913.59	3135061.17	9-R	Khanewal
67	Active	72.09	30.29	677601.03	3136502.13	10-R	Khanewal
68	Active	72.10	30.45	694527.23	3136173.12	8-R	Mianchannu
69	Active	72.11	30.53	703446.88	3137483.00	Abdul Hakeem	Kabirwala
70	Active	72.12	30.58	709263.46	3138190.88	On River Bank	Kabirwala
71	Active	72.13	30.42	691986.25	3139767.04	9-R	Khanewal
72	Active	72.14	30.37	686669.02	3140827.75	10-R	Khanewal
73	Active	72.14	30.22	669084.55	3141670.73	15-L	Mianchannu
74	Active	72.14	30.38	687206.03	3141179.85	9-R	Khanewal
75	Active	72.15	30.15	661651.79	3143004.19	15-L	Mianchannu
76	Active	72.15	30.41	690810.26	3142000.62	9-R	Khanewal
77	Active	72.16	30.15	661735.61	3143589.72	15-L	Mianchannu
78	Active	72.17	30.32	680674.00	3144266.58	10-R	Khanewal
79	Active	72.18	30.12	658449.42	3146180.91	10-R	Jahania
80	Active	71.40	29.45	581892.00	3073442.15	Bahadar Pur Disty	Lodhran
81	Active	71.44	29.50	587544.33	3077150.95	Mubrik Wah Disty	Lodhran
82	Active	71.46	29.47	583890.14	3078767.50	Mubrik Wah Disty	Lodhran

83	Active	71.47	29.45	581904.34	3080150.17	Lodhran Minor	Lodhran
84	Active	71.48	29.55	593558.82	3080024.43	Shahnal disty	Lodhran
85	Active	71.49	29.42	579260.59	3082097.65	Sheikh Wah	Lodhran
86	Active	71.51	29.75	615090.51	3082734.99	Bahishti	Lodhran
87	Active	71.52	29.50	587849.96	3084435.66	Gogaran	Lodhran
88	Active	71.52	30.04	647512.19	3082620.91	Jharr Minor	Lodhran
89	Active	71.56	29.58	597240.34	3087709.11	Shahnal	Lodhran
90	Active	71.56	29.79	620335.03	3087166.75	1R/2L	Dunia Pur
91	Active	71.56	29.83	623865.64	3087100.11	1L/TD/3L	Dunia Pur
92	Active	71.56	29.63	601919.61	3088050.98	Shahnal disty	Lodhran
93	Active	71.57	29.47	584783.63	3089316.51	Kannu Minor	Lodhran
94	Active	71.58	29.64	602957.92	3089351.27	Shahnal disty	Lodhran
95	Active	71.59	29.71	611093.75	3090451.99	Bahishti	Dunia Pur
96	Active	71.59	29.71	610733.55	3090754.54	Melsi Disty	Lodhran
97	Active	71.60	29.50	588117.97	3092654.87	Sheikh Wah	Lodhran
98	Active	71.60	29.60	598516.53	3092321.64	Mehmood	Lodhran
99	Active	71.61	29.66	605672.04	3092096.12	Gopal	Lodhran
100	Active	71.61	29.66	606164.95	3092111.41	Kondi Minor	Lodhran
101	Active	71.62	30.02	646021.59	3091910.47	Lodhran Minor	Lodhran
102	Active	71.63	29.56	594988.78	3095201.30	Lodhran Minor	Lodhran
103	Active	71.63	29.56	594826.59	3095226.22	Gogaran	Lodhran
104	Active	71.63	29.50	588370.22	3095543.32	Gagan Hati	Lodhran
105	Active	71.66	29.48	585624.22	3097852.51	Lodhran Disty	Lodhran
106	Active	71.66	30.53	702160.80	3093928.88	Rapper	Lodhran
107	Active	71.67	29.75	615849.91	3098422.68	Bahishti	Dunia Pur
108	Active	71.67	29.63	603065.15	3098928.25	Jabrani Minor	Lodhran
109	Active	71.68	29.82	623651.51	3098849.96	1/L / T.D	Dunia Pur
110	Active	71.68	29.73	613260.53	3099259.14	Bahishti	Dunia Pur
111	Active	71.69	29.61	600697.12	3100142.72	Raper Disty	Kehroor Pacca
112	Active	71.69	29.81	622495.58	3100055.15	1/L / T.D	Dunia Pur
113	Active	71.70	29.65	604985.00	3101176.21	Jam Wah	Dunia Pur
114	Active	71.71	29.52	590691.53	3102305.58	Dhamki Disty	Kehroor Pacca
115	Active	71.71	29.61	600343.62	3102101.89	Raper	Lodhran
116	Active	71.73	29.53	591182.48	3104362.34	Jabrani Minor	Lodhran
117	Active	71.75	29.80	622064.59	3105182.10	Jam Wah	Dunia Pur
118	Active	71.76	29.94	637315.26	3105721.89	1/L / K. Pur	Dunia Pur
119	Active	71.76	29.54	592735.70	3107532.81	Jabrani Minor	Lodhran
120	Active	71.77	29.77	618342.12	3107267.19	Jam Wah	Dunia Pur
121	Active	71.80	30.31	678092.05	3108594.69	Gopal Disty	Kehroor Pacca
122	Active	71.82	30.49	698858.48	3109259.31	Gopal Disty	Kehroor Pacca
123	Active	71.82	29.76	617953.99	3112440.68	Jam Wah	Dunia Pur
124	Active	71.82	29.63	603541.49	3113261.38	Raper Disty	Kehroor Pacca
125	Active	71.82	29.64	604514.06	3113258.47	Gopal	Lodhran
126	Active	71.82	29.86	628893.59	3112403.38	3L/9L	Dunia Pur

