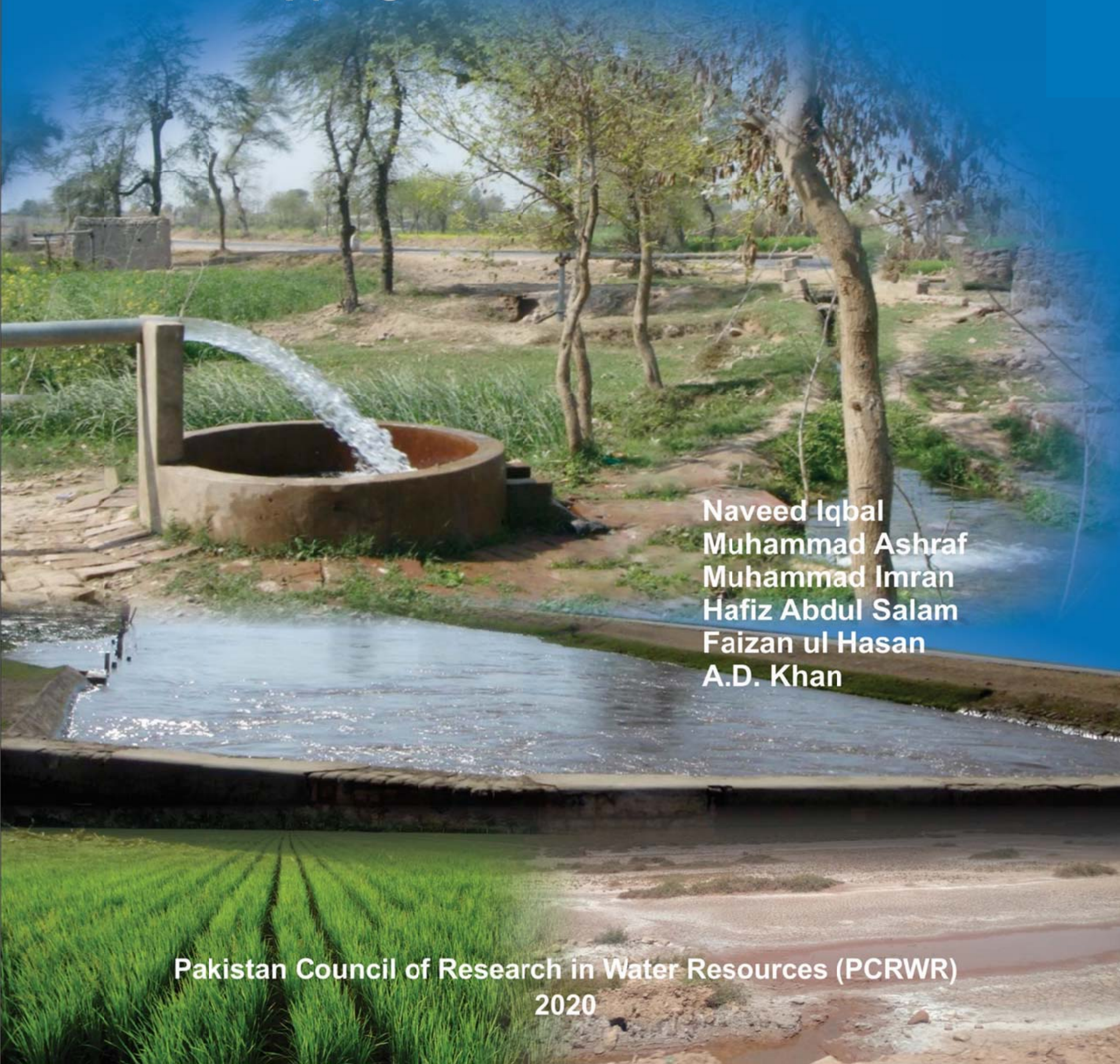
PCRWR

Groundwater Investigations and Mapping in the Lower Indus Plain



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Pakistan Council of Research in Water Resources (PCRWR)
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Executive Summary

The sustainable management of groundwater is imperative to ensure food security as it is the most dependable source to meet domestic, industrial and irrigation water requirements. However, at the same time, it is equally challenging due to its complex nature, anthropogenic factors and climate change. The investigation and mapping of groundwater aquifer, its variability over time and space is important to devise any strategy for its management. However, the groundwater of the Lower Indus Plain has not been evaluated or mapped. This report covers results of investigations carried out in the Lower Indus Plain Aquifer from 2014-2018.

An integrated methodology consisting of geophysical, isotopic and groundwater modeling was applied to analyze different aspects of groundwater. To maintain the consistency with the investigations carried out in the Upper Indus Plain, a uniform grid of 5 km x 5 km, 20 km x 20 km and 25 x 25 km pertaining to resistivity survey, Induced Polarization and exploratory well drilling, respectively was used. For isotopic analysis, the water samples were collected from various sources pertaining to surface and groundwater such as, river, canals, hand pumps and tubewells. The isotopic analysis was used to determine the recharging sources and the aging of the water. The water balance was simulated by applying Visual Modflow model at a grid scale of 2.5 km x 2.5 km. The predictive scenario was developed up to 2025, based on business as usual.

At 0-5 m depth, the major soil types are sandy loam, loam, silty loam and clay that cover about 70% area. Whereas, sandy loam soil is the top soil, which covers about 29% area followed by loam, silty loam and clay, respectively. The clayey strata are more prominent in the areas below Hyderabad particularly in the Indus Delta.

The districts on the left side of the Indus River starting from Ghotki to Tando Allah Yar have normal soil whereas, the remaining area falls under saline and saline-sodic soils. It is noticed that soil salinization and sodification increase with depth as the area under normal soil reduces to half (41% to 26%) while moving from 0-5 m to 6-10 m depth.

About 71% of canal commands is under 1.6 m to 3 m depth. Over the time, the waterlogging persists due to poor drainage in lower parts of the plain. However, in certain areas, depth to water table has increased up to 16 m due to groundwater pumping. These are the pockets of fresh groundwater which falls in the districts of Shaheed Benazirabad (Nawabshah), Matiari and Tando Allah Yar.

The groundwater quality at deeper depths is highly saline. However, a layer of freshwater of varying quality is present with varying thickness in the aquifer in the areas of favorable lithologies where sources of groundwater recharge are available. The groundwater quality is fresh or usable along the River Indus due to its recharge. With increasing distance from the river, the salinity in groundwater increases. The extent of groundwater salinity further increases and intensifies below Hyderabad towards the Indus Delta.

The isotopic analysis shows that seepage from the River Indus and irrigation network constitutes the major part of the groundwater recharge. About 20% area falls under useable groundwater quality. The simulation results indicate that the groundwater system in the Lower Indus Plain is almost at equilibrium as there seems no significant change in the hydraulic head. Therefore, the waterlogging may persist in the plain particularly, in the lower reaches of the River Indus. There is need to develop a strong monitoring and regulatory framework to manage the groundwater on sustainable basis.

Acknowledgement

The authors take this opportunity to express their sincere gratitude to the project team who have been very instrumental in the successful completion of this type of innovative and challenging work. Being Project Director, the efforts of Rao Muhammad Ishtiaque, Director Incharge (DRIP), are highly appreciated for timely and successful completion of the project. The technical expertise extended by Mr. Abdul Salam Arain, Deputy Director is also recognized for successful completion of tedious work of exploratory well drilling. The authors are thankful to Mr. Ghulam Mustafa Khan Chandio, Assistant Director, Mr. Yousaf Abro, Instrument Mechanic and Mr. Zohaib Habib, LDC for conducting ERS probes. Mr. Umer Abro, Computer Operator helped in computerizing the field data. The hard work of Mr. Tariq Mahmood, APS is also appreciated for designing and formatting the report. The support extended by PCRWR Lahore and Bahawalpur offices regarding resistivity survey are also acknowledged.

Pakistan Water Power Development Authority (WAPDA), International water Logging and Salinity Research Institute (IWASRI), SCARP Monitoring Organization (SMO), Punjab Irrigation Department, Pakistan Meteorological Department (PMD) and Pakistan Bureau of Statistics are greatly acknowledged for sharing relevant data. The technical support provided by Pakistan Institute of Nuclear Science and Technology (PINSTECH), Pakistan Atomic Energy Commission (PAEC) for isotopic analysis is highly appreciated. The authors are also thankful to Dr. Ashfaq Ahmed Sheikh, Ex-Director General for his guidance and supervision of the project during implementation.

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1 Introduction

The Indus plain, covering about 20 million hectares (Mha) possess one of the largest volumes of groundwater resource in the world. The groundwater plays a vital role in the agriculture-based economy of Pakistan where over 60% of the irrigation water requirements are met from it. Moreover, over 90% drinking water and almost 100% water used in industry comes from groundwater. The groundwater has played a major role in increasing the overall cropping intensity in Pakistan from about 63% in 1947 to over 120% in 2000 (Khan *et al.,* 2016).

The native groundwater in the Indus Basin is saline because of its marine origin. Seepage from conveyance and irrigation network has developed freshwater layers of varying thickness that overlay deeper saline groundwater. The thickness of fresh groundwater is more near the recharging sources and decreases with an increase in the distance from the recharging sources (Ashraf *et al.,* 2012). Pumping groundwater from such an aquifer becomes complex. The amount of pumping in this case is mostly guided by water-quality considerations rather than water quantity because any excess pumping results in up-coning of saline water (Saeed *et al.,* 2003).

Despite of importance and complex nature of groundwater, there is no regulatory framework available in the country. Anyone can install any number of wells of any capacity, at any depth and can pump any amount of water at any time. Drilling of wells therefore, entirely depends on the advice of the local drillers and wishes of the farmers. This practice has led to the groundwater depletion, both quantitatively and qualitatively. Improper design and installation of the tubewells not only leads to secondary salinization but also increases the installation and operational cost of these wells (Ashraf *et al.,* 2012).

Groundwater has been a neglected subject in Pakistan. Post project monitoring of groundwater was started by WAPDA with the emphasis on water table behavior and tubewell performance. Later on, water quality was included in this program which was expanded further to cover evaluation of SCARPs, water table appraisals, soil monitoring, land-use monitoring and water quality monitoring. Quarterly, by-annual and annual reports have been prepared by WAPDA containing monitoring, and evaluation of the projects. In 1978-79, IWASRI-WAPDA conducted detailed investigations in the Indus Basin covering surface and profile salinity, soil texture, water-table depth, groundwater quality and land use (Basharat *et al.,* 2014).

