Exploring Groundwater Dynamics: A Comprehensive Investigation and Spatial Mapping in Canal Command Areas of Sindh

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Executive Summary

Groundwater stands as the keystone of primary water source and a crucial factor in advancing irrigated farming across numerous global regions. Pakistan solidifies its position as the world's fourth-largest groundwater consumer. The Sindh province of Pakistan has about 80% saline groundwater. The prevalence of higher salinity levels in Sindh province is primarily attributed to inadequate drainage conditions and the existence of shallow and brackish groundwater. However, due to low conveyance efficiency and uneven distribution of surface water, farming communities have been compelled to increasingly depend on groundwater, especially in the downstream areas.

This study was planned in Sindh in line with the National Water Policy, 2018, which emphasizes for the development of Groundwater Atlas for each canal-controlled area. Accordingly, detailed and comprehensive study has been completed in partnership with Sindh Irrigation Department (SID) through Sindh Irrigation and Drainage Authority (SIDA). This study aims to delineate fresh groundwater quality pockets in the 14 canal command areas of Sindh Province. The Sindh Water Policy, 2023 also provides clear guidance to the Government of Sindh on sustainable groundwater management aiming to identify fresh groundwater quality pockets for safe extraction.

This study includes the investigations of both groundwater and surface water. Groundwater studies comprise of characterizing soil properties, Electrical Resistivity Survey (ERS), measurements of depth to water table and groundwater monitoring (pre-monsoon and post-monsoon, 2021) in 14 main canal command areas. For surface water, discharge measurement through Acoustic Doppler Current Profiler (ADCP) and calculation of seepage rates through seepage meter in canal beds were carried out at 20 km cross section.

The findings of the study revealed that Kotri Barrage's command area and the downstream of Sukkur Barrage are characterized by major soil types like clay loam, clay, and loamy soils. The predominant soil type in the upstream of Guddu Barrage is sandy clay loam, followed by loamy soil. Soil salinity findings reveal that within Guddu Barrage's command zone, except the western side of Begari Sindh and Desert Pat Feeder, the soil profile down to 90 cm depth ranges from non-saline (ECe < 4 dS/m) to slightly saline (ECe 4 - 8 dS/m). The downstream segments of the Nara, Akram Wah, Phuleli, Pinyari, and Begari show moderate salinity (ECe 8 - 15 dS/m) to strong salinity (ECe > 15 dS/m) levels, extending from the surface to deeper depths (90 cm) in Mirpurkhas, Sanghar, Badin, Sujawal, Thatta, and Jacobabad Districts.

The Desert Pat Feeder and Begari Sindh Feeder areas have a shallow depth (less than 2.0 m), primarily due to the cultivation of rice in these regions. Additionally, Kalri Baghar and Pinyari canal command areas show prevalence of the shallow water tables. Laboratory analysis of groundwater samples shows fresh groundwater quality at shallow depths upto 16 m depth in areas such as: Ghotki, Khairpur West, Begari Sindh, North West, Rice canal, and downstream Rohri, spanning districts like Ghotki, Khairpur, Shikarpur, Larkana, Matiari and Tando Allahyar. During post-monsoon period, there is a 4% improvement in the quality of fresh groundwater attributed to the recharge of rainfall as well as nearby river and canal irrigation network.

The ERS findings suggest that groundwater at a depth of 25 m in the downstream regions of Phulei, Pinyari, Kalri Baghar Feeder, Akram Wah and Nara canal command area exhibits high salinity levels (EC > 4.0 dS/m). This salinity is likely influenced by factors such as sea water intrusion, flat topography, low-lying tracts, inadequate drainage, and the presence of fine layers like clay loam and clay. The results suggest that groundwater extraction should be conducted safely in the Ghotki, Begari Sindh Feeder, North West canal, Rice, Khairpur West, Khairpur East, upstream and downstream Rohri command areas, particularly in proximity to the River Indus up to a depth of 100 m. This implies that the aquifer recharge is significantly influenced by seepage losses from the canals and the River Indus. This highlights the significance of implementing careful canal lining practices.

The discharge of canals was measured through an ADCP instrument. The results reveal that discharge at head was substantial but gradually reduces due to flow diversions to distributaries as well as minors for irrigation purpose and seepage losses. Seepage rates demonstrate diverse trends across different canals, influenced by local conditions and soil strata.

1. Introduction

Groundwater has emerged as an important water resource, and its increasing demand in agriculture, domestic, and industrial sectors underscore its strategic significance. Global estimates indicate that the annual groundwater extraction worldwide is approximately 750 - 800 km^3, accounting for about one-sixth of the total freshwater abstraction (Shah, 2000). Pakistan is the world's fourth-largest user of groundwater for irrigation. The total groundwater potential is approximately 68 billion cubic meters (BCM), with around 60 BCM currently being exploited (Qureshi, 2018; Basharat and Tariq, 2015).

The available groundwater resource in Sindh is approximately 6.2 BCM and holds ample potential for irrigation. However, the utilization of groundwater is relatively lower (4.3 BCM) than surface water due to two primary reasons (Steenbergen et al., 2015). A significant portion of the area is situated over saline or brackish water and the canal command areas receive sufficient surface irrigation supplies.

About 1.2 million private tubewells are operational in the country, with 85% located in Punjab, 6.4% in Sindh, 3.8% in Khyber-Pakhtunkhwa, and 4.8% in Balochistan (Qureshi, 2020). In Sindh province, the use of groundwater is minimal due to quality concerns, resulting in lower utilization for irrigation compared to Punjab (Ahmad et al., 1998; Young et al., 2019). In Punjab, only 23% of the area has poor groundwater quality, while in Sindh, it is 78% (Bakshi and Trivedi, 2011). In Punjab, groundwater quality ranges from 0.5 to 4.5 dS/m, whereas in Sindh, it rises to 9.0 dS/m (Bhutta, 2002; Qureshi et al., 2009).

About 35% of Sindh's total area have water table within 1.5 m, resulting in significant waterlogging issues (Steenbergen, 2020). In 2013, the average annual depth to the water table ranged from 0.2 to 3.0 m, covering approximately 98% area. Out of this, about 51% area experienced waterlogging conditions with a depth to water table (DTW) less than or equal to 1.5 m (Iqbal et al., 2020). Due to these challenges, the development of private tubewells in Sindh remained limited, and groundwater fluctuations are less noticed compared to other regions. This constraint can be attributed to the restricted exploitation of groundwater due to the reasons explained above.

However, low conveyance efficiency and mismanagement of surface water have compelled the farming community particularly at the tail-ends to rely on groundwater. As a result, groundwater depletion in these areas triggered the saline water up-coning, leading to secondary salinization. The cultivation of high delta crops such as sugarcane, rice, and banana, using traditional irrigation practices, presents another challenge contributing to low water productivity. Generally, canal water is more accessible to head and middle-reach farmers, while tail-end farmers frequently express concerns about the inadequate availability of their rightful share. This situation not only compromises groundwater quality due to reduced recharge but also imposes an additional burden in the form of pumping costs on the shoulders of tail-end communities.

Presently in Sindh, there is no regulation or authority to control the over-extraction of groundwater. Sindh Water Policy, 2023 highlights that groundwater rights have not yet been introduced in the province. The Policy proposed reforms in the associated institutions for the restructuring of Sindh Irrigation Department and Sindh Irrigation and Drainage Authority into Sindh Water Resources Management Department. Under this department, Groundwater, Drainage and Water Quality Directorate will be established dealing with the policy, planning, allocation, regulation, operation and maintenance of vital parts of the system. A mechanism for water governance and crucial policy actions concerning groundwater management will be implemented by preparing and enforcing the appropriate regulations for licensing of groundwater to ensure the safe extraction of groundwater, taking into account the site-specific aquifer conditions in various ecosystems.

According to National Water Policy (Clause 16), the provinces shall be encouraged to prepare a Groundwater Atlas for each canal command and sub-basin, enforce legislation and take regulatory measures. For the development of atlas and management of groundwater, the following information is necessary:

- Identification of depth to water table in different canal commands/zones
- Mapping of water quality zones
- Identification of fresh-saline water interface
- Determination of fresh groundwater potential.

The Sindh Irrigation Department (SID) entrusted Pakistan Council of Research in Water Resources (PCRWR) to conduct comprehensive groundwater investigation for the demarcation of fresh groundwater quality along with identification of depth to water table in 14 major canal command areas of the province.

1.1 Irrigation Network in Sindh

Irrigation in Sindh province has a long history spanning thousands of years. The development of irrigation infrastructure has played a vital role in enabling the existence and fostering the growth of agriculture in this region. Without it, virtually there would have been no agriculture. From Moen-jo-Daro era (5000 years ago) the waters of Indus have governed the overall development of Sindh. Even the name Sindh is derived from one of the original names of the Indus River. The irrigation network infrastructure of the province is given in Table 1. The irrigation was intensified through the construction of barrages and development of canal irrigation system.

Table 1: Barrages with canal irrigation network

Barrage	Canals	Command Area (Mha)	Design Discharge (m^3/sec)	Districts in the Command Area
Guddu	Desert Pat Feeder	1.17	33,980	Ghotki, Sukkur, Kashmore, Kandhkot, Jacobabad, Shikarpur, and Larkana districts of Sindh. Nasirabad and Jafarabad districts of Balochistan province
	Begari Sindh Feeder			
	Ghotki Feeder			
Sukkur	Rohri	3.09	42,450	Sukkur, Kambar Shahdadkot, Khairpur, Shikarpur, Jacobabad, Dadu, Larkana, Sanghar, Tando Allahyar, Umerkot, Mirpurkhas, Tharparker, Naushahro Feroze, Shaheed Benazirabad, Matiari, Tando Allahyar, and Badin.
	Nara			
	Khairpur East			
	Khairpur West			
	North West (Kirthar)			
	Rice			
	Dadu			
Kotri	Pinyari	1.21	24,800	Districts Hyderabad, Thatta, Tando Muhammad Khan, Jamshoro, Badin and Karachi
	Phuleli			
	Akram Wah			
	Kalri Baghar Feeder			

Sindh has been one of the major beneficiaries of irrigation development on the Indus River. There are 3 barrages and 14 main canals that irrigate approximately 5 Mha of area (Steenbergen, 2014), along with 1,446 distributaries/minors and 45,000 watercourses (Memon, 2006). The first barrage in the province was completed in 1932 at Sukkur. Later on, irrigation system was further expanded through construction of Kotri Barrage (1955) and Guddu barrage (1962). The canal system in Sindh is an integral component of the Indus Basin Irrigation System (IBIS), providing irrigation water for agriculture and supporting the economic development of the province. The canal command areas of the 14 distinct canals are shown in Figure 1.

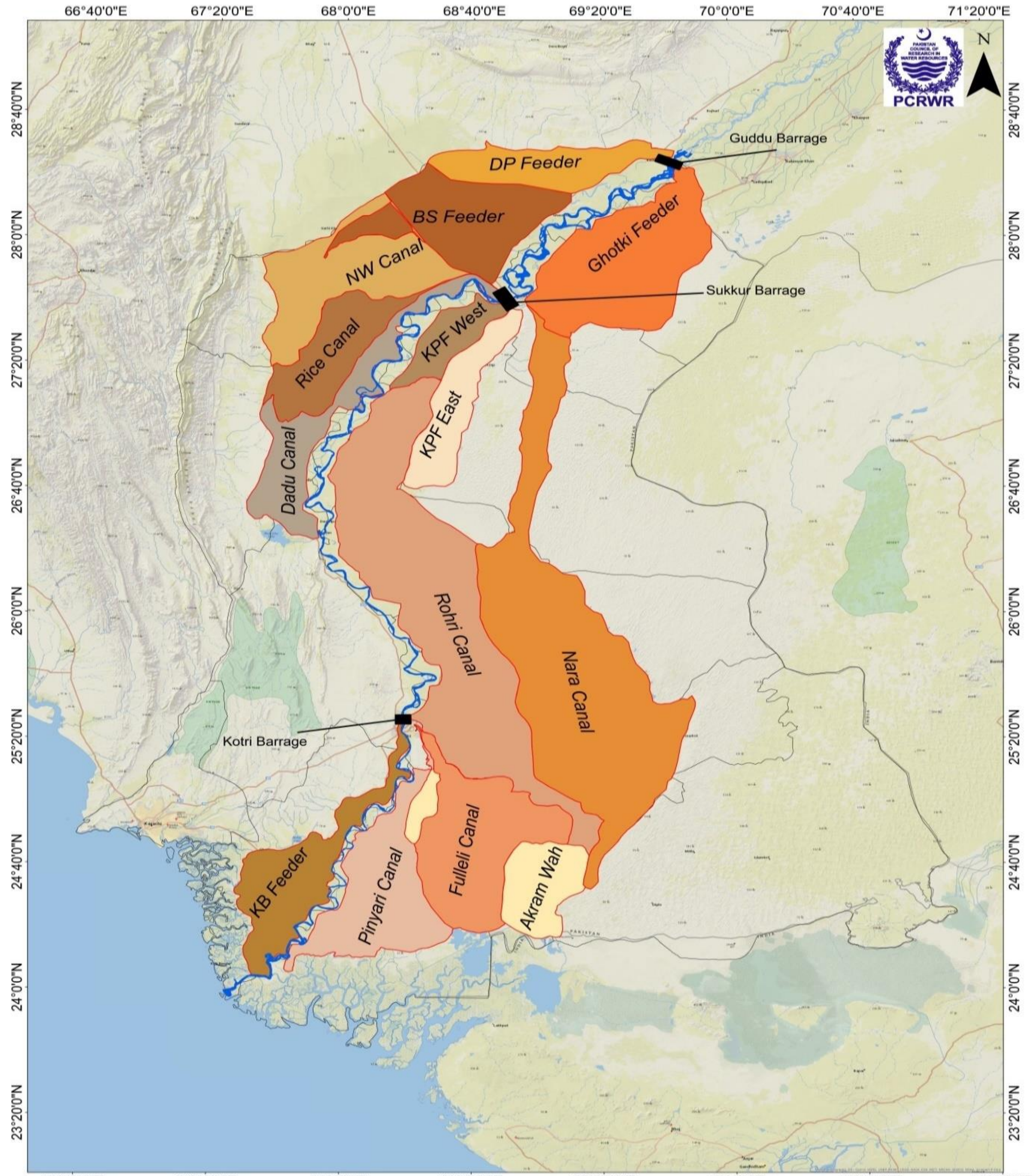

Figure 1: Canal command areas of Sindh

The canal water is not only a source of irrigation, but it also helps in recharging the groundwater. Seepages of freshwater from the canals, major and minor distributaries, watercourses and field application losses have developed a lens of the freshwater of varying thickness overlying on saline groundwater (Ashraf et al., 2012). The abstraction of fresh groundwater from such aquifer is complex process, necessitating careful consideration of water quality rather than focusing solely on quantity due to delicate interface between fresh and saline groundwater. Any excess water abstraction results in salt water up-coning (Saeed et al*.,* 2003). Therefore, groundwater investigation and mapping at canal command scale is imperative for the demarcation of fresh water zones as well as sustainable management. The objectives of the study were:

1.2 Objectives

i) Analyzing spatial variations in depth to water table on seasonal basis (Pre-Monsoon and Post-Monsoon).

ii) Demarcation of spatial variation in groundwater quality and identification of fresh groundwater pockets.

iii) Assessment of canal water discharges and calculation of seepage rate.