127	Active	71.83	29.81	622740.33	3113367.78	11/L	Dunia Pur
128	Active	71.84	29.54	593401.31	3115037.14	Lal Bhogali	Kehroor Pacca
129	Active	71.86	29.69	610083.78	3116305.37	Basant Disty	Kehroor Pacca
130	Active	71.87	29.74	615138.04	3117294.54	Basant Disty	Dunia Pur
131	Active	71.87	29.67	607978.66	3117557.30	Lal Bhogali	Kehroor Pacca
132	Active	71.90	29.68	609480.72	3120913.40	Gopal	Kehroor Pacca
133	Active	71.92	29.60	600295.03	3123127.97	Gopal Disty	Kehroor Pacca
134	Active	71.91	29.64	604258.84	3121844.88	Chale Wahin Minor	Kehroor Pacca
135	Active	71.92	29.53	592846.42	3123166.73	Chele Wahin	Kehroor Pacca
136	Active	71.95	29.57	596821.63	3126015.59	Chele Wahin	Kehroor Pacca
137	Active	71.95	29.68	608614.28	3125661.66	Kehroori Minor	Kehroor Pacca
138	Active	71.96	29.73	615172.61	3126058.22	Gopal Disty	Kehroor Pacca
139	Active	71.97	29.63	603297.28	3127486.76	Chele Wahin	Kehroor Pacca
140	Active	71.98	29.52	591029.33	3129175.75	Mansor Minor	Kehroor Pacca
141	Active	72.00	29.59	599594.40	3130382.52	Chele Wahin	Kehroor Pacca
142	Active	72.01	29.57	596774.33	3131344.49	Zirak Minor	Kehroor Pacca
143	Active	72.02	29.64	604940.21	3132200.19	Chele Wahin	Kehroor Pacca
144	Active	72.02	29.68	609736.90	3132275.97	Jalla Minor	Kehroor Pacca
145	Active	72.09	29.59	599313.11	3139628.91	Zirak Minor	Kehroor Pacca
146	Active	72.10	29.63	603609.34	3139981.40	Zirak Minor	Kehroor Pacca
147	Active	72.05	29.68	609506.84	3135268.04	Jalla Minor	Kehroor Pacca
148	Active	71.51	29.46	583022.02	3084075.98	Sheikh Wah	Lodhran
149	Active	71.09	29.56	593257.35	3042849.79	Panjani	Jalalpur Pirwala
150	Active	71.14	29.54	590636.80	3047019.82	Ghazipur	Jalalpur Pirwala
151	Active	71.14	29.62	599638.68	3047239.52	Panjani	Jalalpur Pirwala
152	Active	71.15	29.58	595525.24	3048760.27	Panjani	Jalalpur Pirwala
153	Active	71.17	29.51	588240.93	3050377.37	Ghazipur	Jalalpur Pirwala
154	Active	71.20	29.57	594067.92	3053624.20	Alipur	Jalalpur Pirwala
155	Inactive	71.20	29.54	590929.90	3053744.70	Alipur	Jalalpur Pirwala
156	Inactive	71.22	29.67	605155.47	3054608.91	Panjani	Jalalpur Pirwala
157	Active	71.23	29.75	614787.74	3055338.85	Sat burji	Shujabad
158	Active	71.23	29.59	596364.14	3056220.49	Hafizwala	Jalalpur Pirwala
159	Active	71.23	29.57	594707.15	3056431.64	Hafizwala	Jalalpur Pirwala
160	Active	71.24	29.89	629888.63	3055660.19	Baktu wah	Shujabad
161	Active	71.24	29.69	608017.92	3056566.19	Panjani	Shujabad
162	Active	71.25	29.81	621271.53	3056861.60	Gardezpur	Shujabad
163	Active	71.25	29.66	604658.83	3057502.08	Hafizwala	Jalalpur Pirwala
164	Inactive	71.25	29.79	618980.17	3057495.19	Sat burji	Shujabad
165	Inactive	71.26	29.66	605153.32	3058590.02	Hafizwala	Jalalpur Pirwala
166	Inactive	71.27	29.93	634126.55	3058294.33	Baktu wah	Shujabad
167	Active	71.27	29.91	632219.18	3058352.75	Baktu wah	Shujabad
168	Active	71.27	29.71	610351.46	3059344.82	Lasuri	Shujabad
169	Active	71.28	29.87	627447.11	3060404.48	Gajju Hatta	Shujabad
170	Active	71.29	29.89	630640.98	3061111.73	Baktu wah	Shujabad