A few studies were conducted by individuals or some institutions such as International Water Management Institute (IWMI) on a limited scale. In 2004, Pakistan Council of Research in Water Resources (PCRWR) started mapping the groundwater in the Upper Indus Plain with the financial support of the Government of Pakistan through Ministry of Science and Technology. Various techniques such as electrical resistivity, seismic, induced polarization and gravity were used to determine the quantity and quality of groundwater. Moreover, exploratory well drilling and isotopes were also used. The main objective of this program was demarcation of spatial variations in groundwater quality, quantification of usable resource, simulation of water balance and understating the processes of groundwater recharge and dating. Four doabs (the area between the two rivers) i.e. Thal, Chaj, Rechna and Bari were mapped (Khan *et al.,* 2016). The groundwater mapping is very important for the design of tubewells and developing operational strategies (Ashraf *et al.,* 2012).

In the Lower Indus Plain, the groundwater management challenges are multifaceted as compared to the Upper Indus Plain. The fresh groundwater availability is mostly limited either along the River Indus or to certain pockets in head reaches of canals and distributaries depending upon the availability of fresh water as well as soil characteristics. The rest of the areas have highly saline groundwater due to marine geology. Moreover, the saline and sodic nature of soils pose serious challenges. On top of that, the poor drainage further intensifies the situation especially in the lower reaches of the Indus plain.

This report covers the results of investigations carried out during 2014-2018 mainly focusing the areas of the Lower Indus Plain – Sindh Province along with the areas falling in Punjab on the right of the River Indus (parts of Mianwali, D.I. Khan, D.G. Khan and Rajanpur districts) and left side of the River Sutlej (parts of Bahawalnagar, Bahawalpur and Rahim Yar Khan districts).

2 Methodology

The Lower Indus Plain Aquifer (LIPA) is a continuous and unconfined aquifer with moderate permeability (1-20 m/d) and the average values of specific yield ranges from 5-15% (Bennet *et al.,* 1967; Bonsor *et al.*, 2017). The thickness of alluvial nature of aquifer varies and the average depth to bedrock is 200 m. As the aquifer contains the sediment material eroded from the Himalaya, the fine material lithologies are prominent in the lower reaches (the Indus Delta).

The average annual rainfall is less than 250 mm. The average evapotranspiration is 1560 mm with maximum of about 2800 mm at Thatta (Ahmad, 1982). The 14 main canals off-taking from the River Indus through Guddu, Sukkur and Kotri Barrages regulate the major agricultural water demand whereas, groundwater is used to meet the supplementary requirements. Out of 5.18 Mha of cultivated area of Sindh, an area of about 1.72 Mha is irrigated through conjunctive use of canal and tubewell water where, the contribution of groundwater is about 21%. There are about 230,390 tubewells in Sindh Province (GoP, 2018).

For comprehensive evaluation of groundwater aquifer of the Lower Indus Plain (LIP), an integrated methodology comprising geophysical, isotopic and groundwater modeling was applied. To maintain the consistency and uniformity, the investigations were carried out at the same grid as previously used in the UIP (Khan *et al.,*2016). The electrical resistivity survey (ERS) method was used as a main surface geophysical method up to the depth of 300 m at a grid of 5 km x 5 km. About 3,909 ERS probes were conducted with ABEM Terra Meter SAS 4000 instrument by using Schlumberger configuration. These resistivity values were modeled through Interpex one-dimensional (IX1D) software and converted into true earth resistivities. These resistivities were further converted into electrical conductivity by developing a regression between resistivity and EC values of water samples analyzed in the laboratory. For this purpose, about 160 exploratory wells were drilled throughout the study area to analyze vertical variation in soil and water.

The water samples (1,633 Nos) and soil samples (1,616 Nos) were collected at 5 m depth interval from 160 spatially distributed sites of exploratory wells drilling. The water samples were analyzed for various physio-chemical parameters whereas; the soil samples were used to perform soil texture and concentration of major cations and anions. The laboratory results of water samples were used for the development of regression equation, used for the conversion of resistivity into electrical conductivity. However, the soil data were used for spatial analysis of soil texture and mapping the behavior of soil salinity. For the evaluation of aquifer thickness, Induced Polarization was also applied at 277 points at a grid of 20 km x 20 km up to the depth of 1,000 m.

The survey data of resistivity and Induced Polarization were processed and analyzed using IX1D and Arc GIS softwares. The modeling of resistivity data inferred values of true resistivities pertaining to various sub-surface water bearing strata, which were converted into values of EC defining quality of groundwater. The groundwater quality was divided into four water quality zones: freshwater (<1.5 dS/m), marginal quality water (1.6-2.5 dS/m), saline water (2.6-4.0 dS/m) and highly saline water (>4.0 dS/m). The depth to water table and groundwater quality maps were compared with earlier work of IWASRI-WAPDA (Basharat *et al.,* 2014).

In collaboration with Pakistan Institute of Nuclear Science and Technology (PINSTECH), the sources of groundwater recharge were identified alongwith groundwater dating by analyzing different oxygen and hydrogen isotopes. The rationing of δO^{18} and δH^{2} have been used for the identification of recharging sources contributed either from rainfall, river, or mixture of both river and rainfall. The groundwater residence time for different recharging sources has been calculated by analyzing the variations in tritium (δH^{3}) isotope which is achieved by dividing the samples into four-time intervals; (<5 years, <50 years, 50 years and >50 years) both at shallow and deep depths. The results of 352 isotopic samples have been used to map groundwater recharge (182 samples) induced by various sources as well as its dating (171 samples). Table 1 shows details of the surveys conducted.

To study the groundwater dynamics, Visual Mod Flow (VMOD) was developed with a uniform grid size of 2.5 km x 2.5 km. The model was calibrated in steady-state and transient conditions against different stress periods and predictive scenarios have been developed for 2015 and 2025. The calibration of groundwater model was based on the long-term data of about 45 piezometers collected from SCARP Monitoring Organization (SMO) over the period 1984 to 2009. The availability of data over time and space have been a major limitation of the study.

Table 1: Details of field surveys in the study area

Description	Lower Indus Plain-Sindh	Remaining Area of UIP - Punjab (D.G. Khan, Rajanpur, Rahimyar Khan, Bahawalnagar, Bahawalpur including D.I. Khan)	Total Probes / Samples
Shallow ERS Grid	5 km x 5 km		-
Shallow ERS Probes	2,466	1,443	3,909
Deep IP Grid	20 km x 20 km		-
Deep IP Probes	162	115	277
Exploratory Wells Grid	25 km x 25 km		-
No of Exploratory Wells	137	23	160
No of Soil Samples	1,116	500	1,616
No of Water Samples	1,213	420	1,633
Isotope Parameters	Oxygen & Hydrogen		-
Isotope Sampling Features	Rivers, Canals, Hand pumps, Tubewells		-
No of Isotope Samples	250	102	352

3 Results and Discussion

3.1 Soil Texture Analysis

The variations in groundwater quality are subject to either surface water-groundwater interaction characterizing the processes of groundwater recharge or sub-surface lithological variations. The soil texture plays an important role in the replenishment of groundwater system through recharge induced by rainfall, seepage from irrigation network and rivers. The existence of fine-grained material such as clay restricts the recharge process as compared to sand. The synthesis of soil texture derived from samples collected from 0-5 m depth shows that sandy loam, loam, silty loam and clay are the four major soils, which cover about 70% area (Table 2, Figure 1). However, the remaining six soil types (sandy clay loam, clay loam, loamy sand, sandy clay, silty clay and silty clay loam) constitute 30% area. The sandy loam soil at the top layer covers about 29% area followed by loam, silty loam and clay.

Table 2: Soil textural analysis in the study area

Soil Class	Percentage from 0-5 m Depth
Sandy Loam	29
Loam	15
Silty Loam	14
Clay	12
Sandy Clay Loam	9
Clay Loam	5
Loamy Sand	5
Sandy Clay	5
Silty Clay	5
Silty Clay Loam	2

The analysis of vertical variations in soil lithologies (Figure 1) reveals that the sandy loam strata increases gradually and becomes maximum (54%) at 65 m depth. Generally, an overall increasing trend was noticed where the area pertaining to loamy sand, sandy clay loam and sandy clay increases with depth upto 300 m. In comparison with the UIP, the prevalence of loam and clay like strata is found more dominant in the

LIP. This phenomenon may be due to deposition of fine-grained material coming from upper reaches of the Indus Basin by leaving coarser material behind. In the UIP, the mixing of clay in the form of clay lenses exists above water table, which is about 10 m on an average. Figure 3 shows that the clay content gradually decreases with depth and becomes negligible after 50 m depth.

The spatial analysis of soil texture shows that clayey strata are more prominent in the areas below Hyderabad, particularly in the Indus Delta alongwith some parts of Bahawalpur, Rajanpur, Dadu, Kashmore, Shikarpur, and Kambar Shahdadkot districts (Figures 2 and 3). After 5 m depth, the clay content decreases and loamy sand and sandy clay soils cover the major part of the plain (Figure 3). However, Malik *et al.,* (2019) found silty-clay loam, sandy loam, silt loam and loam as the dominant soil classes in the Upper Indus plain where, the clay fraction decreases with depth.