1.3 Scope of the Study

The scope of this study covers the irrigated areas falling under the canal commands of 14 major canals in Sindh province including Tharparkar District as well as Malir Area (cultivated area between Hyderabad and Karachi). Considering the natural calamities such as COVID – 19, the 2022 floods, law and order situation in Guddu Barrage command area and time constraint, PCRWR mainly focused the canal command areas of 14 canals whereas; the Malir area could not be completed due to above mentioned limitations. Owing to the challenging law and order conditions in the Katcha region along the Indus River, the measurement of discharge and seepage in four canals namely Desert Pat Feeder, North West canal, Ghotki canal, and Begari Sindh Feeder could not be executed. For Tharparkar, PCRWR has recently published a separate technical report titled, "Beneath the Sands: A Comprehensive Study of Groundwater in Tharparkar Region” (Salam et al*.,* 2023). This report is now accessible from the organization's website (https://pcrwr.gov.pk/wp-content/uploads/2023/09/Beneath-the-Sands-Groundwater-Study-in-Tharparkar-Region.pdf.

2. Methodology

In this study, an integrated methodology was adopted. In order to characterize soil texture, soil salinity and sodicity, samples were collected and analyzed for Electrical Conductivity, Sodium Absorption Ratio and Exchangeable Sodium Percentage. For groundwater investigations, depth to water table was measured to assess the groundwater behavior and groundwater samples were collected to characterize chemical properties. Geophysical technique namely Electrical Resistivity Survey was used to examine the groundwater quality. For surface water, discharge of canals was measured through Acoustic Doppler Current Profiler (ADCP) and seepage rates were determined through seepage meter (Figure 2).

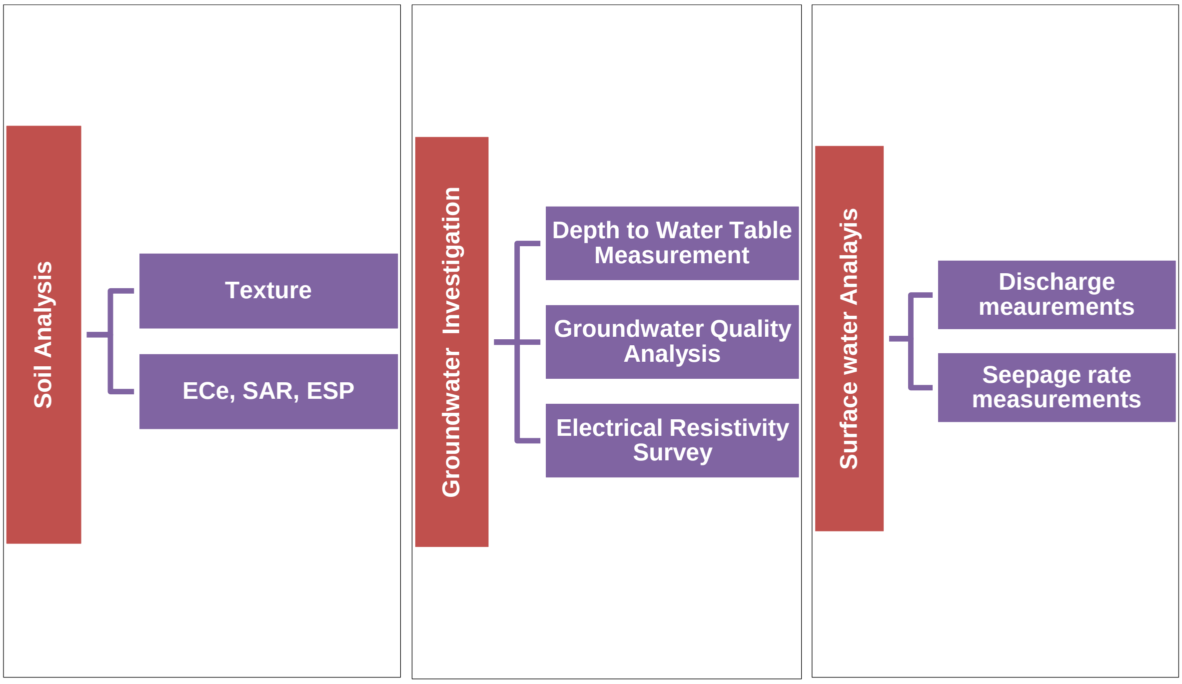

Figure 2: An integrated methodology of the study

Overall, 832 soil samples were collected from 208 locations using an auger, at different depths: 0 - 15 cm, 15 - 30 cm, 30 - 60 cm, and 60 - 90 cm, on a 25 km x 25 km grid interval. The depth to water table (DTW) measurements and groundwater water quality samples were collected twice a year in pre-monsoon (April, 2021) and post-monsoon (December, 2021) as per designed methodology given in Table 2. In total, 4,009 depths to water table measurements were taken. Similarly, 4,257 groundwater samples were collected and analyzed for detailed quality analysis at DRIP, PCRWR, Laboratory.

The ABEM Terrameter equipment of SAS-4000 model was used with Schlumberger configuration. The field data was processed using IX1D software. For mapping purpose, Inverse Distance Weighted (IDW) interpolation technique was used in ArcGIS software for spatial analysis. Moreover, thematic maps were created at different depth intervals upto 300 m to demarcate lateral and vertical variations in groundwater quality.

Table 2: Measurements at cross sections on left and right side of each canal

Survey Description		0 m	300 m	600 m	1 km	5 km	10 km	20 km	30 km	40 km	50 km	60 km
Groundwater	DTW (Pre & Post Monsoon)			✓	✓	✓	✓	✓		✓		✓
	WQ Sampling Pre & Post Monsoon			✓	✓	✓	✓	✓		✓		✓
	ERS Probes	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Surface water	Discharge	✓						✓		✓		✓
	Seepage rate	✓						✓		✓		✓

Electrical resistivity probes (2,212 Nos.) were carried out upto the depth of 300 m on both sides of canals depending upon the length and width of each canal command. The one-time, one-spot discharge and seepage measurements were taken along the length of the canal at every 20 km cross section. For discharge measurement, ADCP is now a commonly used method for measuring streamflow (Figure 3). The ADCP River Ray 600, manufactured by Teledyne Company in the USA, was used for data acquisition up to a depth of 40 m. This instrument has been manufactured in 2015 and provided by UNESCO to PCRWR by ensuring the best available technology. All standard operating procedures for discharge measurement were adopted. The accuracy and consistency through parameters were ensured, such as shape of the stream banks, ADCP draft depth (0.15 m), and un-measured zones extrapolation power factor (1/6) to standardize the measurements. Further steps like clock synchronization, diagnostic test of the ADCP with WinRiver-II software, distance from magnetic materials, minimum water velocity, uniform flow, proper site selection, compass calibration, moving bed (loop test) and 4 - 6 number of transects were carried out successfully. All measurements were taken through GGA mode.

Figure 3: Acoustic Doppler Current Profiler (ADCP)

Seepage in the canal section is an important component of the water mass balance. Seepage meter comprises a seepage bell of 60 cm diameter cylinder having depth of 50 cm and 13 mm nozzle. A simple version of seepage meter with accessories is given in Figure 4. It consists of an inverted drum cut at the bottom and connected at the top through a hose to a flexible water reservoir floating on the water surface. Working under air tight condition, water loss from the drum through seepage from its bottom bed is compensated by the water in the flexible reservoir. Volume of water loss over the given time interval is recorded. The seepage rate of the river channel at the point of measurement is then calculated by dividing the volume of water lost by the area of the drum bed and time lapsed (Malik and Ashraf, 2017).

Figure 4: Seepage meter with accessories

3. Results and Discussion

3.1 Soil Texture Analysis

Soil texture plays a significant role in groundwater recharge and soil moisture. Figure 5 illustrates the dominance of clay loam at all respective depths, followed by clay and loamy soil.

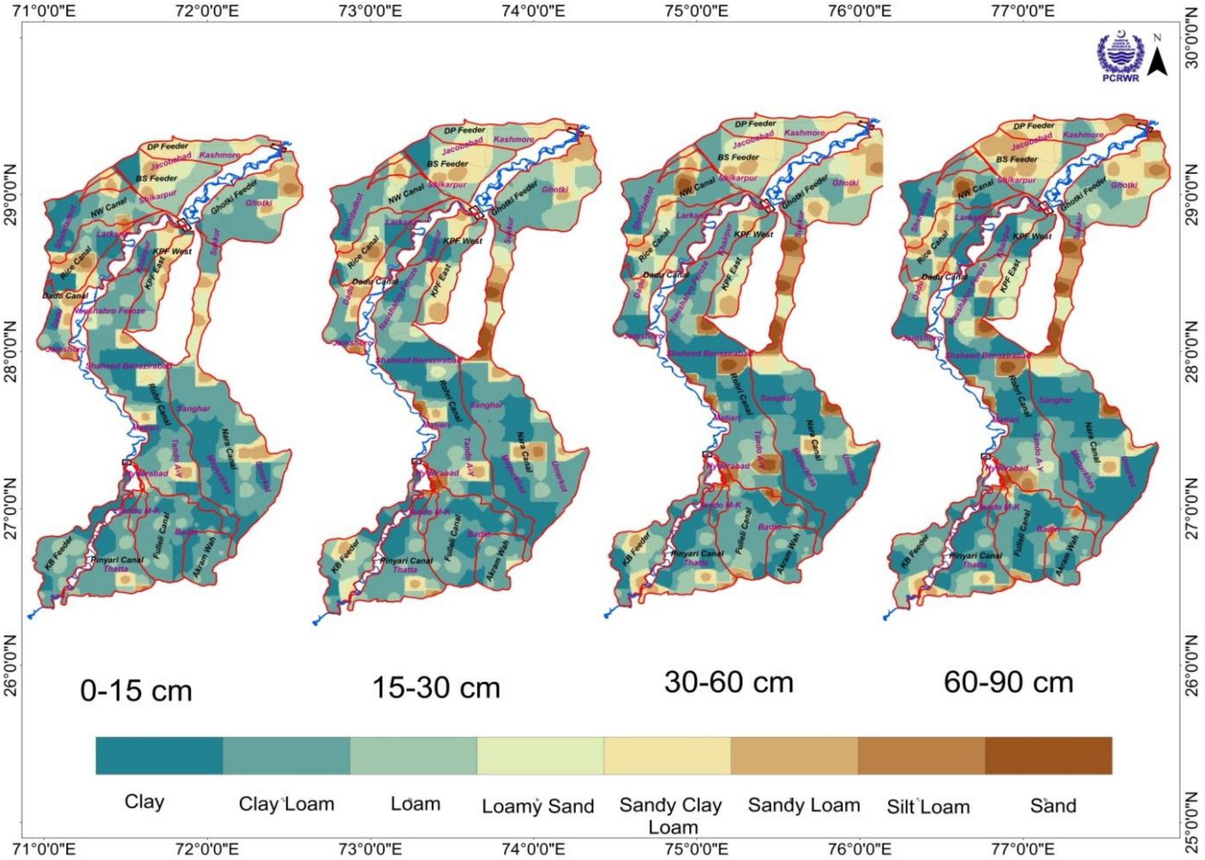

Figure 5: Sub surface lithological variations in 14 CCAs

About 39% of the top soil is covered with clay loam soil, followed by clay (22%), loam (18%) and sandy clay loam (Figure 6). Therefore, the predominant soil texture, constituting 89% of the area, is clay loam, clay, loam, and sandy clay loam. The results are in agreement with those found by Iqbal et al., (2020). They concluded that clayey strata were more prominent in the Indus Delta, including the areas of Tando Allahyar, Tando Muhammad Khan, Thatta, Sujawal, and Badin Districts. Sandy loam soil predominates in the upper part of the Lower Indus Basin, including Ghotki, Sukkur, and Khairpur Districts. Sandy loam soil also dominates in the Potohar region of Upper Indus basin along with two other textural classes loam and silt loam (Malik and Ashraf, 2023).

The clay loam, clay and loamy soils are dominant in Kotri Barrage and downstream of Sukkur Barrage command area. At the upstream of Guddu Barrage, sandy-clay loam is dominant followed by loamy soil. The sub surface soil lithological variation shows that clay and loamy soils gradually decrease to 29% and 15%, respectively at 60-90 cm depth. However, the clay content in the soil texture slightly increases from the top layer to the bottom layer from 22% to 27%. The higher percentage of clay loam soil may be due to the accumulation of clay particles over time, as they tend to settle down through the soil profile. Moreover, high clay content could be due to transportation of fine particles with irrigation water.

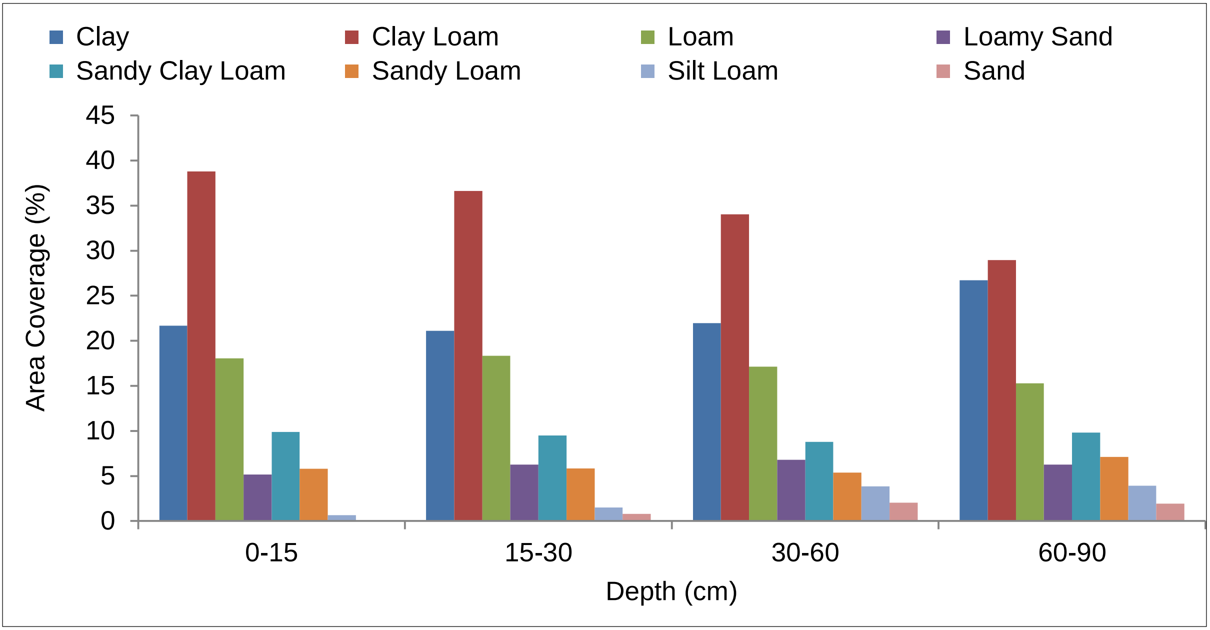

Figure 6: Area coverage of soil texture in 14 CCAs

Clay loam soil has a relatively fine texture with good water retention properties. This means that it can hold water for longer periods. In regions like Indus Delta with high salinity levels in the water, the fine particles in clay loam trap the salts that accumulate over time. As the water evaporates, the salts remain in the soil, leading to increased soil salinity.

3.2 Soil Salinity

Soil salinity refers to the concentration of salts present in the soil, whereas sodium concentration promotes soil sodification. The soil classification based on soil salinity and sodicity is given in Table 3, whereas classification of soil salinity based on Electrical Conductivity (ECe) is presented in Table 4.

Table 3: Classification of soil salinization and sodicity

Soil Type	ECe (dS/m)	SAR	ESP
Normal	< 4	< 13	< 15
Saline	> 4	< 13	< 15
Sodic	< 4	> 13	> 15
Saline – Sodic	> 4	> 13	> 15

Source: Horneck et al., (2011).

Figure 7 shows that the soil profile upto 90 cm depth within the command area of Guddu Barrage is non-saline to slightly saline except few pockets of Begari Sindh and Desert Pat Feeder command areas.