171	Active	71.30	29.88	629175.24	3061505.80	Shujabad branch	Shujabad
172	Active	71.31	29.81	621324.75	3062634.26	Sikander Abad	Shujabad
173	Active	71.31	29.87	628251.14	3062526.72	Gujju hatta	Shujabad
174	Active	71.31	29.96	638414.00	3062506.84	Baktu wah	Shujabad
175	Active	71.32	29.70	608890.05	3063907.60	Matotli	Shujabad
176	Active	71.32	30.09	652618.20	3062734.80	Shujabad branch	Multan
177	Active	71.32	29.83	623214.67	3063972.58	Sikanderabad	Shujabad
178	Active	71.32	29.88	629431.49	3063832.09	Shujabad branch	Shujabad
179	Inactive	71.32	29.74	613341.24	3064414.61	Matotli	Shujabad
180	Inactive	71.33	29.94	635968.58	3064085.15	Chhaju	Shujabad
181	Inactive	71.33	30.02	645194.93	3064653.96	Buch	Multan
182	Active	71.33	30.02	645194.93	3064653.96	Buch	Multan
183	Active	71.34	29.97	638891.48	3064985.30	Chhaju	Shujabad
184	Active	71.34	29.97	638891.48	3064985.30	Chhaju	Shujabad
185	Active	71.35	29.92	633250.78	3066798.87	Khoja	Shujabad
186	Active	71.36	29.69	607885.24	3068188.22	Thath Ghalwan	Shujabad
187	Active	71.36	30.00	642086.04	3067646.16	Sikanderabad	Multan
188	Active	71.37	30.08	651327.84	3067756.52	Shujabad branch	Multan
189	Active	71.37	30.03	646388.55	3068341.85	Shujabad branch	Shujabad
190	Active	71.38	30.15	658856.37	3068214.21	Muzafarabad	Multan
191	Active	71.39	30.11	654942.64	3070051.78	Hamidpur	Multan
192	Active	71.40	29.79	619457.51	3071799.44	Sikanderabad	Shujabad
193	Inactive	71.40	29.79	619927.13	3072026.24	Wali Muhammad	Shujabad
194	Inactive	71.40	30.19	664204.29	3070799.80	Muzafarabad	Multan
195	Active	71.41	29.84	625196.29	3072099.71	Wali Muhammad	Shujabad
196	Inactive	71.42	29.94	636040.20	3073147.64	Wali Muhammad	Multan
197	Active	71.43	29.83	623426.35	3074546.11	Rana	Shujabad
198	Active	71.43	30.08	651340.05	3073943.05	Wali Muhammad	Multan
199	Active	71.39	29.98	640970.22	3070084.01	Wali Muhammad	Multan
200	Active	71.44	30.15	659836.18	3074792.75	Wali Muhammad	Multan
201	Active	71.45	29.87	628190.96	3076165.08	Rana	Multan
202	Inactive	71.45	29.94	636076.62	3076204.52	Qasba	Multan
203	Active	71.45	29.86	627525.48	3076535.48	Rana	Shujabad
204	Active	71.45	30.19	664320.22	3075370.07	Shujabad branch	Multan
205	Active	71.46	30.02	644921.60	3076400.56	Jampur	Multan
206	Active	71.47	30.30	676651.39	3076761.64	Shujabad branch	Multan
207	Inactive	71.49	30.07	650260.47	3079549.44	Gopalpur	Multan
208	Active	71.50	29.96	638835.62	3080539.45	Rana	Multan
209	Active	71.50	29.91	633031.50	3081052.47	Rana	Multan