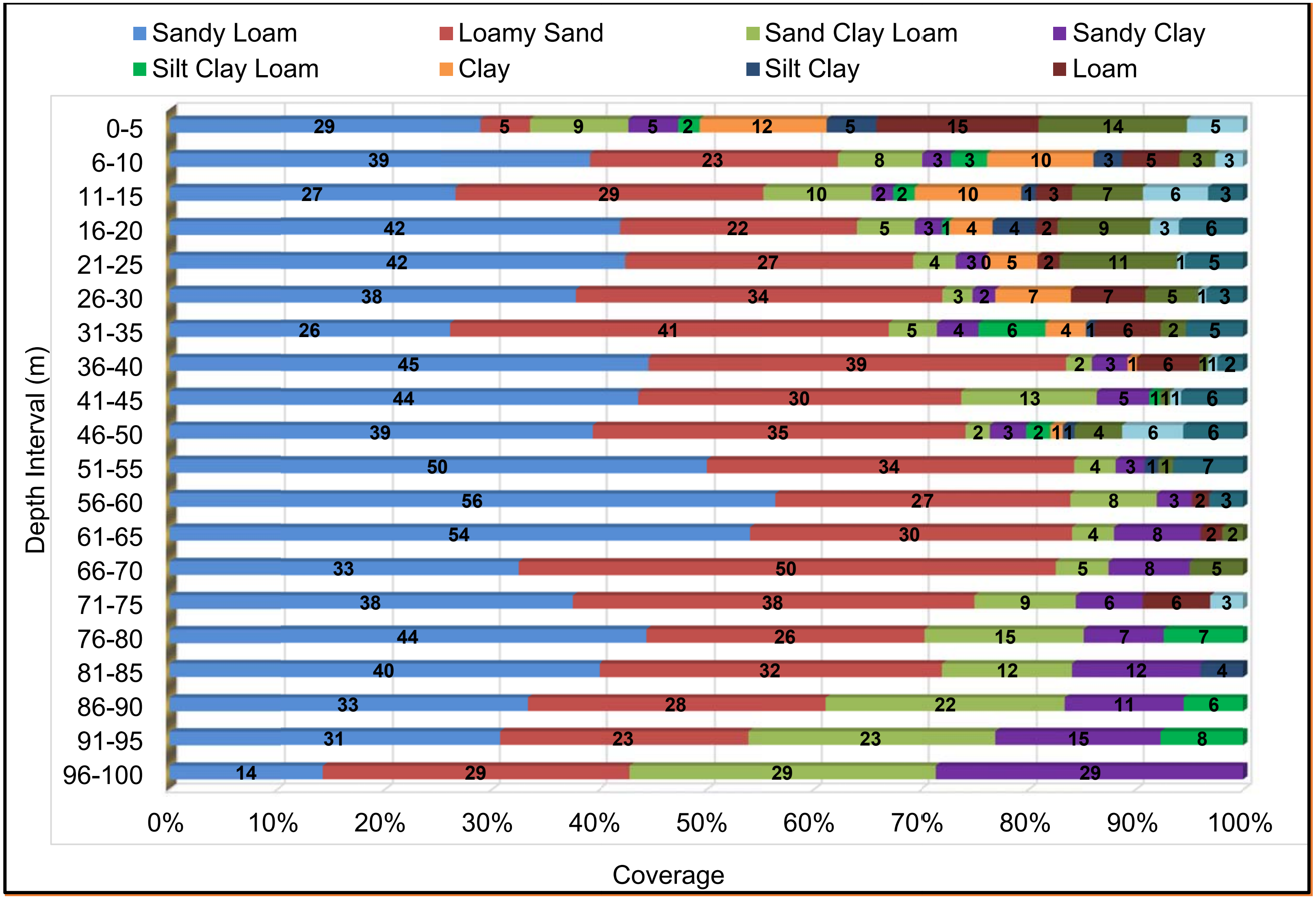

Figure 1: Sub-surface lithological variations in the study area

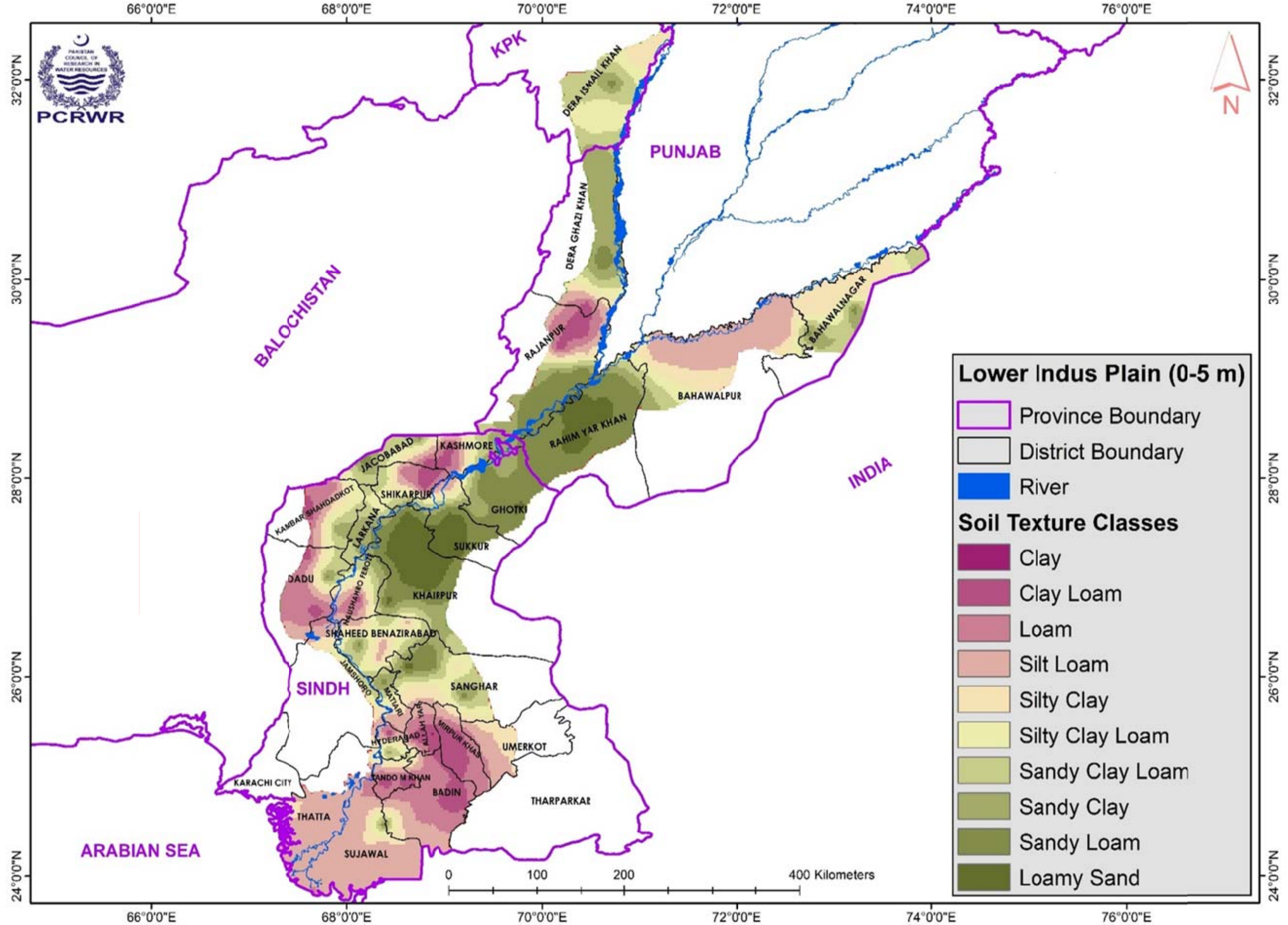

Figure 2: Spatial variations in lithology at 0-5 m depth interval

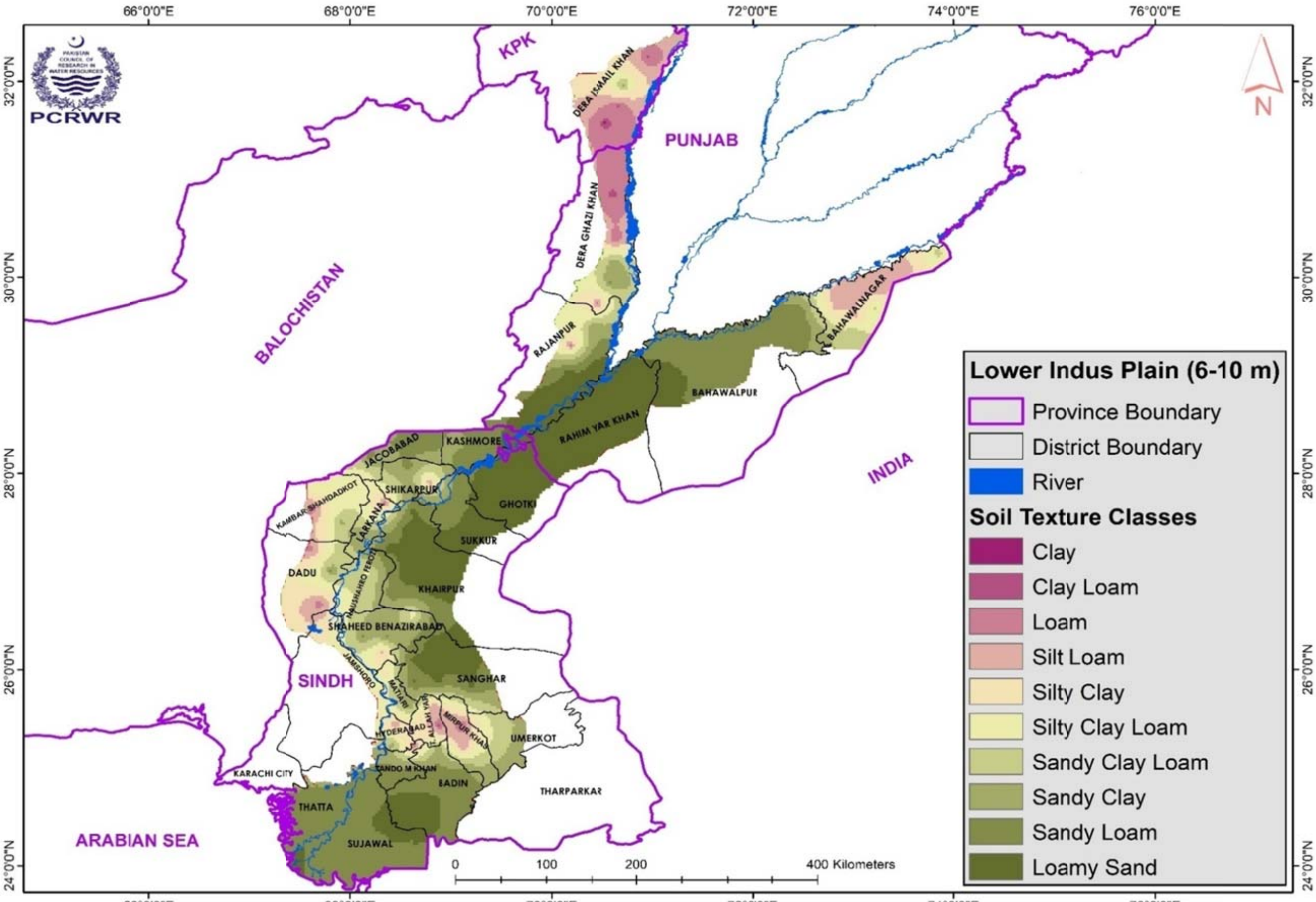

Figure 3: Spatial variations in lithology at 6-10 m depth interval

3.2 Depth to Water Table Variations

It is observed that the groundwater development has somehow facilitated in controlling waterlogging by lowering the water table in the LIB. For analysis purposes, the un-published data of depth to water table from 2013 to 2015 has been collected from IWASRI/SMO and has been mapped in ArcGIS. According to International Waterlogging and Salinity Research Institute (IWASRI), the area, which falls under DTW ≤1.5 m is classified as waterlogged whereas; DTW of 1.6-3.0 m is termed as likely to be waterlogged (Basharat *et al.,* 2014). In 2013, the average annual depth to water table ranged from 0.2 to 3.0 m over an area of about 98% (Figure 4). Out of which, an area of about 51.3% falls under waterlogging condition having DTW less than or equal to 1.5 m. The deep water table (>3 m) was only in certain areas of Rohri and Nara canals where fresh groundwater was being pumped for agriculture. The waterlogging is visible in the Indus Deltaic region of Sindh where River Indus joins the Arabian Sea.