Table 4: Classification of soil salinity based on ECe (dS/m)

Soil Type	ECe (dS/m)
Salt free	< 4
Slightly saline	4-8
Moderately saline	8-15
Strongly saline	> 15

Source: Ghassemi et al*.,* (1995), Steenbergen, et al*.,* (2015).

The soils in the downstream command areas of Akram Wah, Pinyari, Phuleli, Nara canal, and western side of Begari Sindh Feeder are moderate saline (21%) to strongly saline (6%) extending from surface soil to deeper depth (60-90 cm). These command areas comprise the districts of Badin, Thatta, Sujawal, Sanghar, Mirpurkhas, and Jacobabad. The high salinity may be due to high water table, inadequate drainage conditions, and use of poor-quality groundwater. The percentage of ECe in the 14 command areas is illustrated in Figure 8. About 37% of the upper soil layer consists of slightly saline soil (ECe 4-8 dS/m). This condition is noticed throughout the canal command areas.

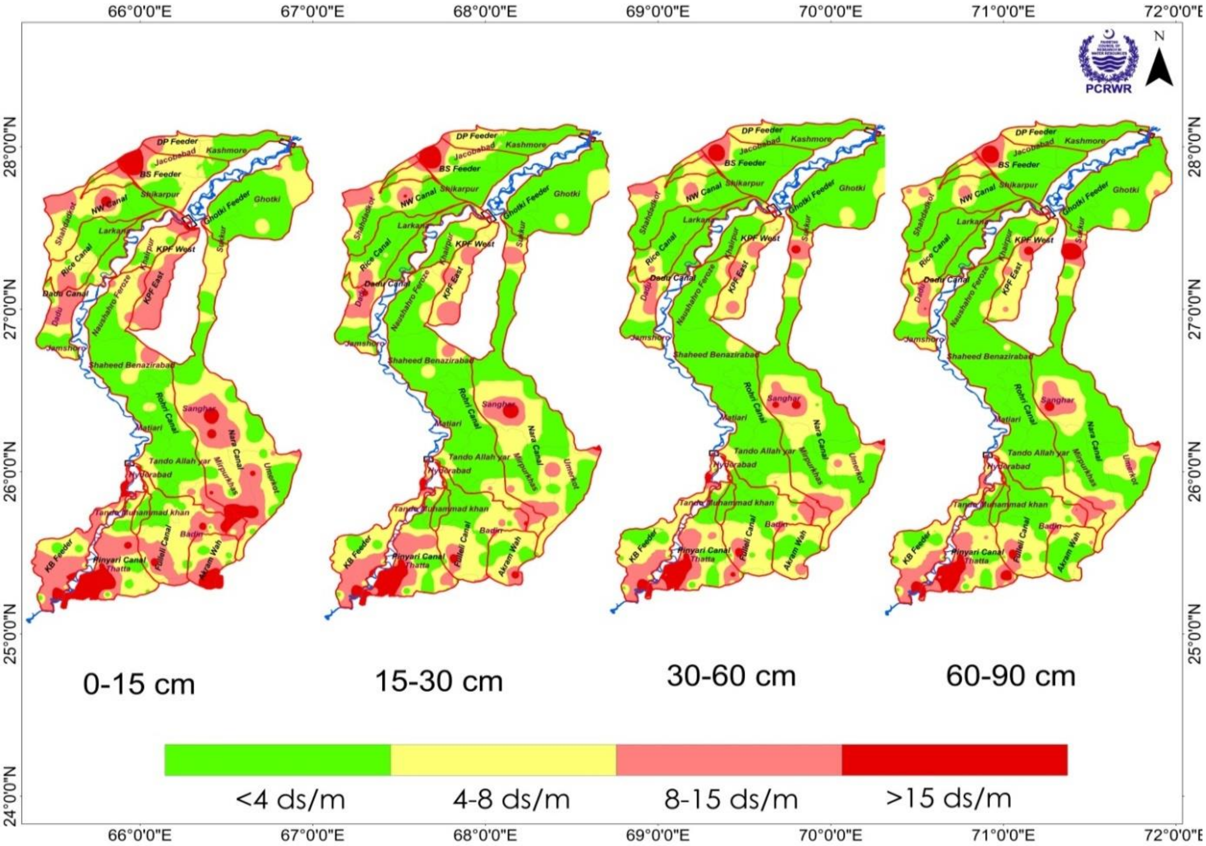

Figure 7: Depth wise spatial variation of soil salinity (ECe) in CCAs

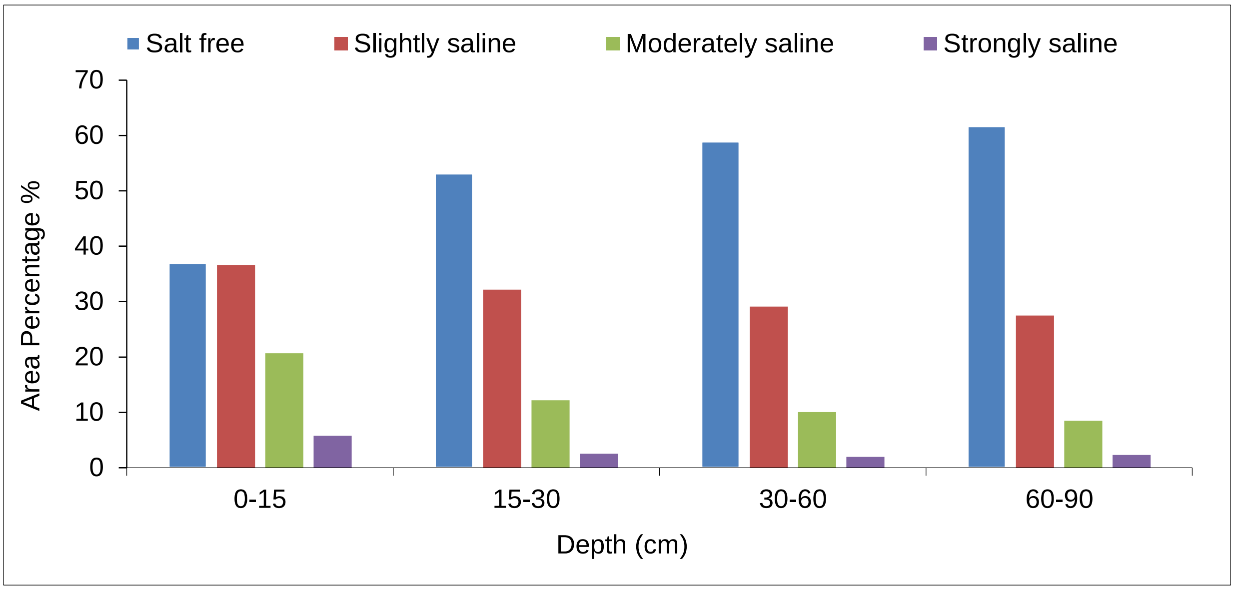

Figure 8: Area coverage of soil salinity (ECe) in 14 CCAs

The non-saline soil varies from 37% to 62%, ranging from the top soil layer (0-15 cm) to the lower layer (60-90 cm). The spatial variation of SAR and ESP is given in Figures 9 to 10.

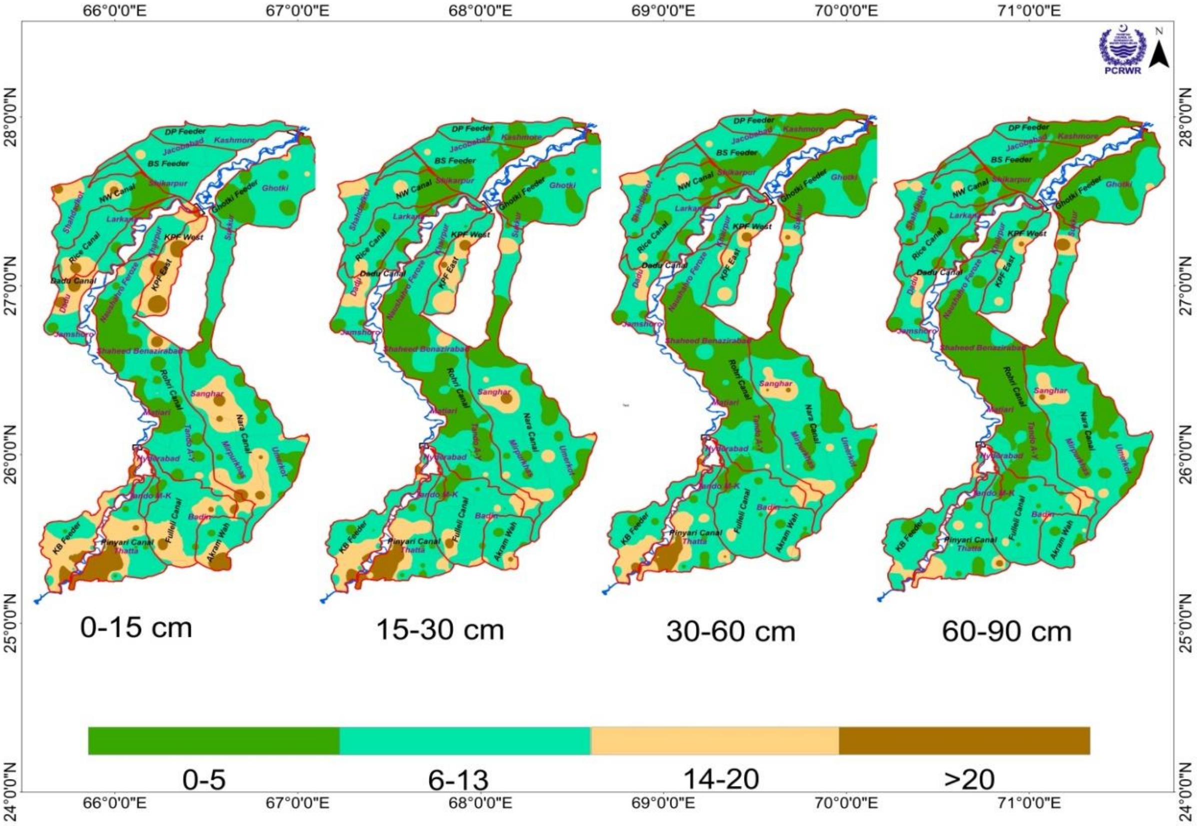

Figure 9: Depth wise spatial variation of SAR in 14 CCAs

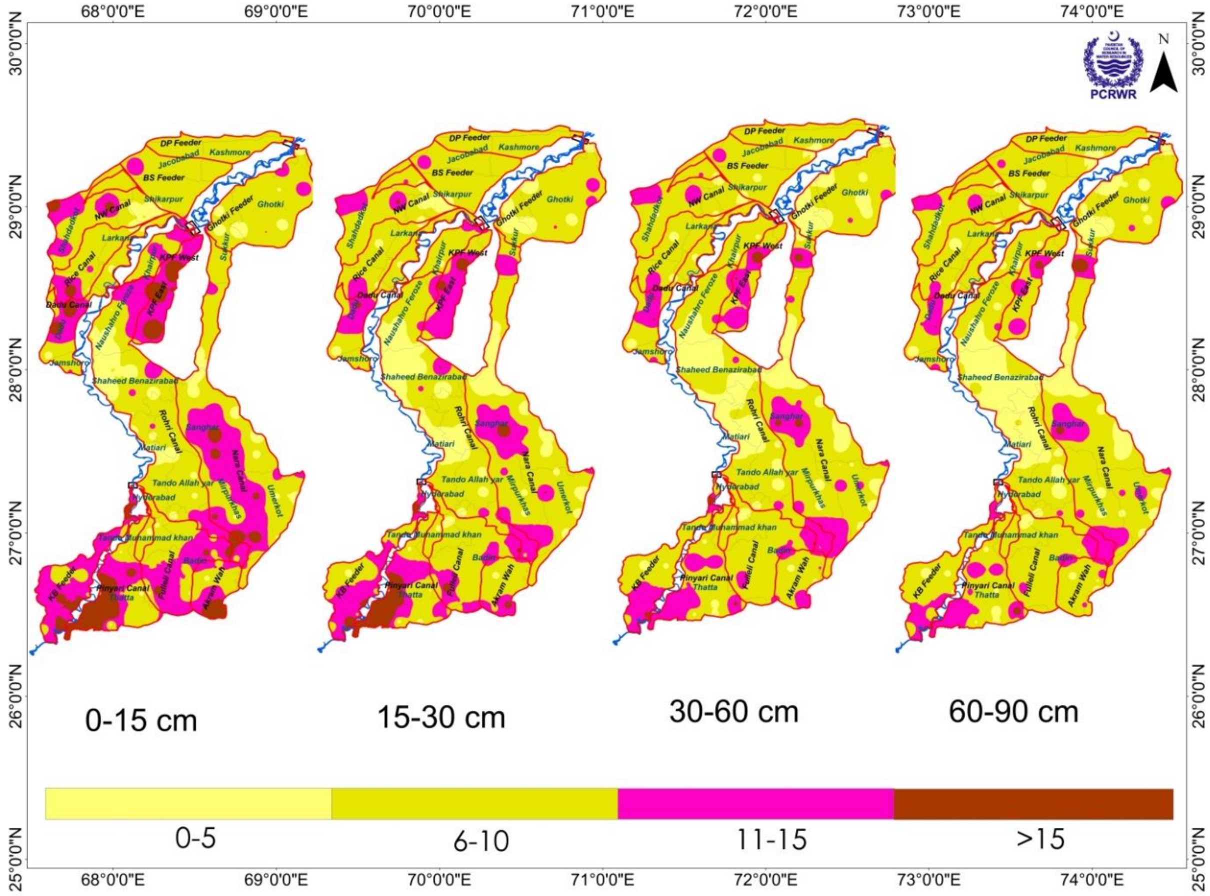

Figure 10: Depth wise spatial variation of ESP in 14 CCAs

The Sodium Absorption Ratio (SAR) and Exchangeable Sodium Percentage (ESP) are on higher side in Dadu, Khairpur East, and lower region of Sindh i.e. downstream Nara, Akram Wah, Phuleli, Kalri Baghar Feeder and Pinyari canal. These results are consistent with those found by Iqbal et al*.,* (2020), that the lower region of Sindh, particularly in the Indus Delta has higher SAR and ESP values.

3.3 Depth to Water Table

Depth to Water Table (DTW) is classified into five classes, ranging from <2 m to greater than 16 m (Figure 11). The DTW analysis reveals that the most significant seasonal variation occurs immediately after monsoon season. The average water-table depth in pre-monsoon season is 4.6 m, whereas in the post-monsoon season, it decreases to 2.4 m. Total command area with 60% falling within 2.1 to 4.0 m water-table depth. Additionally, 28% of the area lies within less than 2 m depth (Figure 12). The Desert Pat Feeder and Begari Sindh Feeder have shallow water-table depths i.e., <2 m. The reason for shallow depth in this region may be due to growing of rice using Pancho irrigation system which is one of the most inefficient irrigation systems (Ashraf et al*.,* 2014).