210	Active	71.51	30.33	680090.40	3080228.37	Shujabad branch	Multan
211	Active	71.52	30.24	670007.65	3081656.40	Kirpalpur	Multan
212	Inactive	71.52	30.24	670007.65	3081656.40	Kirpalpur	Multan
213	Active	71.52	30.33	679944.38	3081381.24	Rata	Multan
214	Active	71.52	29.89	631408.86	3083225.34	Mubarakpur	Multan
215	Inactive	71.54	29.88	629483.30	3084577.97	Mubarakpur	Multan
216	Active	71.54	30.02	645209.92	3084243.53	Mubarakpur	Multan
217	Active	71.55	30.22	667836.32	3084909.73	Multan branch	Multan
218	Inactive	71.56	30.10	653725.92	3085647.93	Gulzarpur	Multan
219	Inactive	71.56	30.10	653725.92	3085647.93	Gulzarpur	Multan
220	Inactive	71.56	30.35	681412.60	3084804.38	Tahirpur	Multan
221	Active	71.56	30.20	665000.96	3085753.39	Bhaini	Multan
222	Inactive	71.56	29.93	635318.97	3086878.91	Mubarakpur	Multan
223	Inactive	71.58	30.06	650254.07	3087719.41	Gulzarpur	Multan
224	Active	71.58	30.10	654087.84	3088179.82	Gulzarpur	Multan
225	Active	71.58	30.16	661288.66	3088017.85	Miani	Multan
226	Active	71.58	30.33	680086.83	3087519.78	Tahirpur	Multan
227	Active	71.60	30.00	642936.32	3089921.96	Sial	Multan
228	Active	71.60	30.17	662233.41	3089537.87	Lunda	Multan
229	Inactive	71.60	30.40	687856.11	3088726.74	Bosan	Multan
230	Active	71.60	30.04	647228.53	3090259.50	Sial	Multan
231	Inactive	71.62	30.28	673938.28	3091441.32	Shakh Madina	Multan
232	Active	71.64	30.13	657830.61	3093220.25	Mukhdoom Rashid	Multan
233	Active	71.64	30.31	678227.05	3092604.54	Jaal wala	Multan
234	Inactive	71.65	30.08	652726.26	3094358.47	Shujabad branch	Multan
235	Inactive	71.65	30.08	652726.26	3094358.47	Shujabad branch	Multan
236	Active	71.65	30.21	666390.10	3094052.04	Sher singh	Multan
237	Active	71.65	30.23	668613.87	3094242.62	Multan branch	Multan
238	Active	71.67	30.29	675862.65	3095491.32	Jalwala	Multan
239	Active	71.67	30.24	669770.94	3096556.50	Riaz abad	Multan
240	Active	71.68	30.02	646310.31	3097659.35	Jalil	Multan
241	Active	71.69	30.08	652944.78	3098903.74	Jalil	Multan
242	Active	71.70	30.51	699621.62	3097793.71	Shujabad branch	Multan
243	Inactive	71.71	30.05	649171.45	3101097.57	Terpai	Multan
244	Inactive	71.72	30.15	660007.61	3100987.91	Jalil	Multan
245	Active	71.73	30.25	671174.46	3101507.15	Riaz abad	Multan
246	Active	71.73	30.32	679417.86	3101245.94	Riaz abad	Multan
247	Inactive	71.75	30.21	667302.48	3103515.24	Terpai	Multan
248	Inactive	71.76	30.15	660033.78	3105242.92	Terpai	Multan
249	Active	71.22	29.53	590421.85	3054991.57	Mubrik Wah Disty	Jalal Pur
250	Active	71.33	29.53	590905.33	3065719.81	Patti Minor	Jalal Pur
251	Active	71.39	29.61	599750.08	3071407.67	Shahnal disty	Jalal Pur