However, in 2014 post monsoon period, the extent of waterlogging (DTW ≤1.5 m) has further increased upto 61% canal command area (CCA) of Sindh province (Figure 5). This increase is related to the abnormally high above normal rainfall, which was received during the month of September 2014 covering major parts of the Country including Sindh (PMD, 2014). This waterlogging condition is found more visible in the upper and lower areas of Sindh including the Indus Delta except parts of Naushero Feroze, Shaheed Benazirabad, Jamshoro, Matiari, Tando Allah Yar, Umerkot, Mirpur Khas and Badin districts where, DTW is greater than 3 m (Figure 5). After monsoon, the water table becomes shallower. On one hand, this shallow water table is a nuisance; but it is a boon if managed properly. Ashraf *et al.,* (2017) and Kahlown *et al.*, (2005) found that under shallow water-table conditions, the groundwater contribution could be an important component of the water balance and could help reduce the surface water applications substantially. They found 1.5 m to 2.5 m as the optimum depths for most of the crops grown in the Indus Basin.

The seasonal variations in DTW before and after monsoon period are also very significant in the LIP (Basharat *et al.,* 2014). Due to reduction in canal flows during Rabi season, the additional irrigational requirements are met through groundwater abstraction, resultantly, an increase in depth to water table. During pre-monsoon period in 2015, the GIS mapping (Figure 6) suggests that the area covered by DTW >1.5 m has increased from 39% (post monsoon, 2014) to 89% (pre monsoon, 2015). Whereas, the area under DTW from 1.5-3.0 m has increased upto 72% which was 32% in post monsoon, 2014. This increase in area coverage is augmented by reduction in recharge due to decrease in canal flows in Rabi season coupled with groundwater pumping to meet additional irrigation requirements. However, in certain areas, the depth to water table has increased up to 16 m due to groundwater pumping. These are the pockets of fresh groundwater which falls in the districts of Larkana, Naushero Feroz, Shaheed Benazirabad, Matiari and Tando Allah Yar. Gradually, the number of tubewells has increased to 230,390 in the Province of Sindh (GoP, 2018). In the beginning, only the public tubewells were installed for drainage purpose. Over the time, the development of private tubewells has increased exponentially (GoP, 2018).

Steenbergen *et al.,* (2015) has provided temporal variations from 1980 to 2012 pertaining to waterlogging in the Lower Indus Plain. This has been updated by integrating further information for the year 2013 and 2014. The extent of waterlogging has been calculated through GIS (Figures 4 and 5) using un-published data collected from IWASRI/SMO. To see the recent temporal trends in the LIP, the analysis has been conducted from 1990-2014.

Figure 7 indicates trends in the extent of waterlogging condition in irrigated areas of Sindh over the period of 1990-2014. During first decade (1990-2002), a gradual decreasing trend has been noticed where; waterlogged (DTW ≤1.5 m) area coverage has decreased from 62% to 35%. The decrease was pre-dominantly associated with drought, which prevailed from 1998-2002 and affected most of Pakistan (Basharat *et al.,* 2014). However, the waterlogged area has increased during the decade covering the period 2002-2012 with maximum of 69% in 2012. This increasing trend is the indicative of normal period after drought where massive flooding event of 2010 has further intensified the condition. In 2013, the area has decreased upto 51% whereas; another spell of above normal rainfall, received in monsoon period of 2014, has increased it upto 61%. During the period 1990-2014, the average area under waterlogging condition was recorded as about 55%. This reveals that the decadal trends are significantly influenced by climatic extreme events (droughts and floods). These events are more prevalent in the Indus Basin as Pakistan is among top seven countries of the world, which are most vulnerable to climate change (Eckstein *et al.,* 2018). Though DTW fluctuates seasonal to annual basis, however, waterlogging persists due to poor drainage in the lower parts of Sindh province.