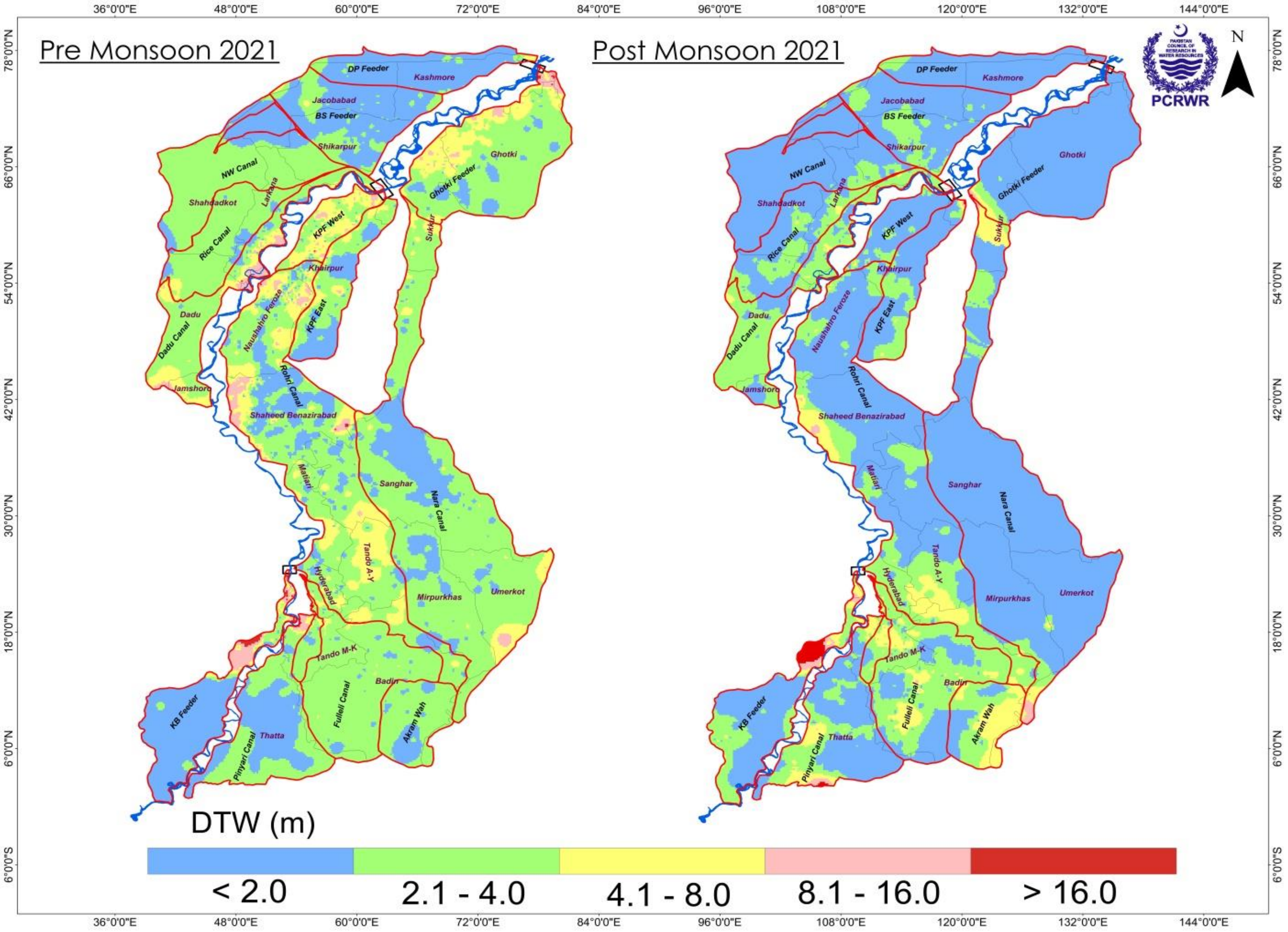

Figure 11: Pre-monsoon and post-monsoon DTW covering 14 CCAs in 2021

The reason of shallow depth to water table in Kalri Baghar and Pinyari canal command may be due to low lying area, sea water rises, and growing high water demanding crops such as rice, sugarcane and banana. The water table rose up to 2 m in 69% of the canal command area in post-monsoon, 2021. The reason for this may be recharge due to rainfall and high flows in canals during the post-monsoon season. Further, 25% area lies under 2.1-4.0 m water-table depth. During the post-monsoon period in 2021, the extent of waterlogging (DTW ≤ 1.5 m) has increased to 42% in canal command areas.

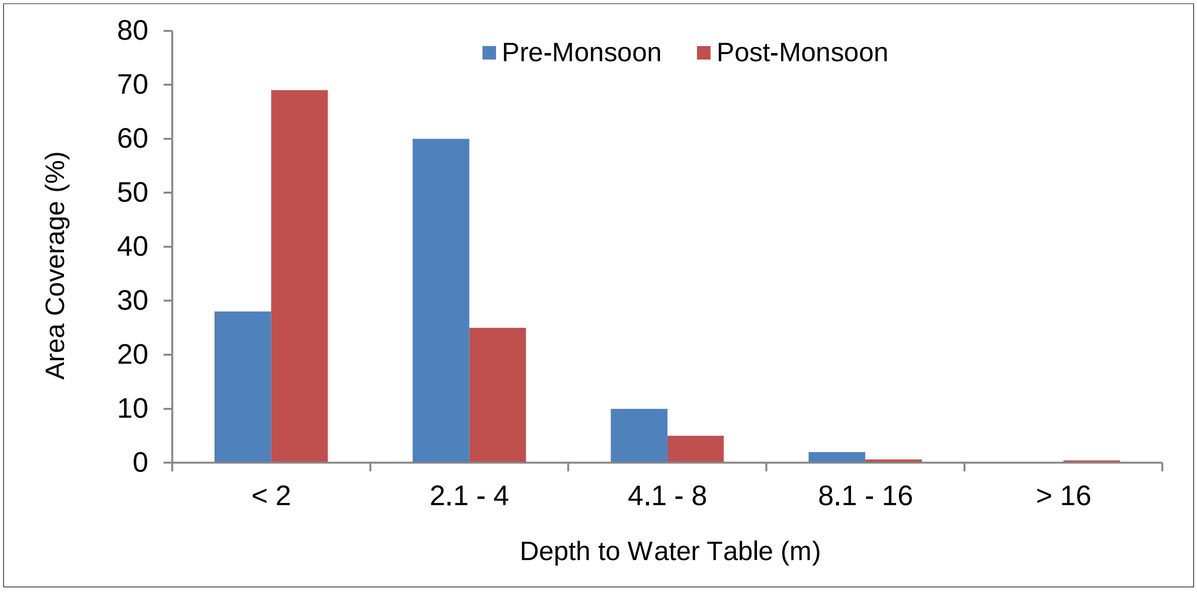

Figure 12: Area coverage of DTW covering 14 CCAs in 2021

The areas under DTW range of <2 m have increased significantly in post monsoon from 28% to 69%. Conversely, the area under DTW 2.0-4.0 m decreased from 60% to 25%. This may be due to increase in shallow water table area (<2 m).

3.4 Groundwater Quality Sampling and Analysis

Groundwater has a broad range of applications in domestic, agriculture and industrial sectors. Therefore, it is important to monitor its quality regularly. The quality of groundwater in terms of EC was measured in the Laboratory and divided into four water quality zones (Table 5). The spatial variation of groundwater quality is given in Figure 13.

Table 5: Water quality zoning

Water Quality Zones	EC (dS/m)
Fresh	< 1.5
Marginal	1.5 – 2.5
Saline	2.6 – 4.0
Highly Saline	> 4.0

Source: Iqbal et al., (2020).

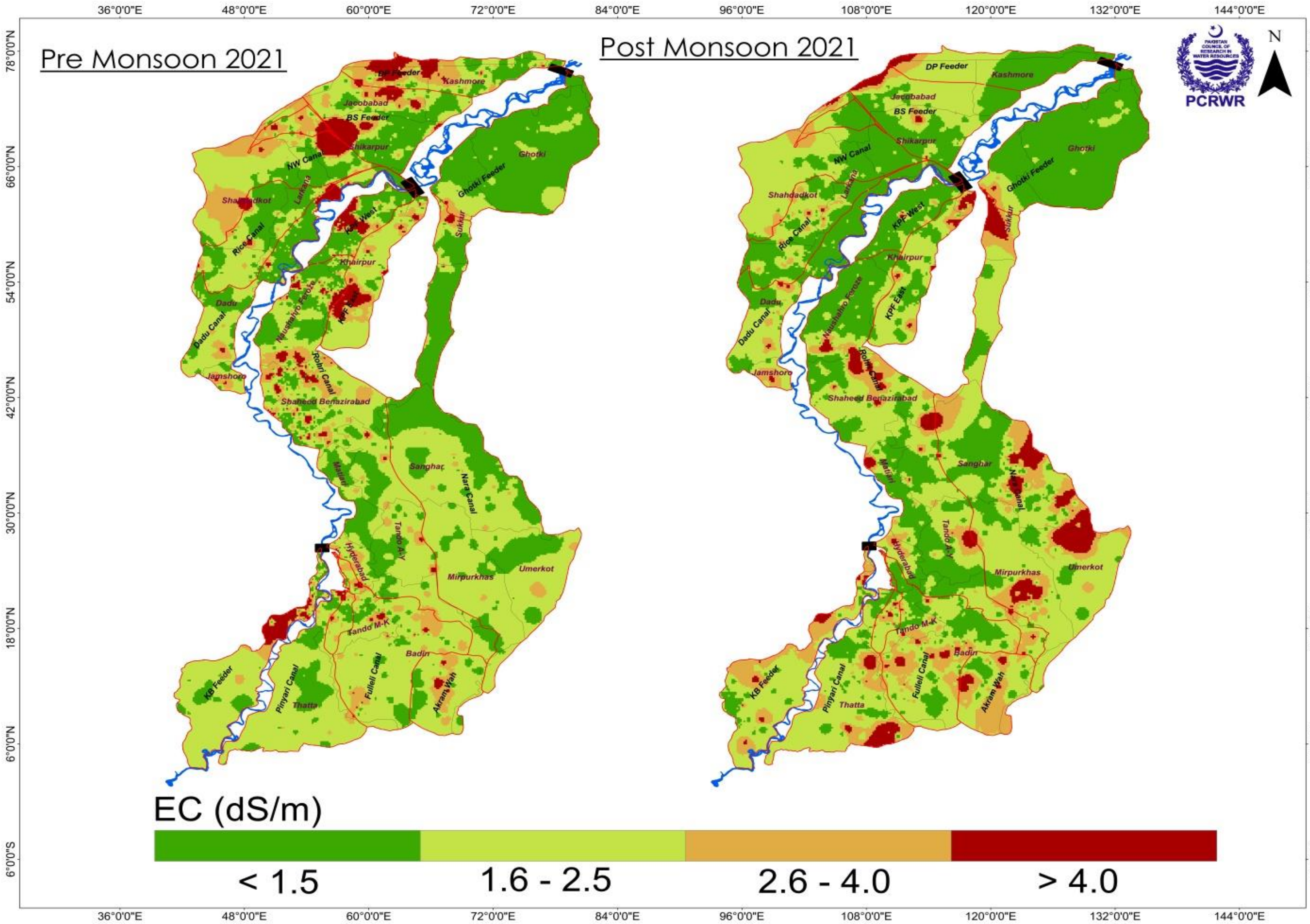

Figure 13: Pre-monsoon and post-monsoon EC variations covering 14 CCAs at varying depths in 2021

Figure 14 illustrates that 52% of the area falls under marginal groundwater quality, 34% area falls under fresh groundwater quality, and remaining 14% of the area falls under saline to highly saline groundwater. The groundwater of fresh quality was found in shallow pockets upto 16 m in Ghotki, Khairpur West, Begari Sindh, North West, Rice canal and downstream Rohri canal commands in the Districts of Ghotki, Khairpur, Shikarpur, Larkana, Matiari and Tando Allahyar.

The reason for fresh groundwater quality at shallow depth may be recharge from river and canal irrigation network as well as cropping pattern. During the post-monsoon, fresh groundwater quality (<1.5 dS/m) is improved by 4%. It shows that in post monsoon, due to recharge from rainfall and high flows in canals, the groundwater quality was improved.

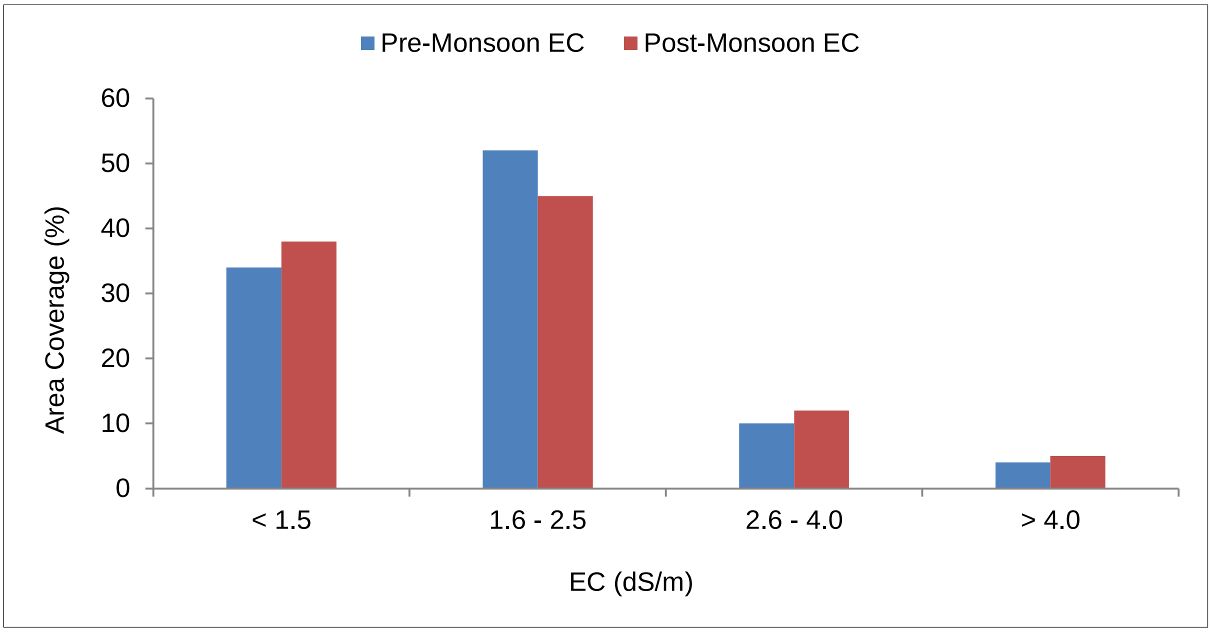

Figure 14: Area coverage of EC covering 14 CCAs in 2021

The majority of area (pre-monsoon, 52% and post monsoon, 45%) falls under marginal groundwater quality at shallow depth (16 m). This water can be used conjunctively with surface water for irrigation purpose (Sheikh and Ashraf, 2009).

3.5 Groundwater Quality Mapping through ERS

The sustainable groundwater management depends on monitoring the groundwater use and evaluating the groundwater quality. The spatial variation of groundwater quality evaluated through ERS is given in Figure 15. The groundwater at a depth of 25 m in the command areas of Phuleli, Pinyari, Kalri Baghar Feeder, Akram Wah, and tail end of Nara canal is highly saline. Saltwater intrusion, low-lying areas, flat topography, inadequate drainage, and the prevalence of fine layers (clay loam and clay) could be the potential factors contributing to increased groundwater salinity in the Kotri Barrage and downstream of the Nara command areas.