252	Active	71.39	29.67	606173.79	3071431.96	Mehmood Disty	Shujabad
253	Inactive	71.43	29.59	597066.75	3075165.45	Jhago Minor	Jalal Pur
254	Active	71.43	30.15	659467.85	3073478.04	Mehmood Disty	Shujabad
255	Active	71.45	29.70	610097.50	3077075.60	Mehmood	Shujabad
256	Active	71.47	29.74	614244.65	3079120.50	Bahashti Disty	Shujabad
257	Active	71.49	29.72	612374.70	3081077.46	Shahnal disty	Shujabad
258	Inactive	72.11	30.14	660368.46	3139306.12	15-L	Mianchannu
259	Inactive	71.83	30.00	643682.36	3112055.33	Maqsooda Minor	Mailsi
260	Inactive	71.88	29.98	642601.16	3117513.01	7R	Mailsi
261	Inactive	71.92	29.96	639860.11	3121152.47	Lower. P.C	Mailsi
262	Inactive	71.92	29.69	609676.09	3122549.58	Gopal Disty	Kehroor Pacca
263	Inactive	71.95	29.67	607631.71	3125485.00	Kehroori Minor	Mailsi
264	Active	71.98	29.79	620922.73	3128074.39	Harri Minor	Mailsi
265	Active	71.98	29.53	592327.23	3129207.78	Harri Minor	Mailsi
266	Inactive	72.00	30.07	652735.07	3128938.02	7R	Mailsi
267	Inactive	72.01	29.84	627427.68	3130603.06	Jabrani Minor	Mailsi
268	Inactive	71.78	29.55	594317.94	3109297.27	Jahan Minor	Mailsi
269	Active	72.06	29.83	625657.36	3135107.05	Harri Minor	Mailsi
270	Active	72.07	29.74	615967.37	3137083.53	Harri Minor	Mailsi
271	Active	72.09	29.81	624196.11	3138600.78	Tail Charg Minor	Mailsi
272	Inactive	72.10	29.99	643770.86	3138393.61	9/L	Mailsi
273	Active	72.12	29.94	638258.52	3140760.31	9/L	Mailsi
274	Active	72.13	29.83	626709.24	3142509.24	Mailsi Canal	Mailsi
275	Inactive	72.14	30.07	653245.14	3142200.47	7R	Mailsi
276	Active	72.15	30.00	645457.44	3143291.61	Dhamki Disty	Mailsi
277	Active	72.16	29.87	630604.01	3144812.30	Dhamki Disty	Mailsi
278	Active	72.17	29.85	628880.90	3145588.17	Harri Minor	Mailsi
279	Active	72.12	29.76	618365.99	3141126.87	Dhodo Minor	Mailsi
280	Active	72.16	29.74	616498.05	3145540.96	Karam Branch	Mailsi
281	Active	72.11	29.86	630113.99	3139956.05	Mailsi Minor	Mailsi