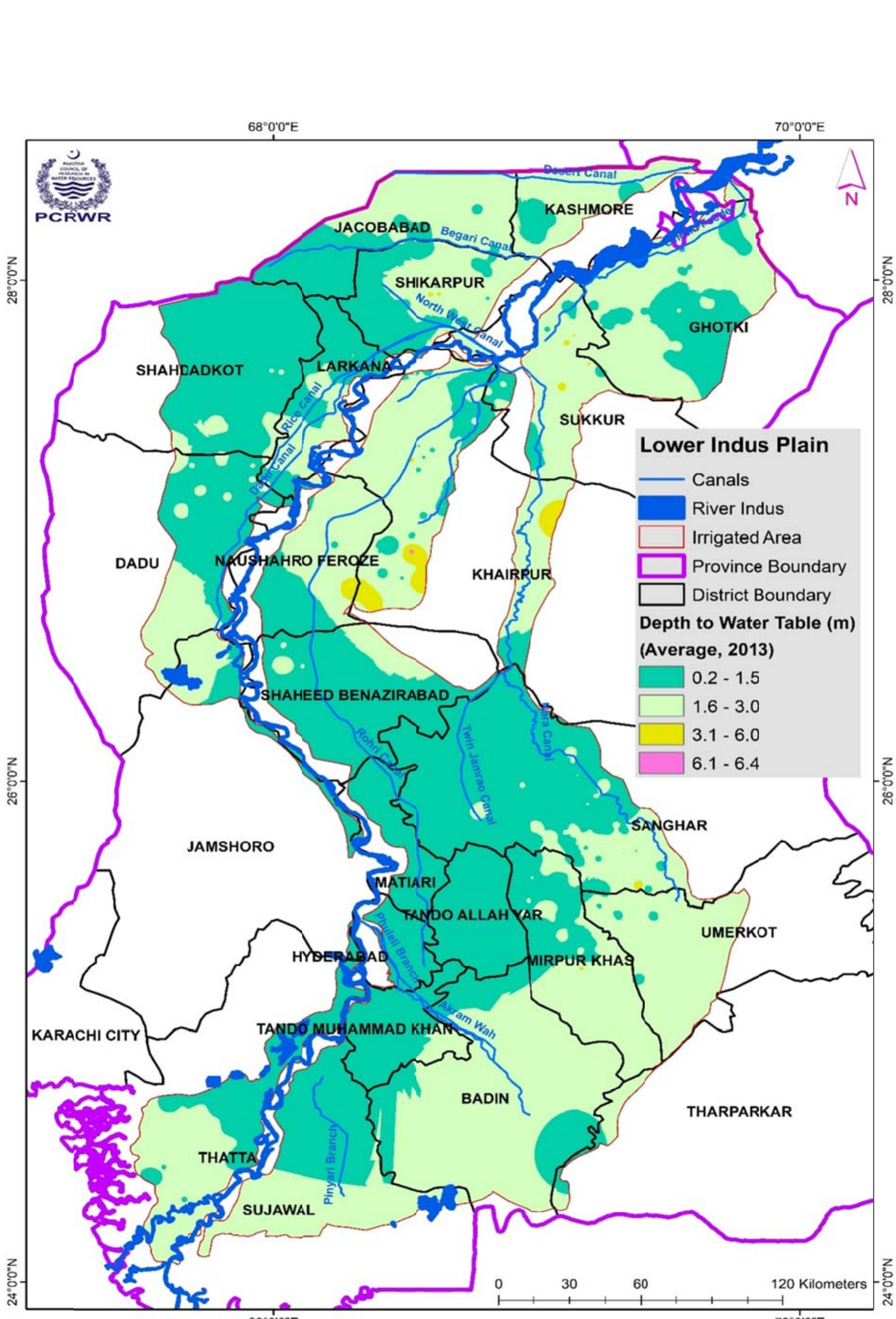

Figure 4: Spatial variations in depth to water table in CCA of Sindh in 2013

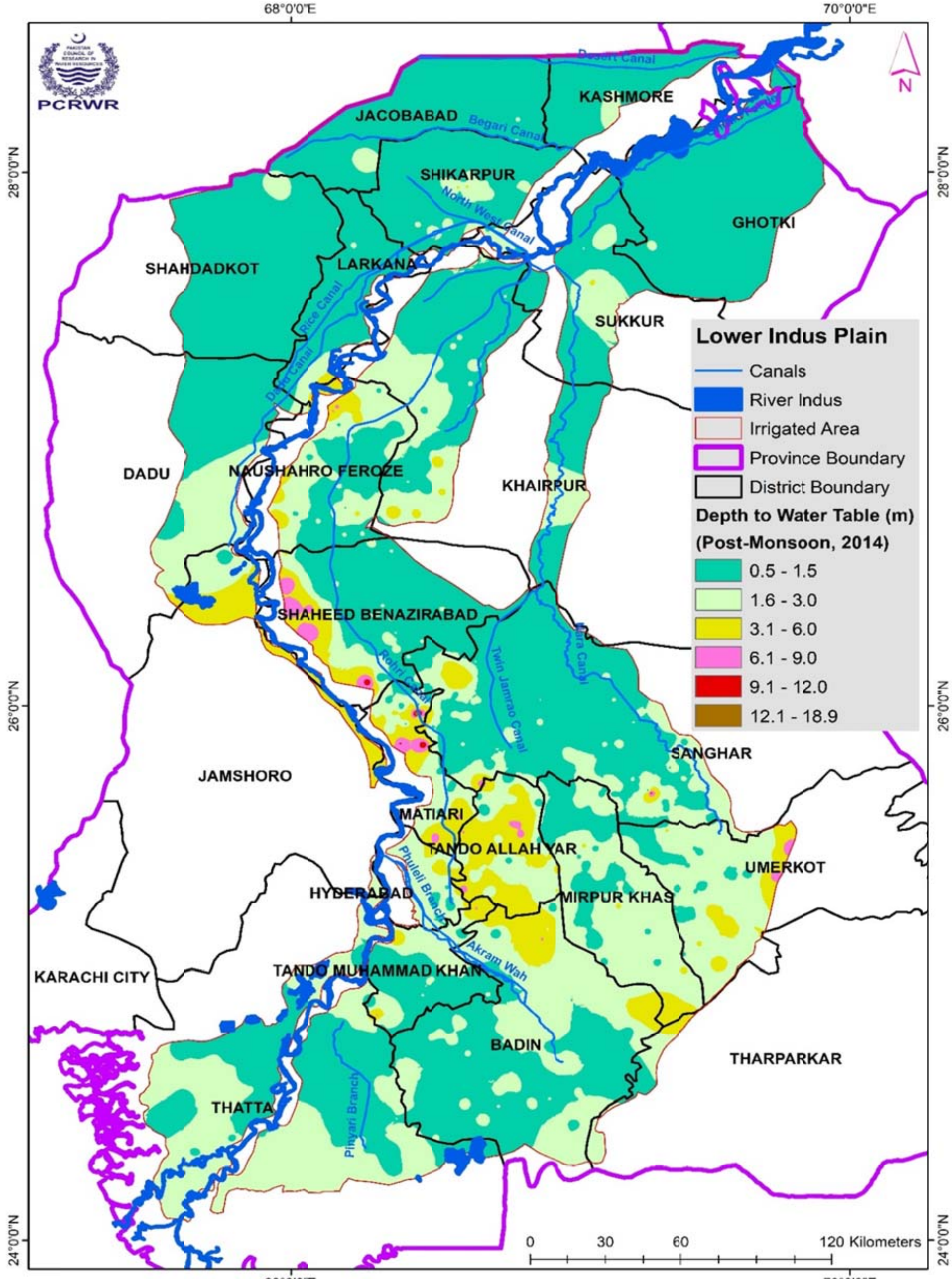

Figure 5: Spatial variations in depth to water table in CCA of Sindh in 2014 (post-monsoon)

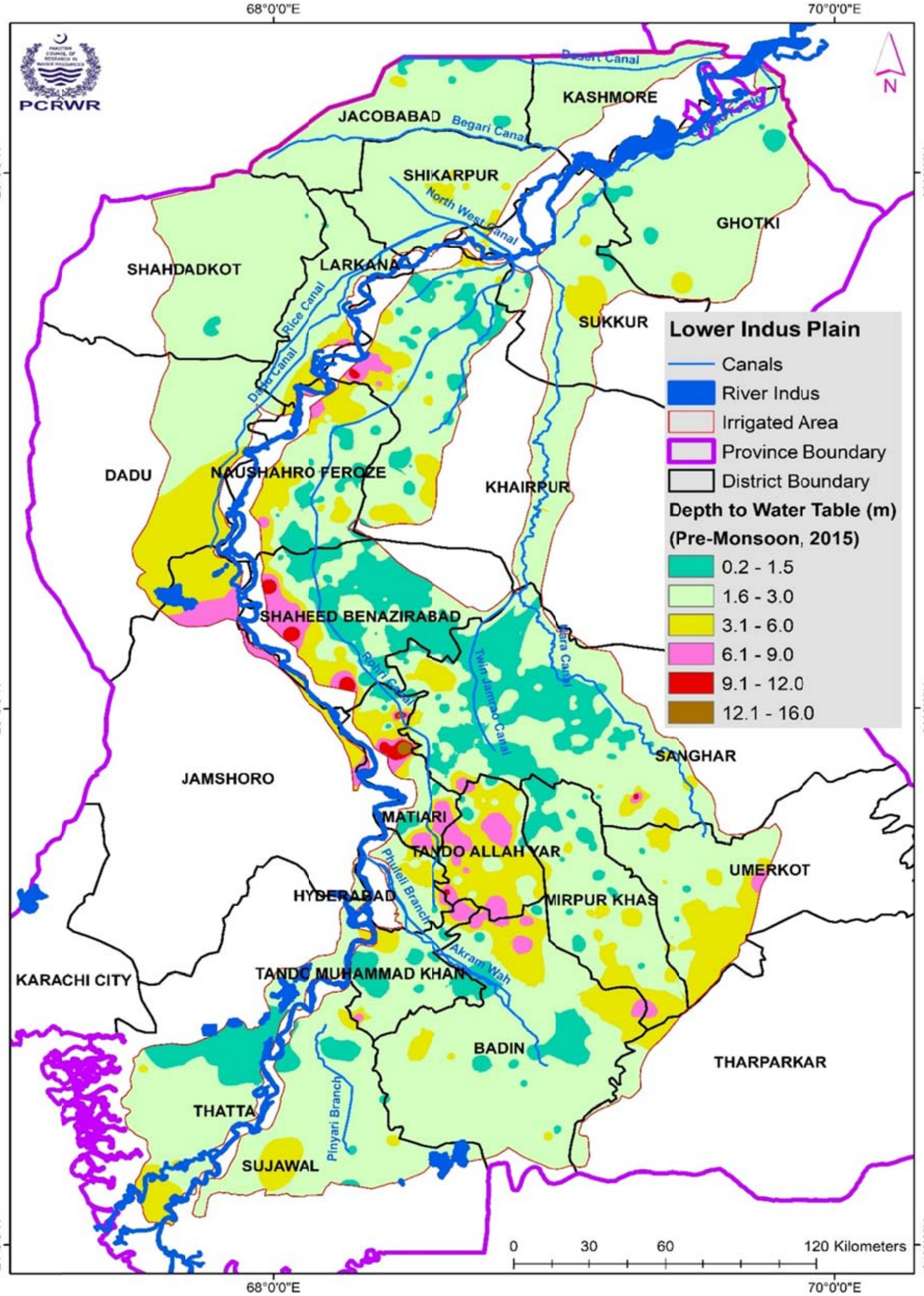

Figure 6: Spatial variations in depth to water table in CCA of Sindh in 2015 (pre-monsoon)

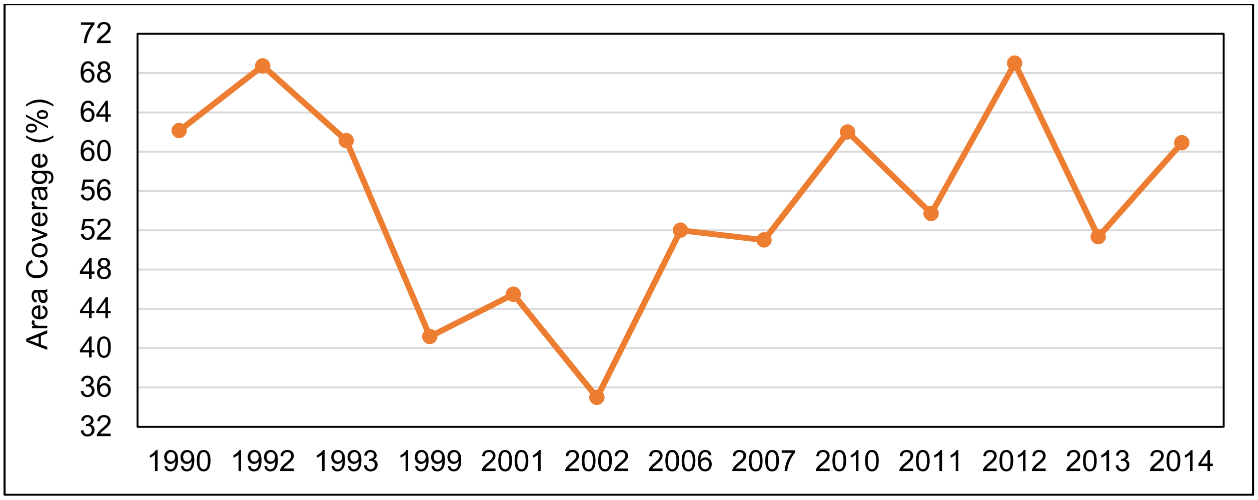

Figure 7: Long-term variations in waterlogging condition in the LIP
(Source: Steenbergen et al., 2015 and authors calculations)

3.3 Soil Salinity

Generally, soils are characterized on the basis of Electric Conductivity (EC), Sodium Absorption Ratio (SAR) and Exchangeable Sodium Percentage (ESP). Horneck *et al.*, (2011) defined the criteria for the characterization of soil health based on different ranges of EC, SAR and ESP (Table 3).

Table 3: Classification of soil salinization and sodicity

Soil Type	EC (dS/m)	SAR	ESP
Normal	Below 4	Below 13	Below 15
Saline	Above 4	Below 13	Below 15
Sodic	Below 4	Above 13	Above 15
Saline-Sodic	Above 4	Above 13	Above 15

Most of the soil salinity in the Indus Basin is inherited. According to Qureshi *et al.,* (2008), about 33 million tons (MT) of salt are brought by the Indus river and its tributaries annually. Out of this, only 9.0 MT (27%) are washed out of the system and the remaining about 24.0 MT (73%) are retained in the soil profile. Out of the salts deposited in the basin, 13.6 MT and 10.4 MT are retained in Punjab and Sindh, respectively.

The soil salinity coupled with sodicity adversely affects the soil in the form of land degradation. It not only reduces the crop yields but also destroy the soil structure.

The soil salinity refers to the concentration of salts present in the soil whereas the concentration of sodium increases sodification in the soil. The reclamation of saline soils is relatively easy through deep ploughing and application of fresh water, which helps to leach down the salts from the root zone. However, the reclamation of sodic soils are difficult, as it requires a combination of physical interventions and chemical amendments (Azhar *et al.,* 2001; Ashraf *et al.,* 2004; Qadir and Oster, 2004).

For the analysis of soil salinity, the spatial variation in EC, SAR and ESP have been mapped in Arc GIS at 0-5 m and 6-10 m depth intervals (Figures 8 to 13). The spatial analysis reveals that the values of EC, SAR and ESP are high in the lower part of Sindh especially in the Indus Delta. However, the values of EC, SAR and ESP also found higher than permissible limits in the upper reaches covering the areas of Rahimyar Khan, Rajanpur and Kambar Shahdadkot.