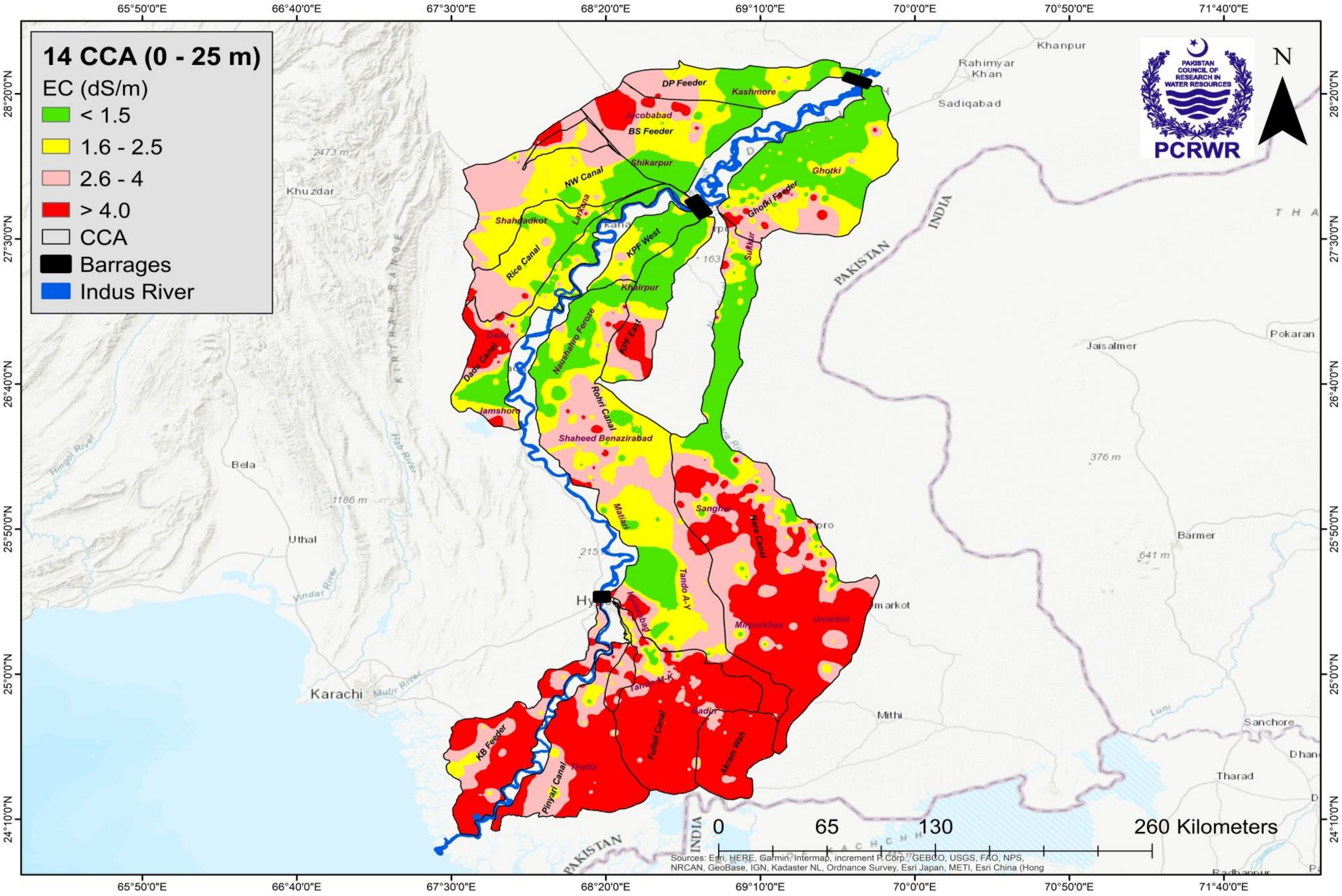

Figure 15: Spatial variation of groundwater quality at 25 m depth

The canal commands closer to River Indus on both sides have fresh groundwater quality that may be due to recharge from the river. The groundwater quality at a depth of 25 m is predominantly highly saline at 30% area, followed by 26% saline, 23% marginal, and 21% fresh (Figure 16).

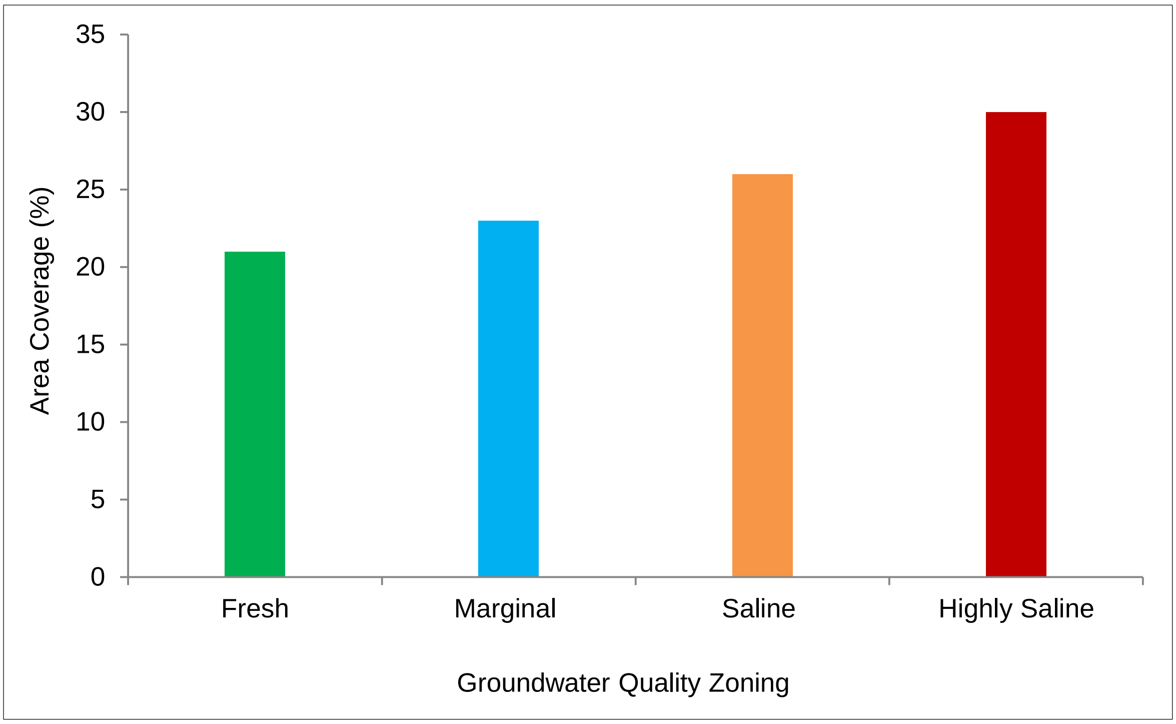

Figure 16: Area coverage of groundwater quality at 25 m depth in 14 CCAs

Most importantly, groundwater quality in the command area of Ghotki, Begari Sindh Feeder, North West, Rice, Khairpur East, and Khairpur West Feeders near the Indus River, covering the districts of Ghotki, Kashmore, Shikarpur, Larkana, Khairpur, Naushero Feroze, Matiari and Tando Allahyar, is suitable for irrigation purposes. The upstream and downstream command areas of Rohri canal have fresh groundwater quality.

The groundwater quality at 26 to 100 m depth is given in Figures 17 to 19. Kotri Barrage command area and downstream Nara canal have highly saline groundwater with EC > 4.0 dS/m. The groundwater can be pumped safely in Ghotki, Begari Sindh Feeder, North West canal, Rice, Khairpur West, Khairpur East, upstream and downstream Rohri command areas close to River Indus upto the depth of 100 m.