Table 5. Observation wells located in vulnerable zones

Sr. #	Longitude	Latitude	Disty_Min	Tehsil	District
1	71.674	29.941	10-R	Jahania	Khanewal
2	71.779	30.032	10-R	Jahania	Khanewal
3	71.788	30.293	Hans	Kabirwala	Khanewal
4	71.956	30.171	10-R	Jahania	Khanewal
5	72.009	30.291	10-R	Khanewal	Khanewal
6	72.071	30.348	10-R	Khanewal	Khanewal
7	72.092	30.294	10-R	Khanewal	Khanewal
8	72.142	30.215	15-L	Mianchannu	Khanewal
9	71.405	29.451	Bahadar Pur Disty	Lodhran	Lodhran
10	71.445	29.501	Mubrik Wah Disty	Lodhran	Lodhran
11	71.460	29.467	Mubrik Wah Disty	Lodhran	Lodhran
12	71.520	29.501	Gogaran	Lodhran	Lodhran
13	71.521	30.040	Jharr Minor	Lodhran	Lodhran
14	71.569	29.472	Kannu Minor	Lodhran	Lodhran
15	71.605	29.595	Mehmood	Lodhran	Lodhran
16	71.617	30.024	Lodhran Minor	Lodhran	Lodhran
17	71.633	29.562	Lodhran Minor	Lodhran	Lodhran
18	71.634	29.561	Gogaran	Lodhran	Lodhran
19	71.635	29.503	Gagan Hati	Lodhran	Lodhran
20	71.657	29.477	Lodhran Disty	Lodhran	Lodhran
21	71.674	29.750	Bahishti	Dunia Pur	Lodhran
22	71.693	29.809	1/L / T.D	Dunia Pur	Lodhran
23	71.699	29.651	Jam Wah	Dunia Pur	Lodhran
24	71.726	29.525	Jabrani Minor	Lodhran	Lodhran
25	71.757	29.941	1/L / K. Pur	Dunia Pur	Lodhran
26	71.760	29.538	Jabrani Minor	Lodhran	Lodhran
27	71.766	29.769	Jam Wah	Dunia Pur	Lodhran
28	71.802	30.308	Gopal Disty	Kehroor Pacca	Lodhran
29	71.823	29.634	Raper Disty	Kehroor Pacca	Lodhran
30	71.823	29.643	Gopal	Lodhran	Lodhran
31	71.837	29.542	Lal Bhogali	Kehroor Pacca	Lodhran
32	71.857	29.692	Basant Disty	Kehroor Pacca	Lodhran
33	71.869	29.737	Basant Disty	Dunia Pur	Lodhran
34	71.953	29.675	Kehroori Minor	Kehroor Pacca	Lodhran
35	71.969	29.627	Chele Wahin	Kehroor Pacca	Lodhran
36	71.982	29.516	Mansor Minor	Kehroor Pacca	Lodhran
37	72.021	29.683	Jalla Minor	Kehroor Pacca	Lodhran
38	71.359	29.687	Thath Ghalwan	Shujabad	Multan
39	71.430	29.825	Rana	Shujabad	Multan
40	71.444	30.153	Wali Muhammad	Multan	Multan
41	71.560	30.197	Bhaini	Multan	Multan
42	71.601	30.035	Sial	Multan	Multan
43	71.647	30.207	Sher singh	Multan	Multan

44	71.649	30.227	Multan branch	Multan	Multan
45	71.665	30.292	Jalwala	Multan	Multan
46	71.677	30.024	Jalil	Multan	Multan
47	71.726	30.248	Riaz abad	Multan	Multan
48	71.726	30.322	Riaz abad	Multan	Multan
49	71.328	29.534	Patti Minor	Jalal Pur	Multan (BWP)
50	71.389	29.612	Shahnal disty	Jalal Pur	Multan (BWP)
51	71.431	30.150	Mehmood Disty	Shujabad	Multan (BWP)
52	71.451	29.704	Mehmood	Shujabad	Multan (BWP)
53	71.982	29.786	Harri Minor	Mailsi	Vehari
54	72.057	29.826	Harri Minor	Mailsi	Vehari
55	72.074	29.738	Harri Minor	Mailsi	Vehari
56	72.159	29.867	Dhamki Disty	Mailsi	Vehari
57	72.116	29.758	Dhodo Minor	Mailsi	Vehari
58	72.161	29.740	Karam Branch	Mailsi	Vehari

Appendix B

A review of groundwater monitoring practices

Remote sensing applications in groundwater monitoring

The availability of remote sensing data, which provides geographical and temporal information at different scales, has strengthened resource monitoring. Groundwater dynamics can be better understood by using satellite-based remote sensing techniques, including optical images and Synthetic Aperture Radar (SAR) (Shaikh & Birajdar, 2024). Remote sensing, along with groundwater monitoring and modelling, supports sustainable groundwater management by identifying surface water-groundwater interactions, tracking groundwater levels, and detecting factors related to groundwater quality (Conant et al., 2019).

Satellite data can provide spatial and temporal information on rainfall, evapotranspiration, and cropping patterns. Increasingly, GRACE satellite data coupled with remote sensing and GIS tools, is being used to assess the change in groundwater storage over time. GRACE is suitable at the basin or sub-basin level, but it is also used at smaller scales.

Geophysical investigation-based techniques

Geophysical investigation techniques such as vertical electrical sounding (VES) do not require an observation well for monitoring. A survey is conducted to capture information about groundwater levels and water quality. A major disadvantage of this technique (VES) is that it does not provide temporal variations in groundwater levels. So, this method is used for mapping changes in the DTW and if enough resources are available, can also be used multiple times during a season to understand salinity trends. It is also used before installing new tubewells to assess the likelihood of fresh groundwater sources (Masood et al., 2022).