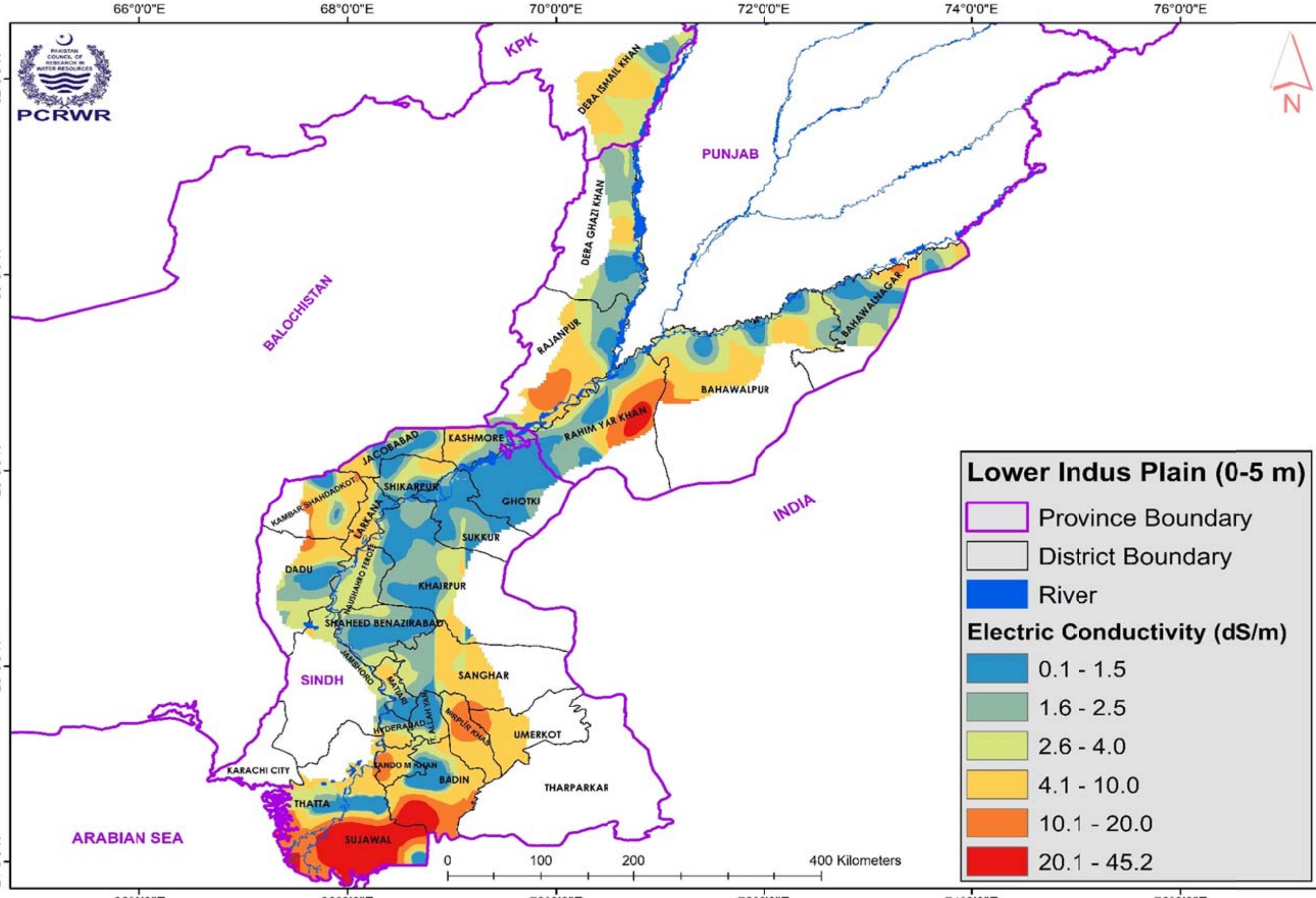

Figure 8: Spatial variations in EC at 0-5 m depth interval

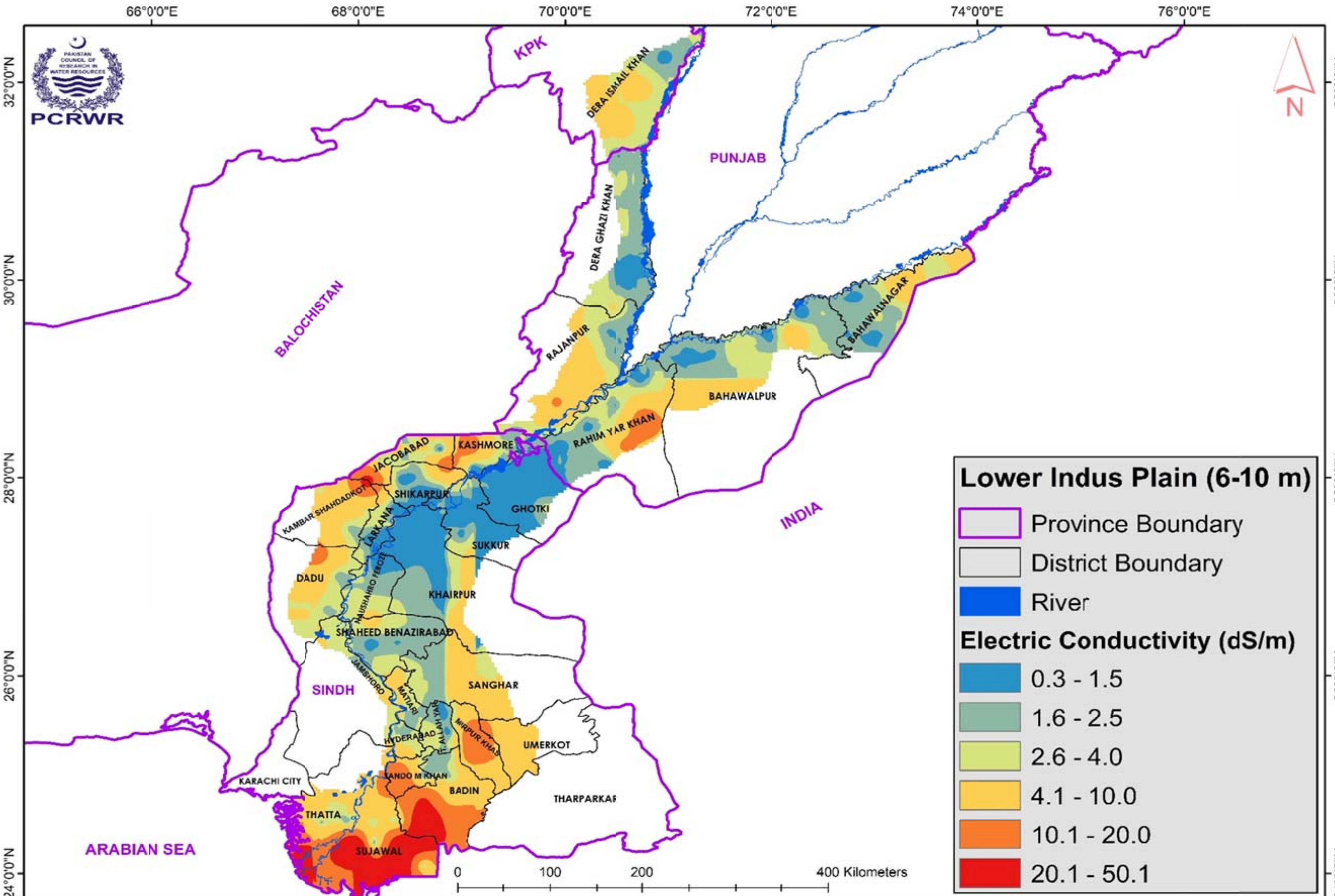

Figure 9: Spatial variations in EC at 6-10 m depth interval

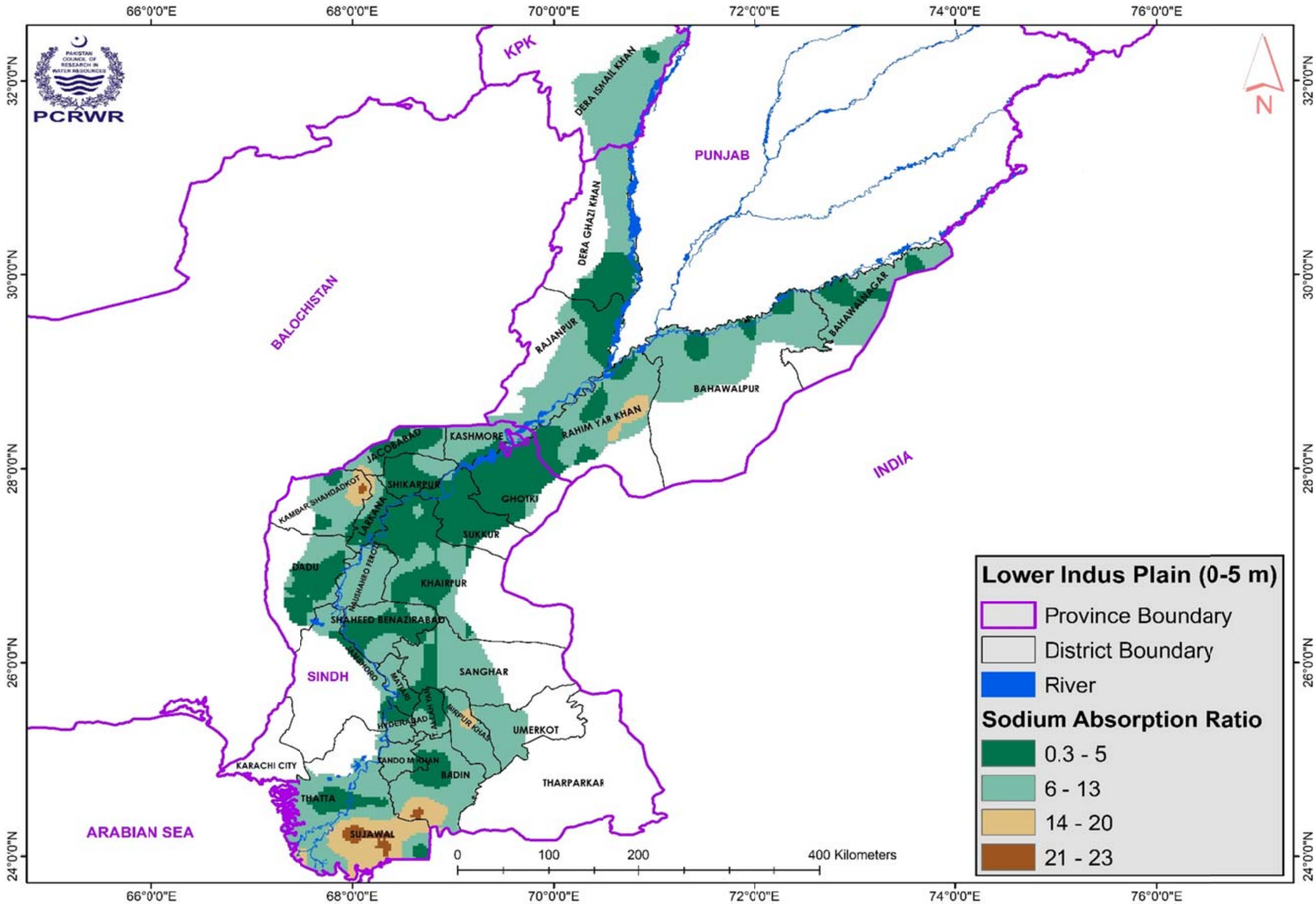

Figure 10: Spatial variations in SAR at 0-5 m depth interval

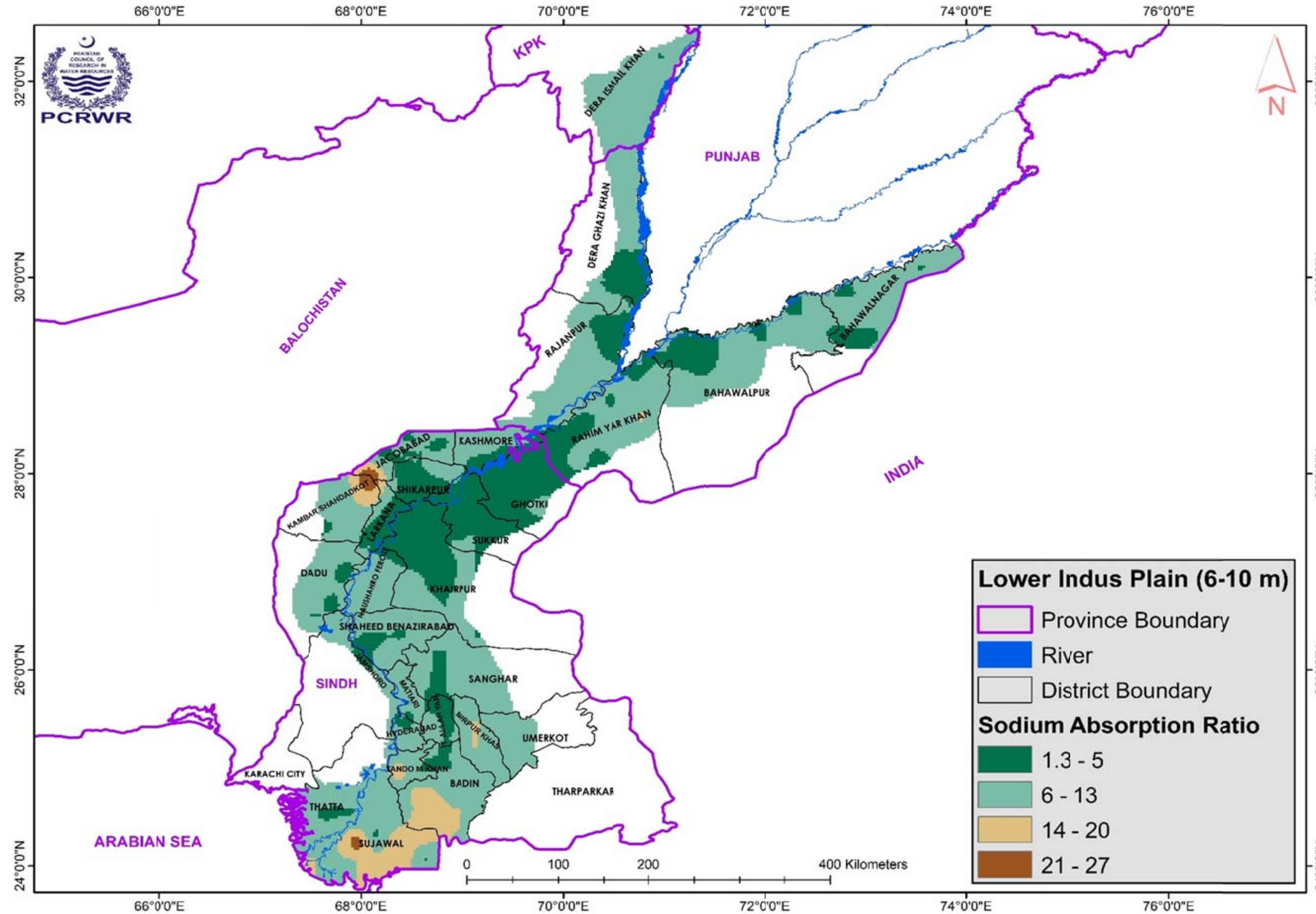

Figure 11: Spatial variations in SAR at 6-10 m depth interval

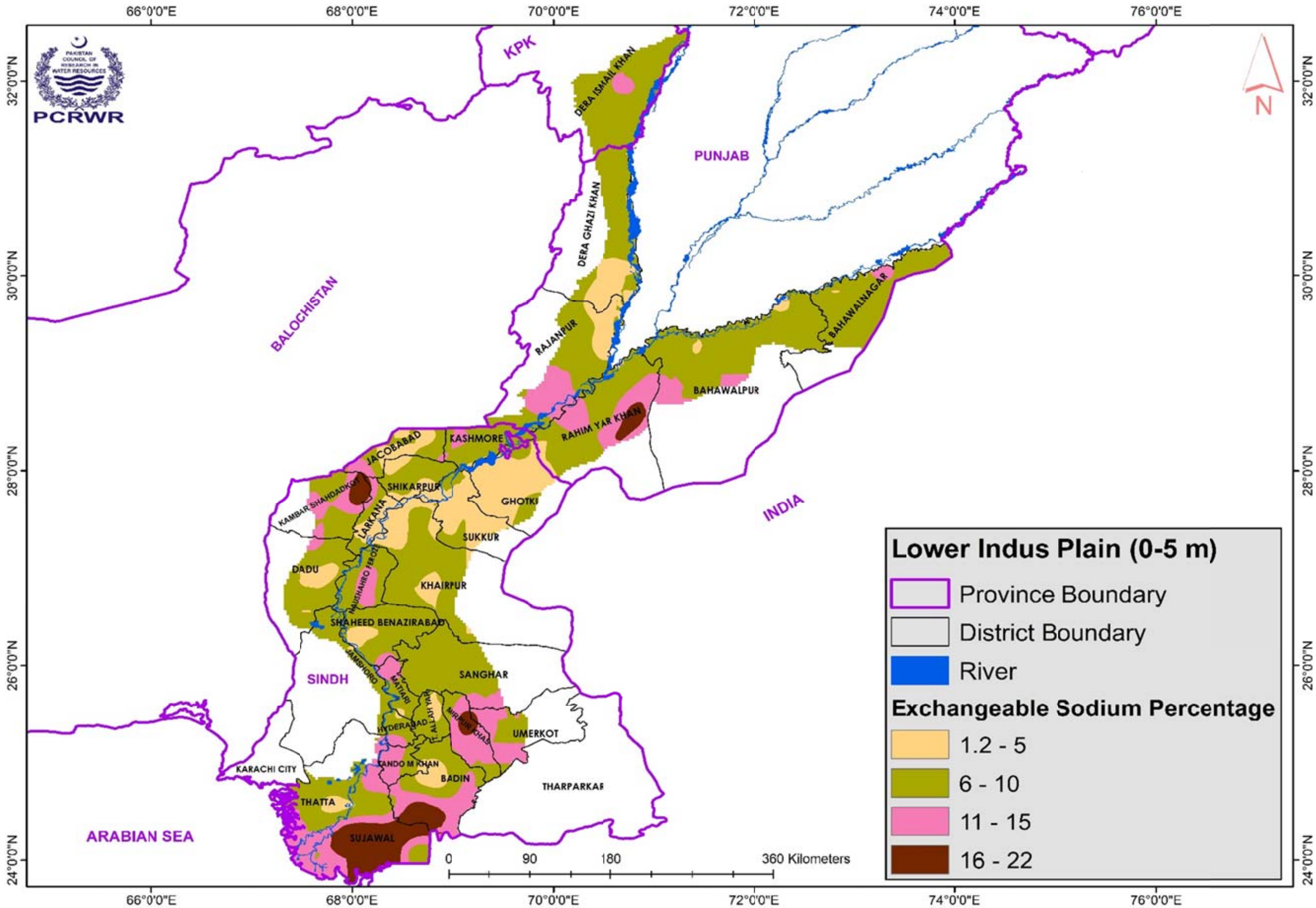

Figure 12: Spatial variations in ESP at 0-5 m depth interval

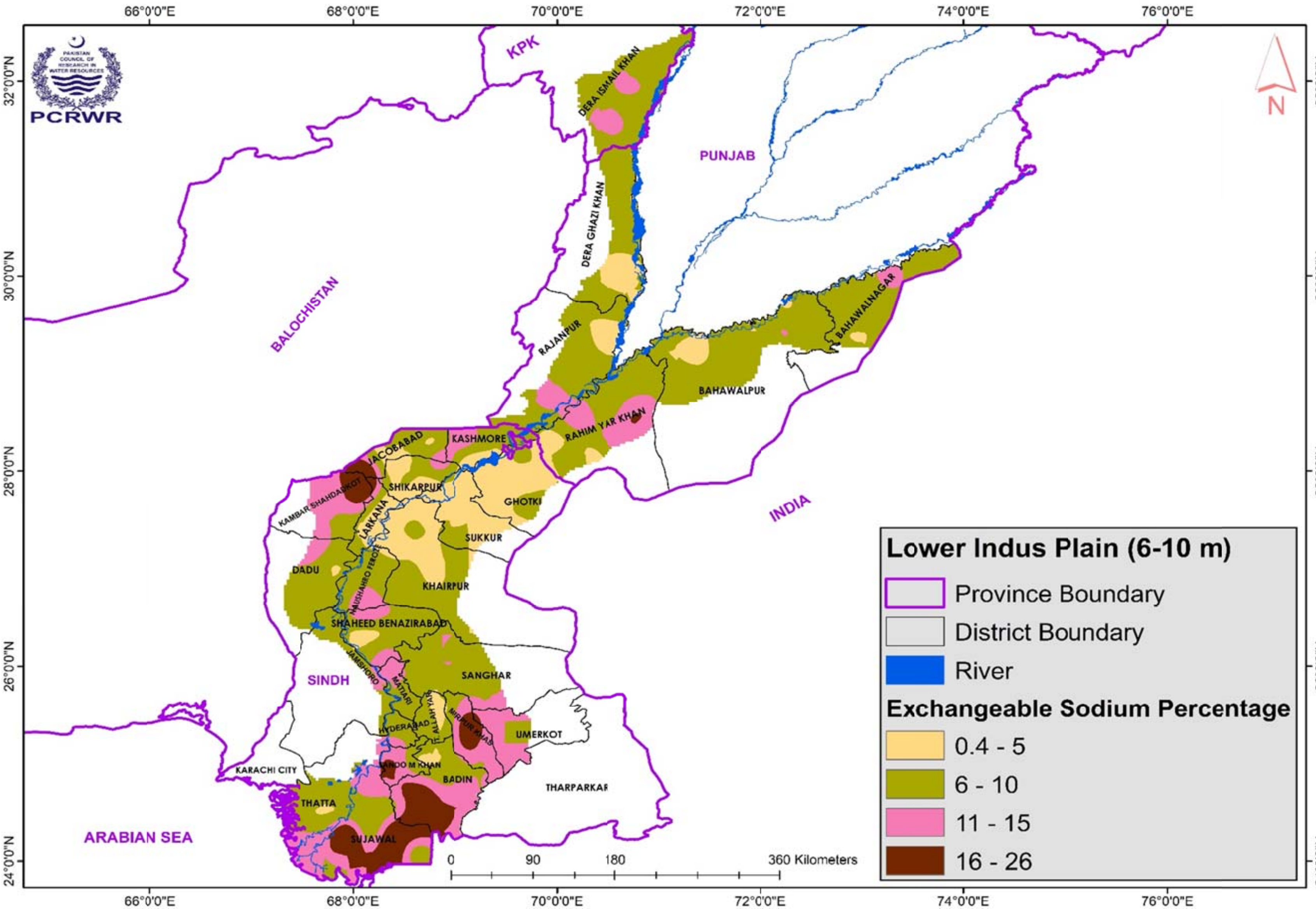

Figure 13: Spatial variations in ESP at 6-10 m depth interval