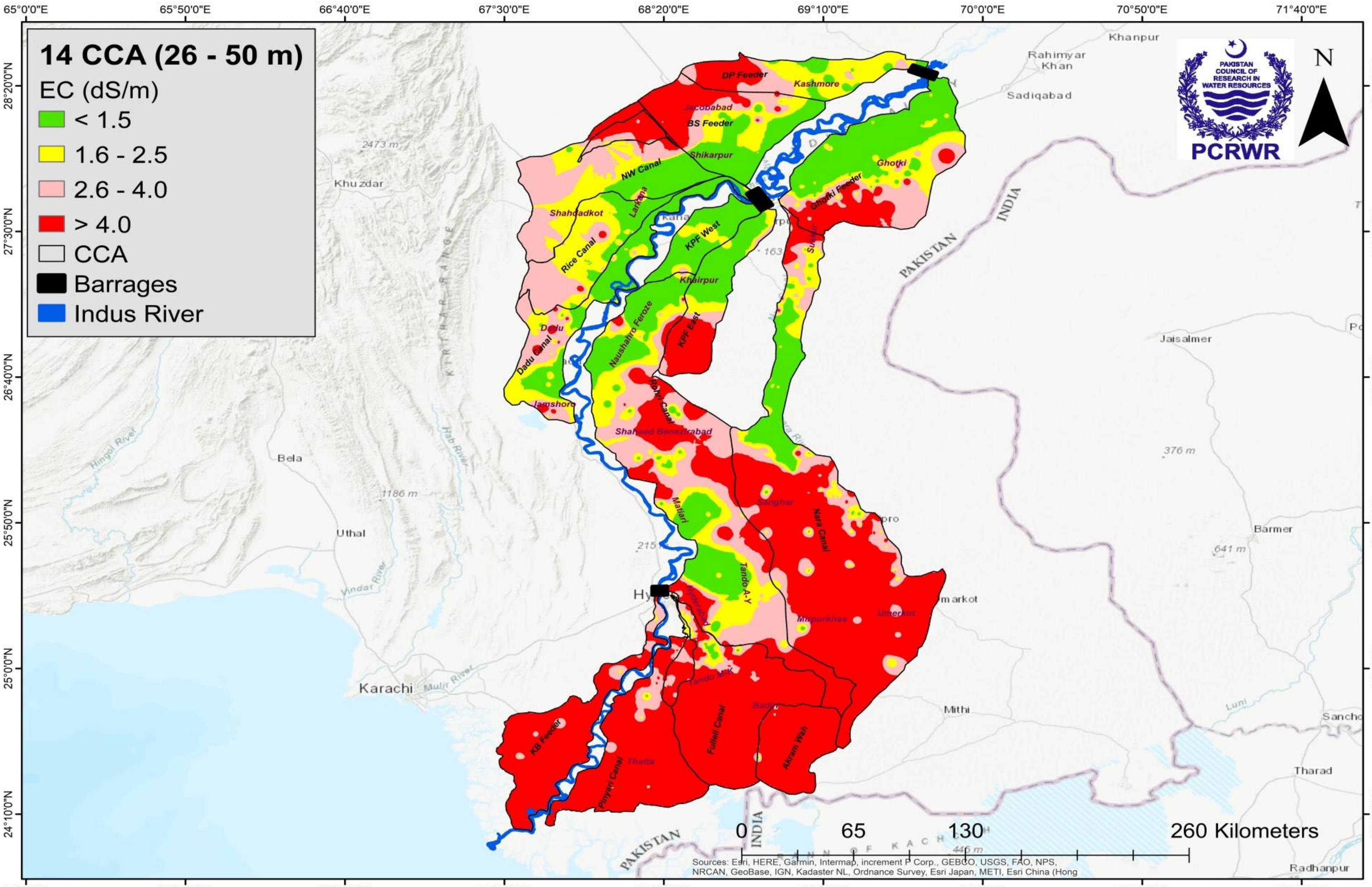

Figure 17: Spatial variation of groundwater quality at 50 m depth

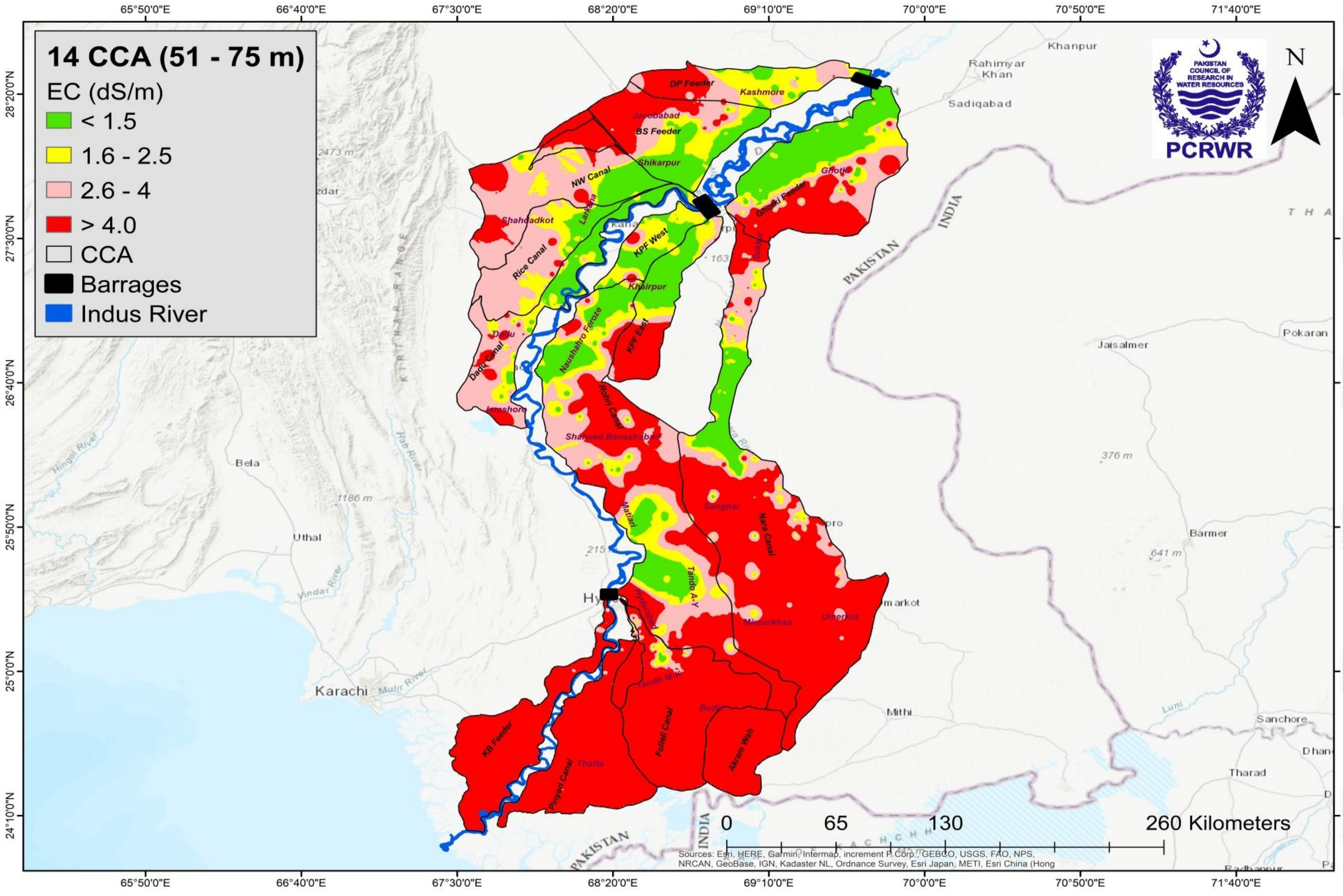

Figure 18: Spatial variation of groundwater quality at 75 m depth

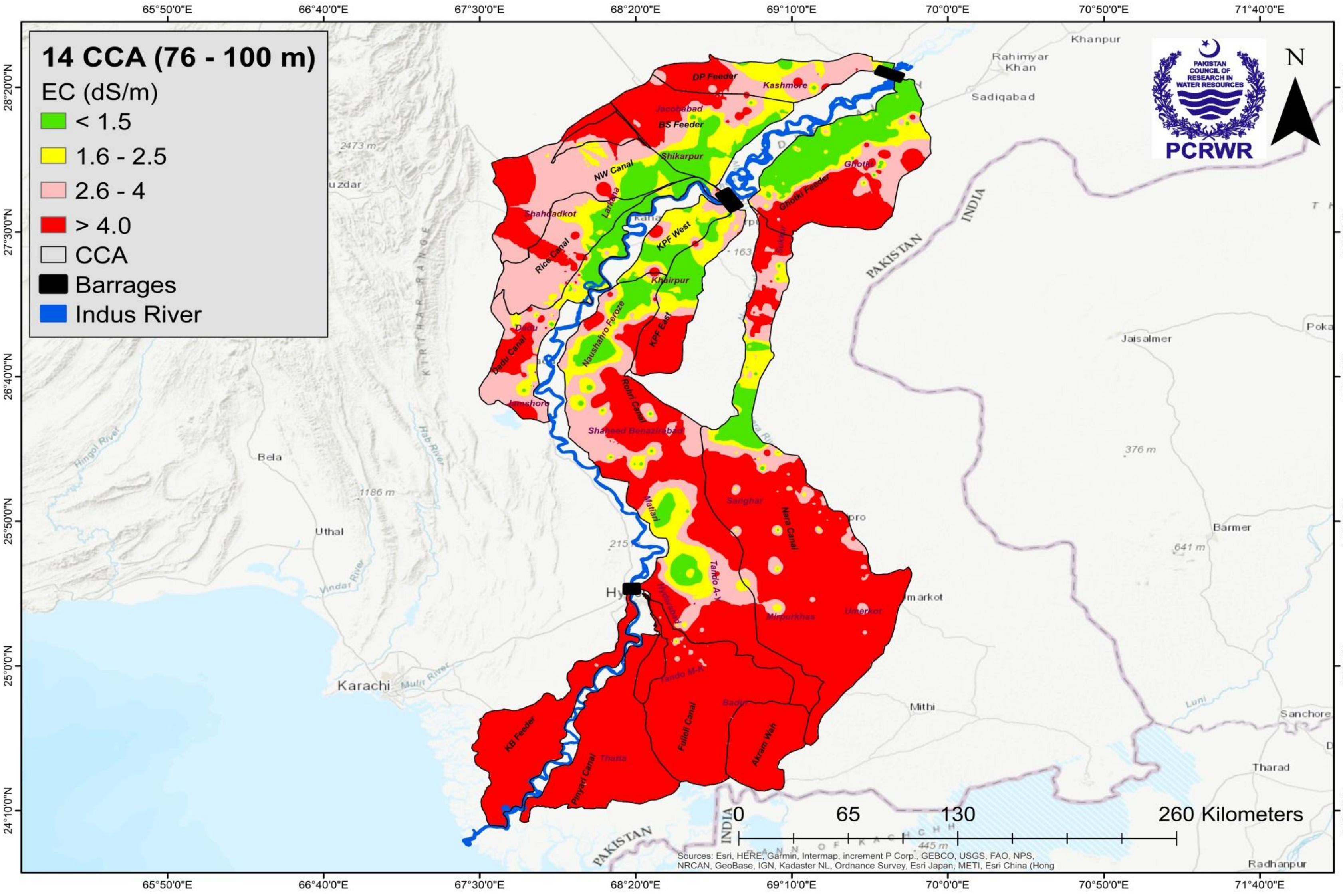

Figure 19: Spatial variation of groundwater quality at 100 m depth

About 45-58% area at 26-100 m depth is highly saline mostly in Kotri Barrage command area and downstream of Nara canal (Figures 20-22). The groundwater covering an area of 11-21% in the command areas of Guddu and Sukkur Barrage near River Indus is suitable for irrigation purposes. The reason for the fresh groundwater quality in these areas could be excessive irrigation in rice fields and recharge of river and canals.

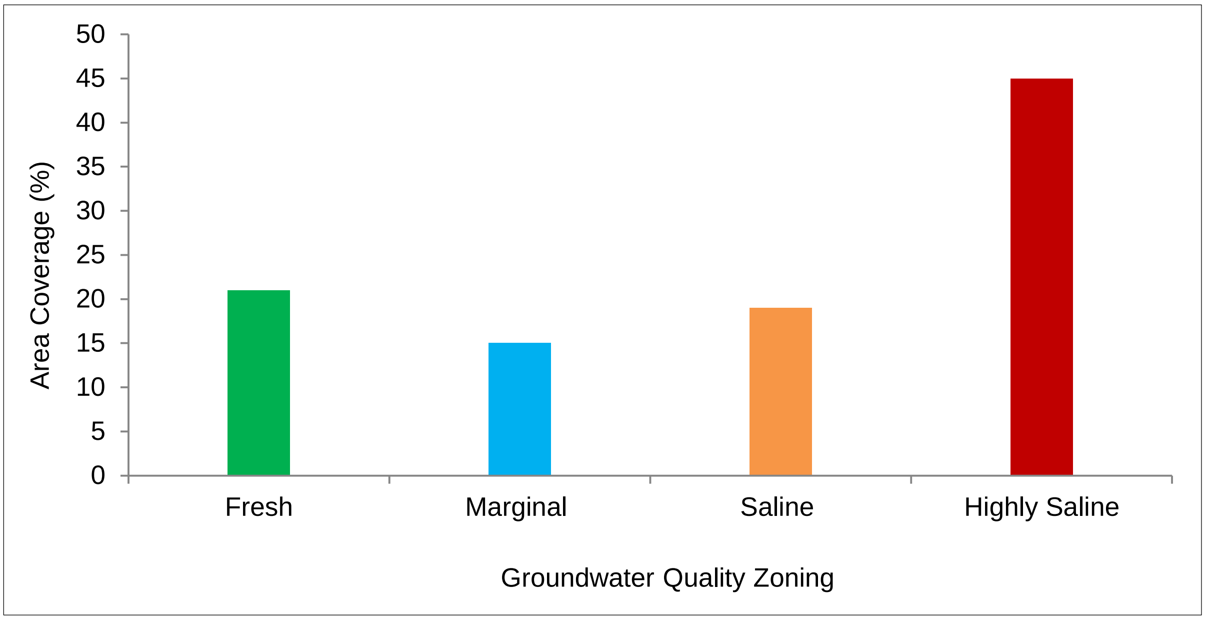

Figure 20: Area coverage of groundwater quality at 50 m depth in 14 CCAs

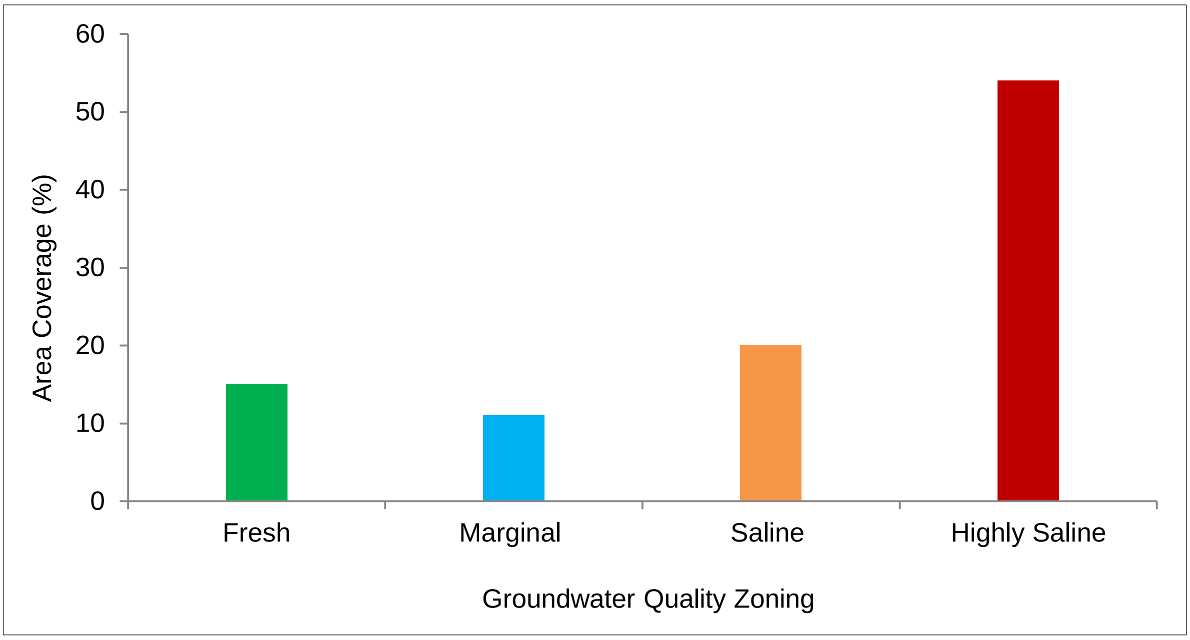

Figure 21: Area coverage of groundwater quality at 75 m depth in 14 CCAs

This shows that seepage from above mentioned canals and Indus River plays a vital role in recharging the aquifer.

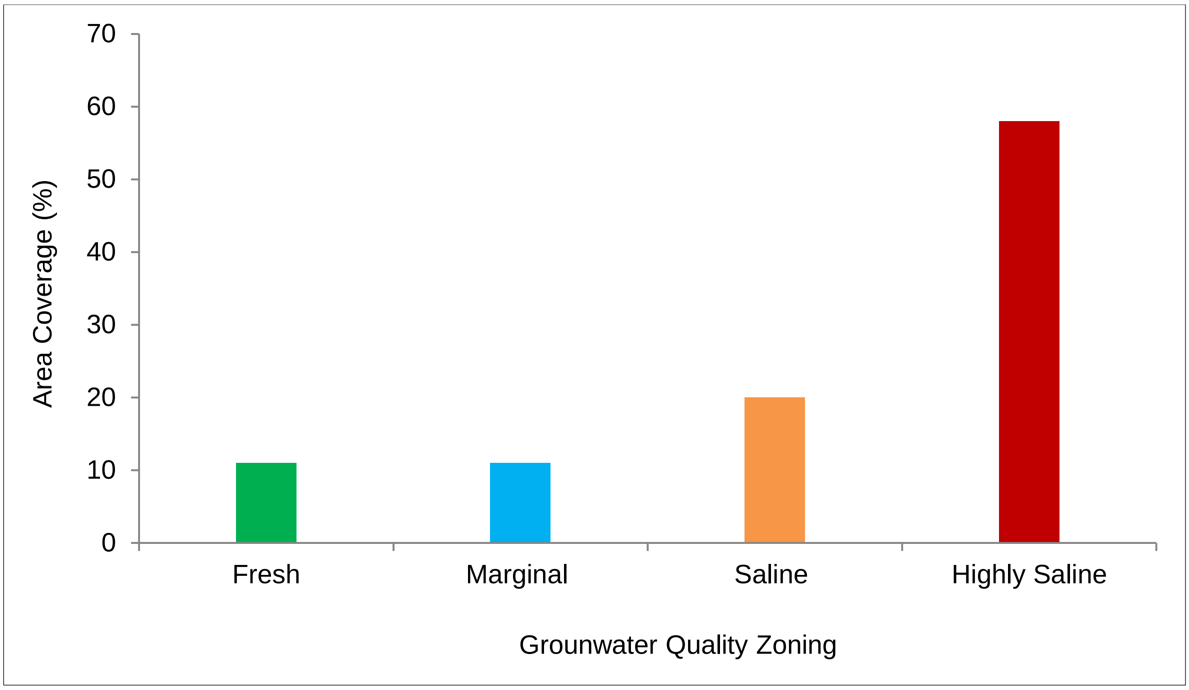

Figure 22: Area coverage of groundwater quality at 100 m depth in 14 CCAs

About 11-23% area upto 100 m depth lies under marginal groundwater quality which can be used through conjunctive use of surface and groundwater. The groundwater quality in pockets of Ghotki Feeder, Rice and downstream of Rohri canal command areas adjacent to River Indus in District Ghotki, Larkana, Naushahro Feroze and Tando Allhayar show the fresh groundwater quality even at deeper depth (101-200 m) and usable for irrigation purpose (Figures 23-24).

The command areas of Kotri Barrage with four canals (Phuleli, Pinyari, Kalri Baghar Feeder, and Akram Wah), along with the downstream of Nara canals, show high salinity. One possible reason for this could be the proximity of these areas to the sea, as well as flat and low-lying topography.

The area coverage of EC in groundwater at 150-200 m depth (Figures 25-26) in 14 canal command depicts that 72-84% area is highly saline. The areas mostly include Kotri Barrage command area, downstream section of the Nara canal, and areas on the right side of the River Indus, situated away from it.

It is pertinent to mention that the area under the saline zone (EC 2.5-4.0 dS/m) shows relatively less coverage (12-26%) across the entire investigation depth (0-300 m).