Point to satellite-based groundwater monitoring

Point-based monitoring data are interpolated spatially to provide a water level map. However, when groundwater monitoring at individual locations is inadequate due to the low density of monitoring wells and inaccessibility to bore sites in remote locations, a combination of remote sensing and GIS techniques or a steady state model can provide useful information on groundwater conditions. Remote sensing and geographic information systems supported by borehole data can be particularly valuable tools for groundwater mapping and assessing regional water storage.

Measuring water levels using digital water level recorders

Measuring water levels through digital recorders has recently started in Indian Punjab. A water level sensor is installed with a digital water level recorder that records the real-time reading of water levels and stores the data on a memory chip (US Geological Survey, 2010).

Measuring water levels using submersible pressure transducers

A data logger, steel tape, cable and suspension are required to measure the groundwater level in a bore well. Measurement error through this apparatus is minimal – up to 0.01 feet. This technique is highly recommended and is used by the US Geological Survey (2010).

Technical aspects of groundwater monitoring

Fulton et al. (2015) framed some important guidelines for groundwater monitoring. While designing a groundwater monitoring network, the following factors need to be considered:

- The measurement of ground surface elevation at each monitoring point.
- The level at which the observation wells are perforated and whether they reflect typical extraction wells in the region.
- The type of monitoring wells to be used in measuring water levels.
- The type of groundwater level measurement devices to be used.
- The location and number of monitoring wells.
- The frequency and season of the monitoring program.
- Recordkeeping and processing.

We also recommend digitalising monitoring data records, including data collected in the past, and ensuring ease of access to monitoring data for researchers and resource managers.

Measuring surface elevations at monitoring sites

Prior to groundwater level monitoring, it is important to survey the surface elevations of the monitoring locations. There are multiple ways to measure surface elevations; for example, manual surveys or topographic maps using a digital elevation model (DEM). However, reliance on DEM data can introduce errors. The water level in reference to a datum (usually sea level) can then be calculated by subtracting the depth to groundwater from the surface elevation. This approach can further assist in computing flow gradients based on the elevation difference of groundwater level contours.

Selection of monitoring wells

Groundwater levels can be monitored using domestic and agricultural tubewells. Domestic and irrigation wells offer a way for groundwater monitoring through the existing well column rather than digging a separate observation well. Specialised monitoring wells drilled in Pakistan often have too tiny a diameter to accommodate a pump to pump out the groundwater for water quality measurements. Dedicated monitoring wells specifically designed for site conditions are the preferred option. Also, nested piezometers are required to understand salinity gradation with depth.

Suitable location for groundwater monitoring

Hydrogeology, land and water use, and environment and site access are some of the considerations for the location of monitoring wells. Hydrogeological considerations include the interaction of surface and groundwater sources, aquifer depth, and lithology that may influence the groundwater movement and direction. The change in land use land cover (LULC), such as agricultural or built-up areas, may influence the location and number of monitoring wells in a particular area.

Time of monitoring

Groundwater levels are usually observed before and soon after the monsoon season in Pakistan and other South Asian countries. Monitoring water levels twice yearly does not give an accurate picture of intra-seasonal groundwater dynamics. For instance, groundwater level responses to events such as the 2010 floods were monitored several weeks after the event. Therefore, real-time monitoring using data loggers/divers offers the means for collecting high-frequency data to provide accurate data for managing groundwater resources efficiently.

Monitoring techniques being used globally

There are several techniques available for groundwater monitoring. Developing countries like Pakistan still use conventional (manual) methods for groundwater monitoring through bore wells and piezometers. A variety of techniques used for groundwater monitoring in different countries is outlined in Table 6.

Table 6. Groundwater monitoring practices being used globally. Source: adapted from IGRAC (2020)

Countries	Monitoring technique	Monitoring frequency	Product
Algeria, Malaysia, Colombia, Uruguay, Tunisia, etc.	Manual	Less than 3 months to yearly	–
Australia, Paraguay, Switzerland, Myanmar, Somalia, etc.	Water level logger	Daily or several times a day	GWL status and trend maps
Chile, France, Serbia, etc.	Automatic and manual	Wide range of frequencies	Statistics, GWL maps and GWL graphs, respectively
New Zealand	Automatic	Daily or several times a day	Statistics
India, Pakistan, Bangladesh, etc.	Manual	Twice a year	GWL maps

Note: for references, see References section of the main report.

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