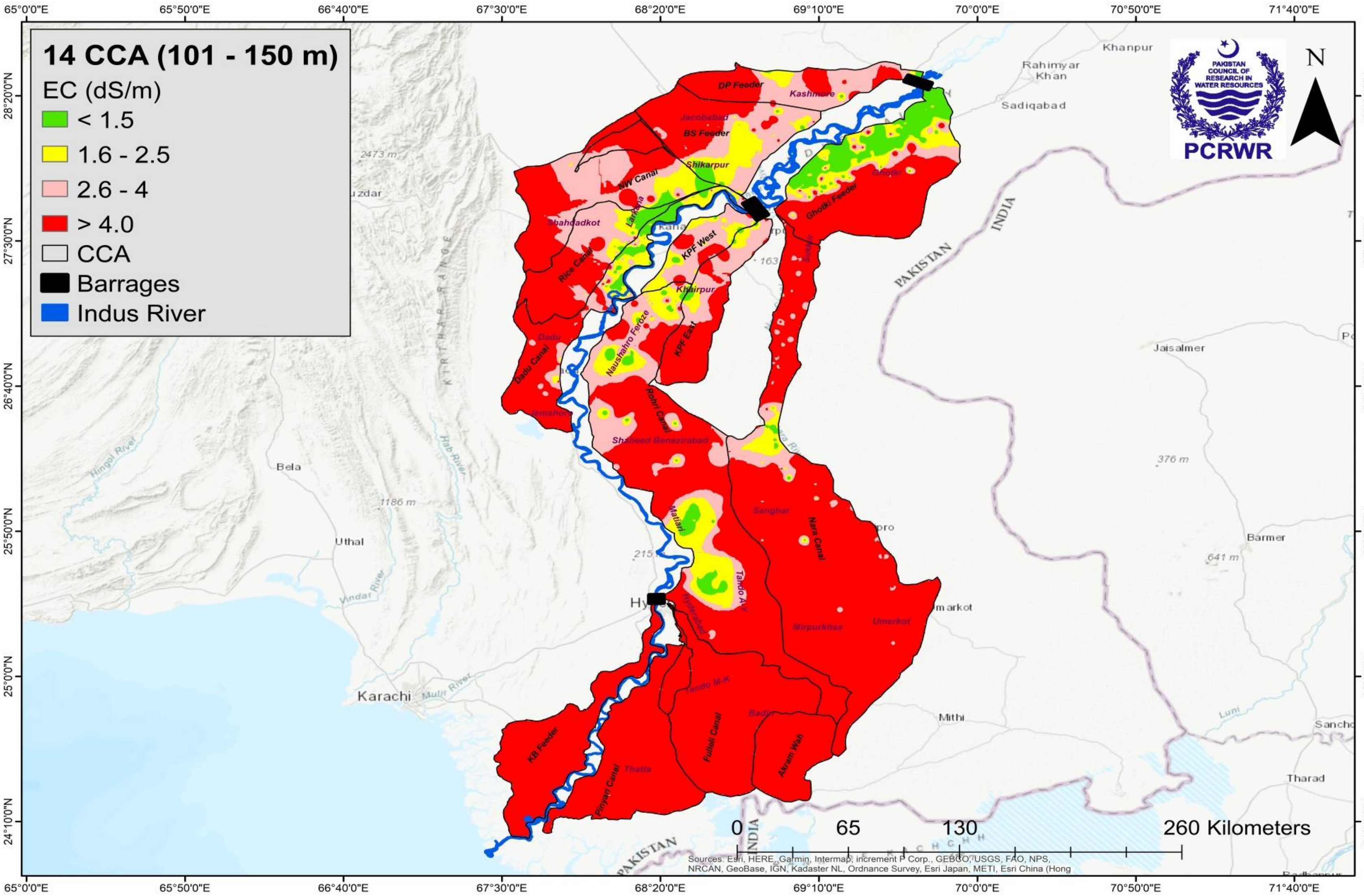

Figure 23: Spatial variation of groundwater quality at 150 m depth

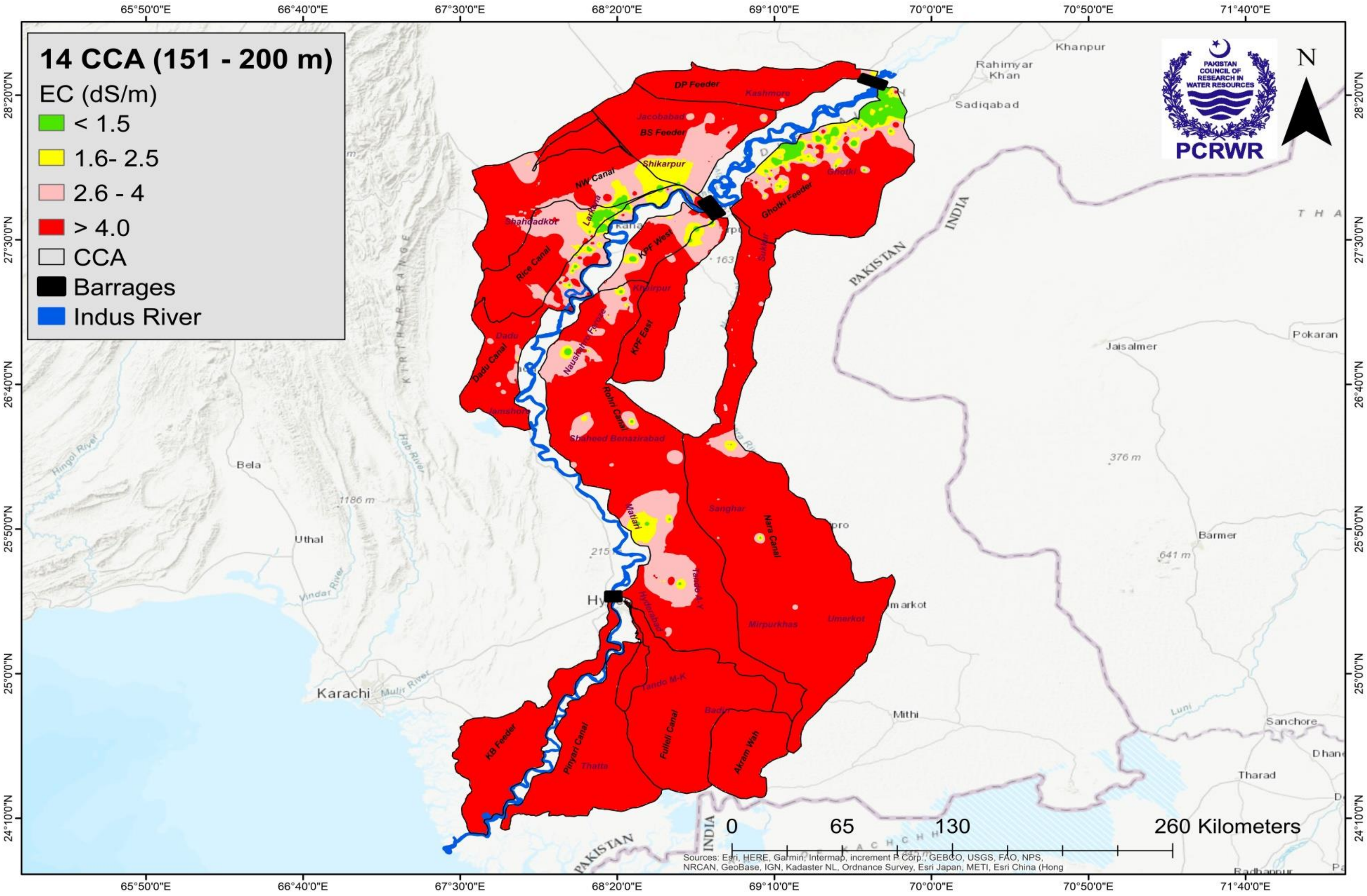

Figure 24: Spatial variation of groundwater quality at 200 m depth

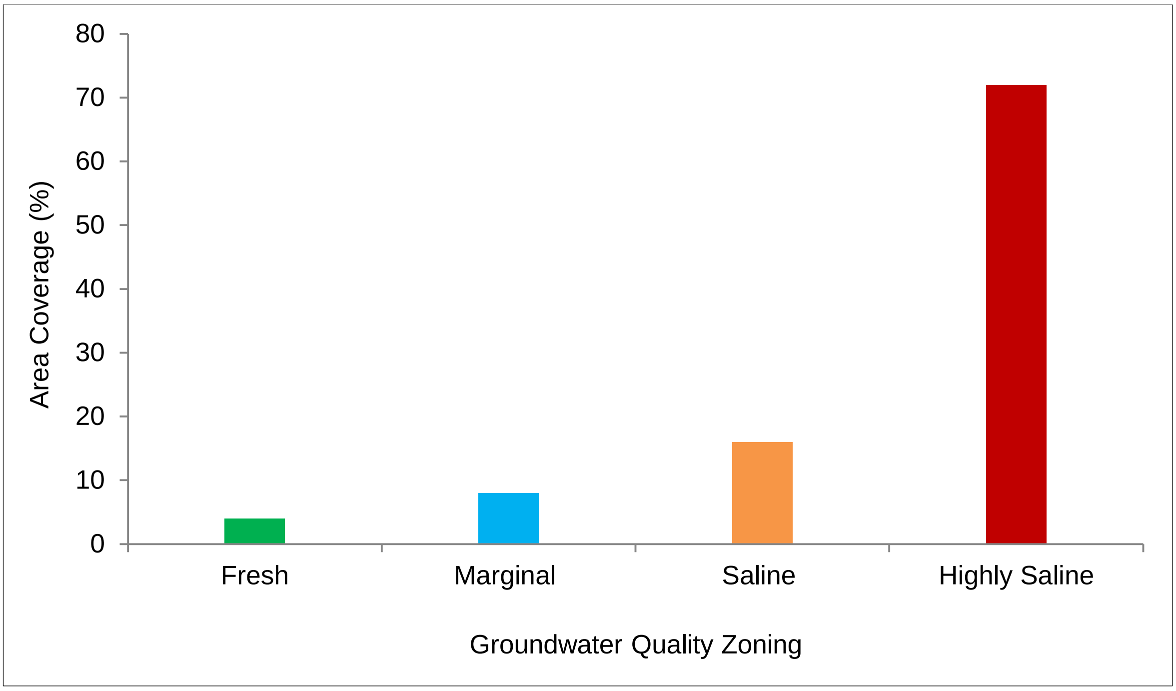

Figure 25: Area coverage of groundwater quality at 150 m depth in 14 CCAs

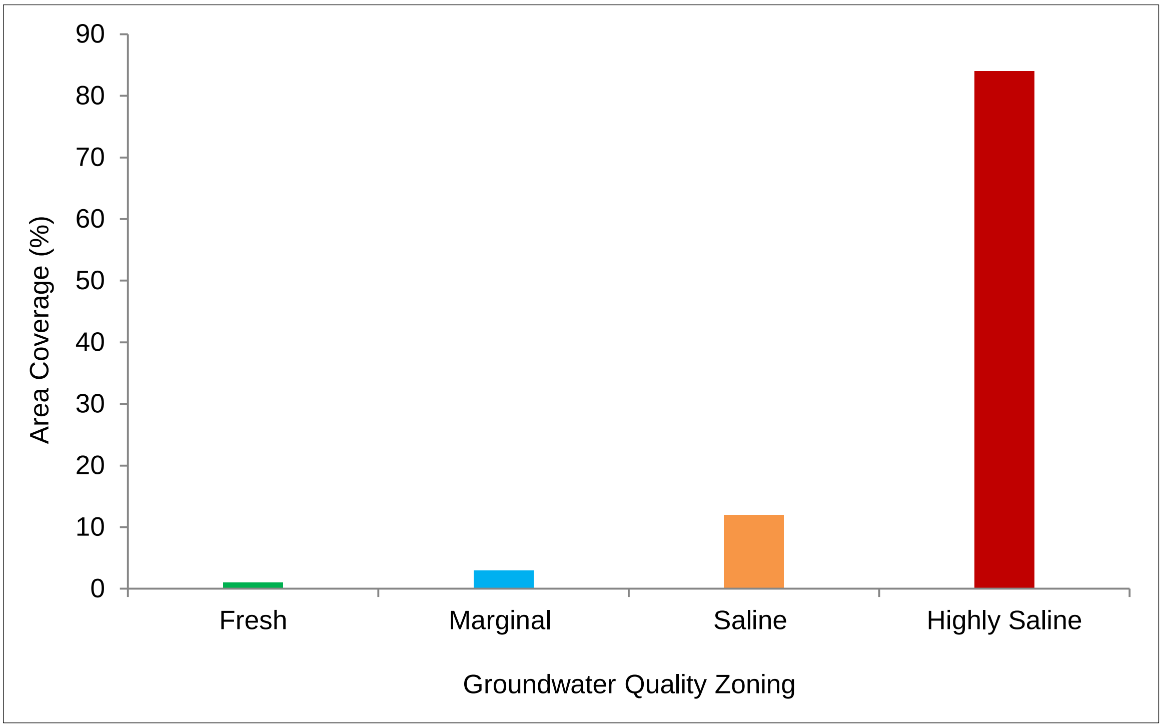

Figure 26: Area coverage of groundwater quality at 200 m depth in 14 CCAs

In the Ghotki Feeder command area, there are some pockets close to River Indus at 250-300 m depth (Figures 27-28), which show the fresh groundwater quality and can be used for irrigation and domestic purposes. However, the rest of the area in all commands is highly saline at this depth.

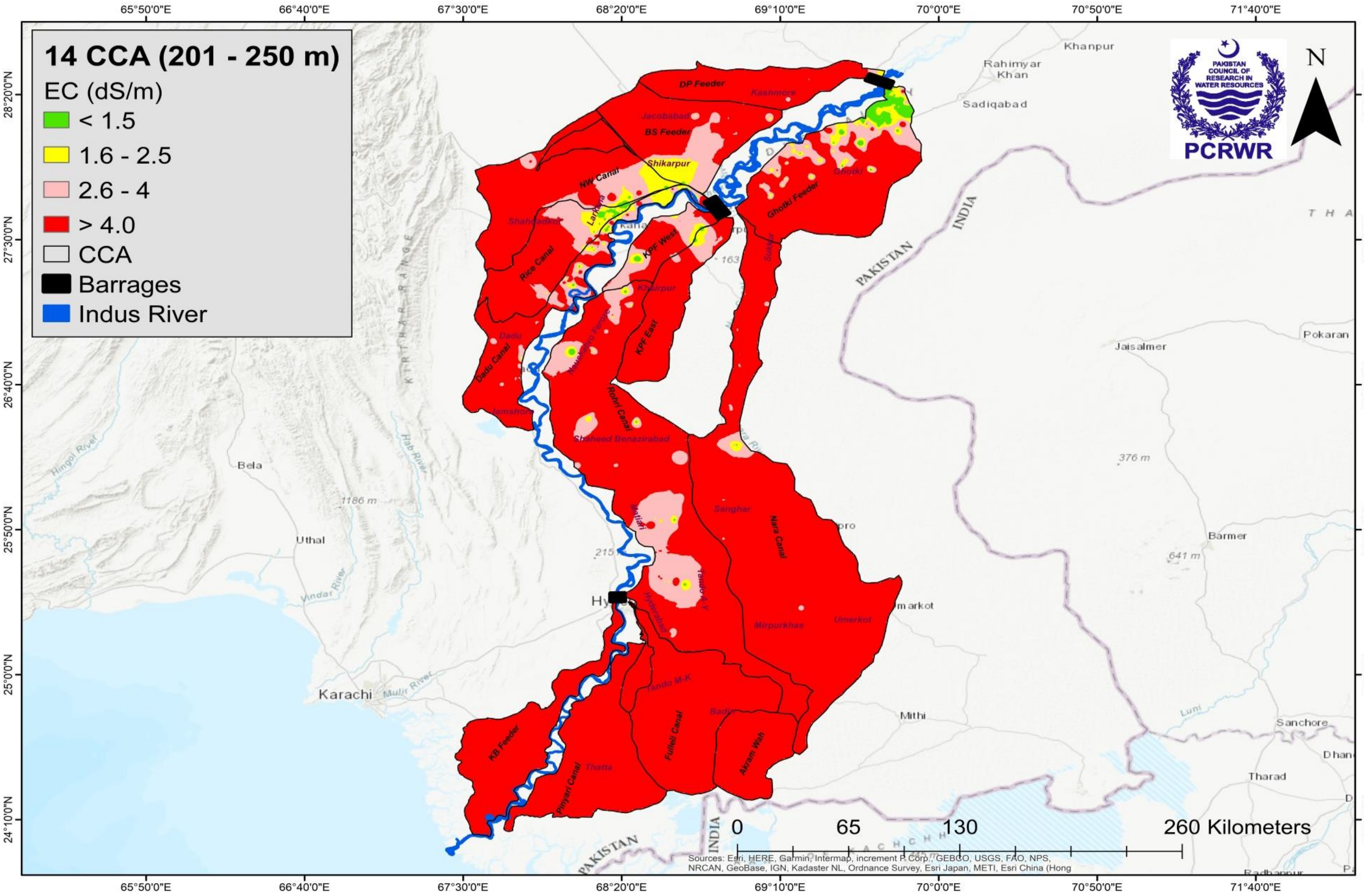

Figure 27: Spatial variation of groundwater quality at 250 m depth

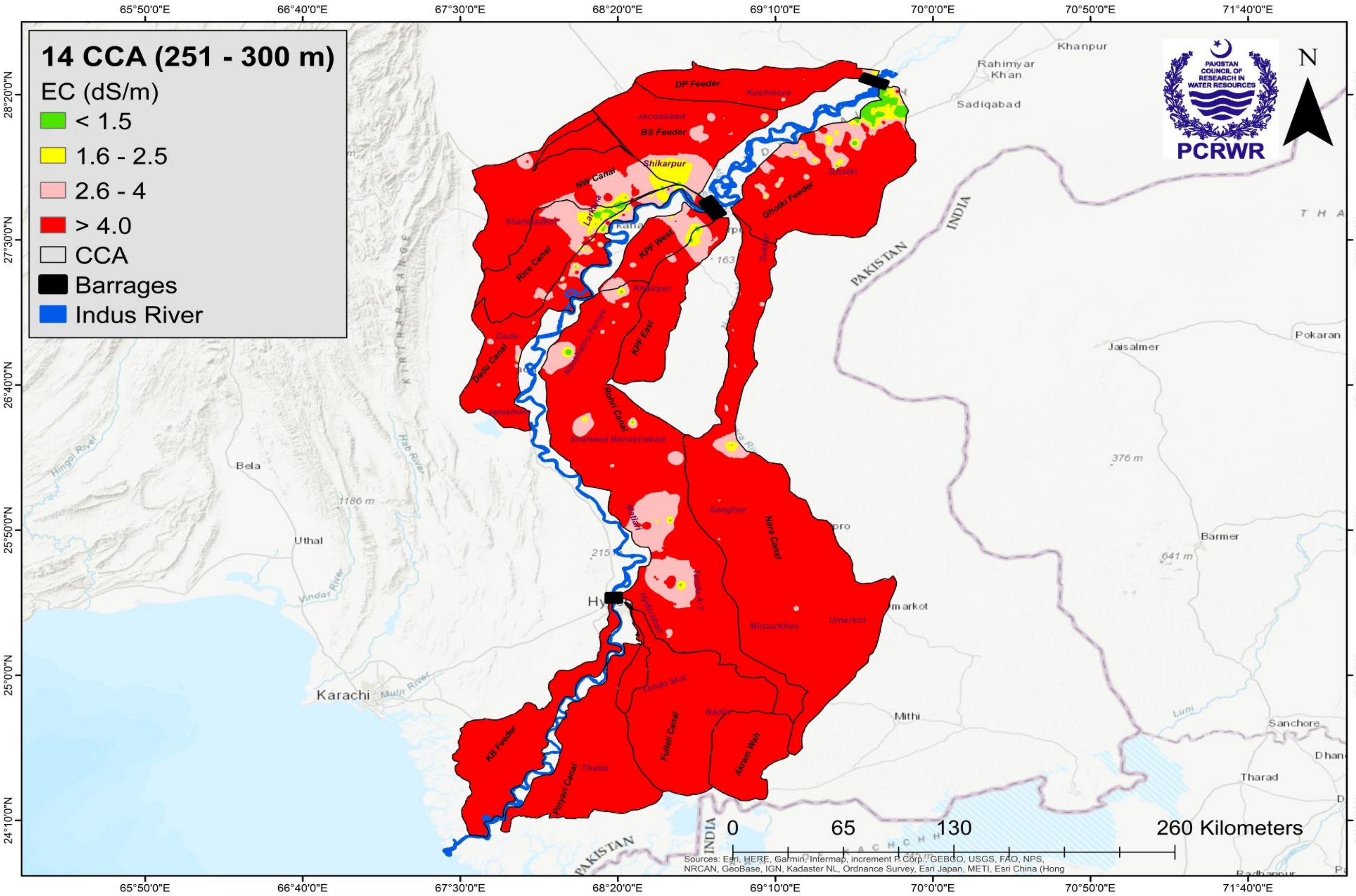

Figure 28: Spatial variation of groundwater quality at 300 m depth

The area coverage of groundwater quality at 201-300 m depth in 14 canal command areas is given in Figures 29-30. The groundwater quality at these depths is highly saline encompassing about 87-90% of the area.

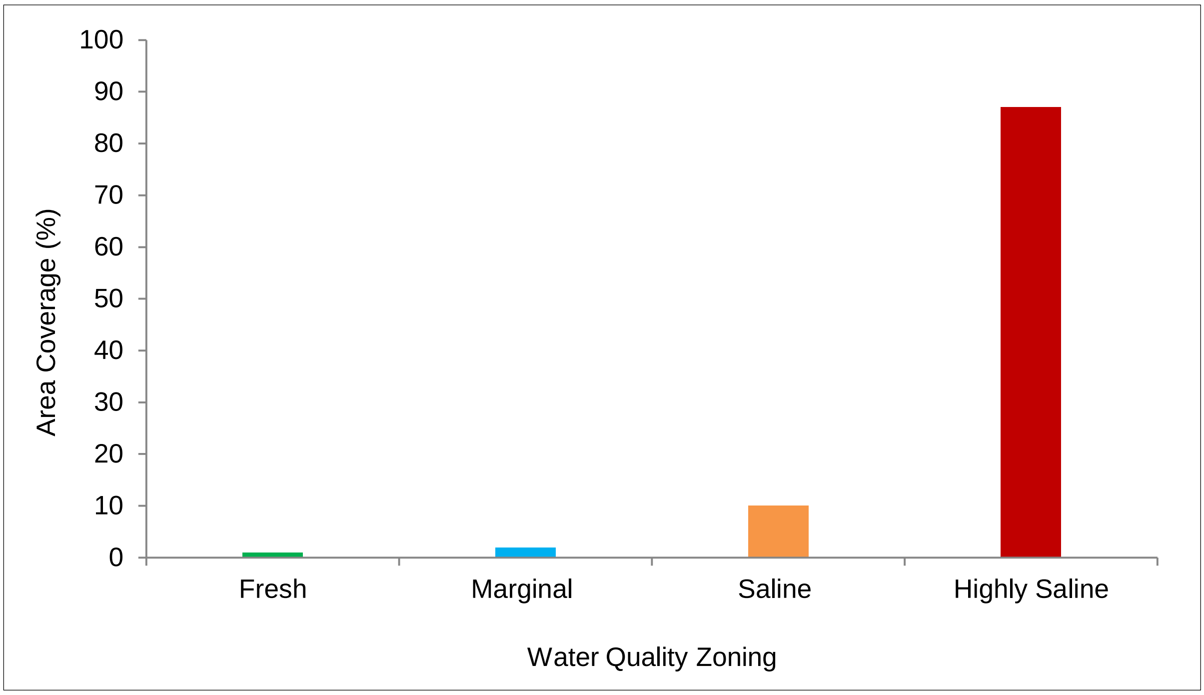

Figure 29: Area coverage of groundwater quality at 250 m depth in 14 CCAs

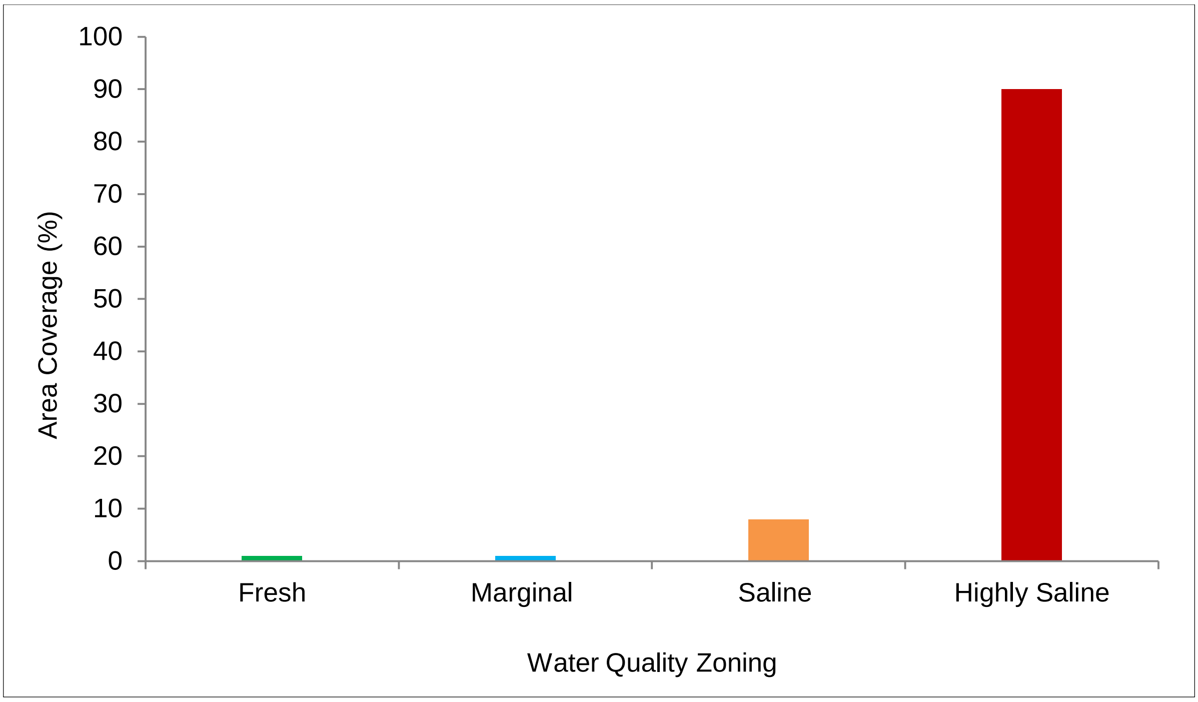

Figure 30: Area coverage of groundwater quality at 300 m depth in 14 CCAs

Evidently, at greater depths (201-300 m), the groundwater quality becomes highly saline. High salinity at deeper depths may be due to various factors, including low recharge, poor drainage, flat topography, and geological characteristics. By understanding the causes and consequences of high salinity, and by implementing effective mitigation strategies, it is possible to reduce its impact on agriculture, water resources, and the environment, ensuring a sustainable future for the region.

3.6 Discharge Measurements

Acoustic Doppler Current Profiler (ADCP) provides rapid and reliable measurement of river /canal flow regime. However, moving bed test, compass calibration, magnetic declination, deviation and multipath errors require special consideration (Malik and Ashraf, 2021). Aligned with the objectives of the study, discharge in the canals was measured with ADCP (Figure 31). The width, area, and mean velocity of the canal's cross sections vary from one canal to other. The detailed data with time and date of discharge in the canals is maintained by PCRWR. The summary of discharge is given in Table 6.

Figure 31: Discharge measurement through ADCP in canals

The discharge of Nara canal shows a consistent rise up to 180 km may be due to the drainage and sewerage from Rohri city, industrial effluents, and the outflow of flood water into the canal. Following this, Nara canal was bifurcated into four segments: New Jamrao canal, Old Jamrao canal, Ranto canal, and the Nara canal itself. The flow gradually decreased until reaching 240 km may be due to closure of Pak Siri regulator. The canal flow was increased at 260 km. This increase might be due to inclusion of water from the Ranto canal originating from the Chotiyari dam. After this, the flow gradually decreased until reaching its conclusion, where it was distributed into various distributaries. The discharge data through ADCP shows that flow gradually reduces due to flow diversion to minors, and distributaries for irrigation purposes and seepage losses in Rohri, Khairpur West, Dadu, Rice, Pinyari, and Kalri Baghar Feeder. The discharge of Khairpur East shows gradual decrease up to a distance of 40 km.

Table 6*: Discharge of canals at 20 km cross section*

S. No.	Name of Canal	Discharge (m^3/sec)																	
		0	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300	320	340
		km	km	km	Km	km	km	km	km	km	km	km	km	km	km	km	km	km	km
1	Nara	280	294	303	300	300	294	320	328	320	311	119	121	11	36	31	28	27	22
2	Rohri	267	211	200	207	211	152	148	134	133	129	117	108	106	79	31	13	10	-
3	Khairpur East	42	17	7	17	7	6	-											
4	Khairpur West	35	23	16	-														
5	Dadu	24	22	19	17	15	16	12	14	7	4	3	-						
6	Rice	41	40	39	37	27	19	7	-										
7	Phuleli	41	61	43	37	36	-												
8	Akram wah	24	22	13	11	39	34	-											
9	Pinyari	43	43	41	39	37	-												
10	Kalri Baghar Feeder	61	60	58	54	-													

Afterwards, slight increase was observed at 60 km due to the inclusion of water from Sathio Wah/minor, followed by a subsequent decrease at the tail end. The discharge of Akram Wah at 80 km increased, possibly due to the addition of water from Alipur X-Regulator (RD-230) of Phuleli canal. The discharge at the 20 km cross-section of Phuleli has increased. This rise may be due to the inclusion of effluent from Hyderabad city and its surrounding areas. Due to the complex situation involving inflows, such as the inclusion of city sewage, and outflows, like flow diversion through minors/distributaries for irrigation, along with the legal or illegal lifting of water through pumps for drinking or irrigation purposes, flow variations at the head regulators etc., it is difficult to accurately determine conveyance losses along the full length of the canals.

Discharge measurement is crucial for ensuring the efficient allocation and utilization of water resources for drinking, irrigation, industrial processes, and ecological preservation. The data highlight the dynamic nature of flow rates in canals, which are influenced by various factors such as discharge variation at the head of canal, distributaries or minor outlets, inflows and other anthropogenic activities. This underscores the importance of regular and comprehensive discharge assessments along various reaches of the canals.

3.7 Seepage Measurements

Table 7 shows the results of the seepage tests (Figure 32) carried out on the canals of the Sukkur and Korti Barrages. Point measurement of seepage rate is not supposed to reflect the seepage rate of the canal reach as it represents the measurement on a very small area (Malik and Ashraf, 2021).

Figure 32: Seepage measurement in the active canal bed

Table 7*: Seepage rate in canals at 20 km cross section*

S. No.	**Name of Canal**	**Seepage rate (mm/day)**																	
		0 km	**20 km**	**40 km**	**60 km**	**80 km**	**100 km**	**120 km**	**140 km**	**160 km**	**180 km**	**200 km**	**220 km**	**240 km**	**260 km**	**280 km**	**300 km**	**320 km**	**340 km**
1	Nara	5	5	0.4	1	1	11	8	7	6	14	7	5	3	11	2	3	3	-
2	Rohri	12	3	7	7	1	-	3	7	4	0.4	-	1	7	3	1	4	1	-
3	Khairpur East	7	2	7	15	5	13	-											
4	Khairpur West	11	22	10	-														
5	Dadu	20	6	5	17	16	13	5	13	4	13	8	-						
6	Rice	11	6	17	16	-	1	16	-										
7	Phuleli	8	7	4	4	3	-												
8	Akram Wah	Lined Portion				3	2	-											
9	Pinyari	6	2	2	2	2	-												
10	Kalri Baghar Feeder	16	3	2	-	-													

However, such measurements can give reasonable estimates of seepage rates for various reaches. Akram Wah has only two seepage measurements, and no measurements were taken in its lined portions. The seepage rate varies randomly along the entire length of the canal sections. Seepage rates though have mixed trends depending on local strata but are generally more in upstream and lowest at the downstream reaches of Rohri, Dadu, Phulei, Pinyari and Kalri Baghar Feeder canal sections except Khaipur East, Khairpur West and Rice canals. The elevated seepage rate in the upstream reach appears to be attributed to the less graded bed material compared to the downstream. Material with a less-graded composition has a narrower range of particle sizes, leading to poor packing and increased permeability in the strata. In contrast material that is well-graded possesses a wide range of particle sizes, allowing for effective packing and resulting in less permeable strata (Bouteiller et al., 2011). In Nara canal, highest and lowest seepage rates are 14 mm/day (180 km) and 0.4 mm/day (40 km), respectively, but seepage rate values vary randomly along the reach of the canal.

The investigation into seepage measurement in canals has provided valuable insights into the losses due to seepage. This information is essential for managing water resources efficiently and ensuring that canals continue to serve their intended purpose effectively. The observed variations in seepage rates highlight the need for periodic assessments to monitor and address potential issues.

4. Conclusions

i) The most prevalent soil types at the Kotri Barrage and downstream of Sukkur Barrage command area are clay loam, clay, and loamy soils. At the upstream of Guddu Barrage, sandy-clay loam is dominant, followed by loamy soil.

ii) The soil profile up to a depth of 90 cm within the command area of Guddu Barrage is non-saline to slightly saline, with the exception of few pockets adjacent to Balochistan province in the Begari Sindh and Desert Pat Feeder command areas.

iii) The soil in the downstream command areas of Akram Wah, Pinyari, Phuleli, Nara canal, and the western side of Begari Sindh Feeder ranges from moderately saline to strongly saline at depths extending from the surface to a depth of 90 cm. These regions include the districts of Badin, Thatta, Sujawal, Sanghar, Mirpurkhas, and Jacobabad.

iv) The average water-table depth in pre-monsoon is 4.6 m and 2.4 m in post-monsoon. The command areas of Desert Pat Feeder, Begari Sindh Feeder, Kalri Baghar, and Pinyari canals have shallow water-table depths, i.e., less than 2 m. After post-monsoon period, about 42% area is under waterlogging conditions (≤1.5 m depth).

v) Groundwater quality is fresh at shallow depths, extending up to 16 m within the command areas covering Ghotki, Khairpur West, Begari Sindh, North West, Rice canal, and downstream Rohri canal. These areas include districts Ghotki, Khairpur, Shikarpur, Larkana, Matiari, and Tando Allahyar.

vi) The groundwater at a depth of 25 m in the command areas of Phuleli, Pinyari, Kalri Baghar Feeder, Akram Wah, and at the tail end of Nara canal is highly saline. The groundwater quality in the command areas of Ghotki, Begari Sindh Feeder, North West, Rice, Khairpur East, Khairpur West Feeders, and upstream and downstream command areas of Rohri canal near the Indus River is suitable for irrigation purposes upto 100 m depth.

vii) The discharges at the head of canals were substantial but gradually reduced due to flow diversions to distributaries, minors and seepage losses. Seepage rates exhibit diverse trends across various canals, influenced by local conditions and soil strata.

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