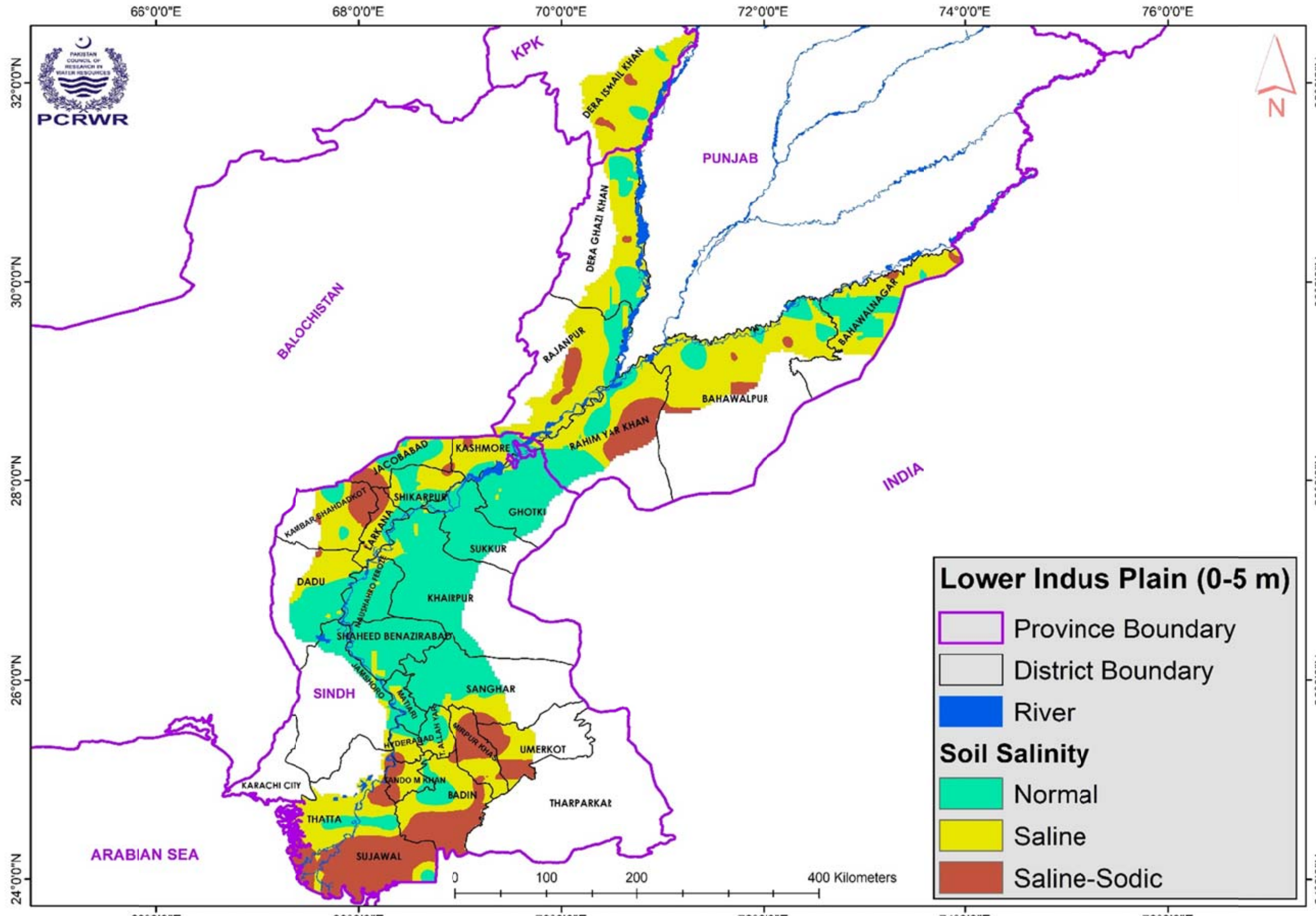

Figure 14: Spatial variations in soil salinity at 0-5 m depth interval

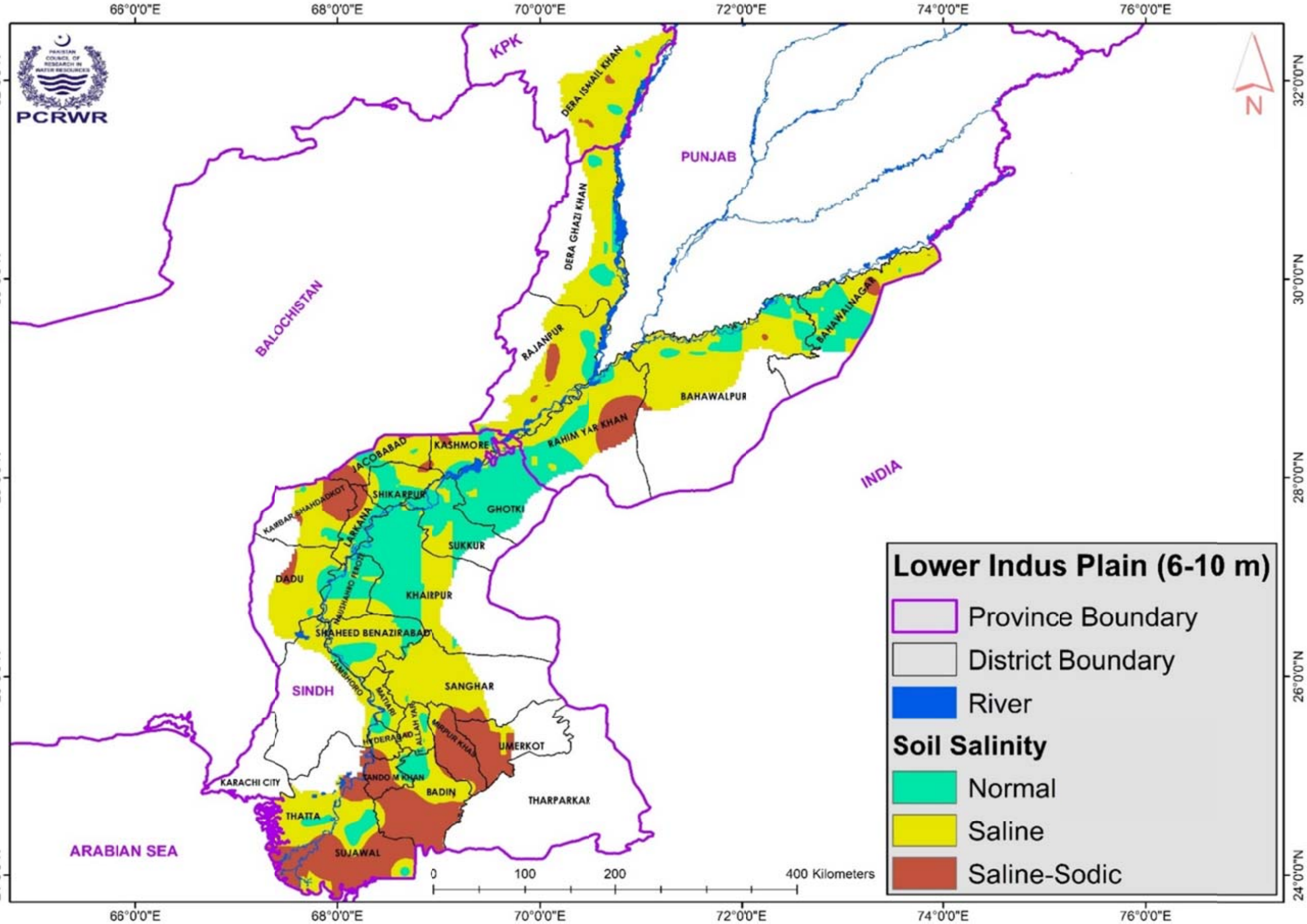

Figure 15: Spatial variations in soil salinity at 6-10 m depth interval

The districts on the left side of the River Indus starting from Ghotki to Tando Allah Yar have normal soil whereas, the remaining areas have either saline or saline-sodic soils. The soil salinization and sodification increase with depth as the area under normal soil reduces to half (51% to 29%) when move from 0-5 m to 6-10 m depth. Similarly, the area under saline and saline-sodic soils increase from 28% to 47% and 20% to 24% with depths of 0-5 m and 6-10 m, respectively (Figure 16). At 6-10 m depth, the areas of Ghotki and parts of Sukkur, Khairpur and Shikarpur districts have normal soils. The soil salinization and sodification processes intensifies with depth in the lower part of Sindh especially in the Indus delta. These results are for 0-5 m depth and show the average variation in soil salinity below earth surface. The samples were collected through exploratory wells drilling but not from the top surface. Therefore, the results of soil salinity sampling collected directly from top soil may vary.

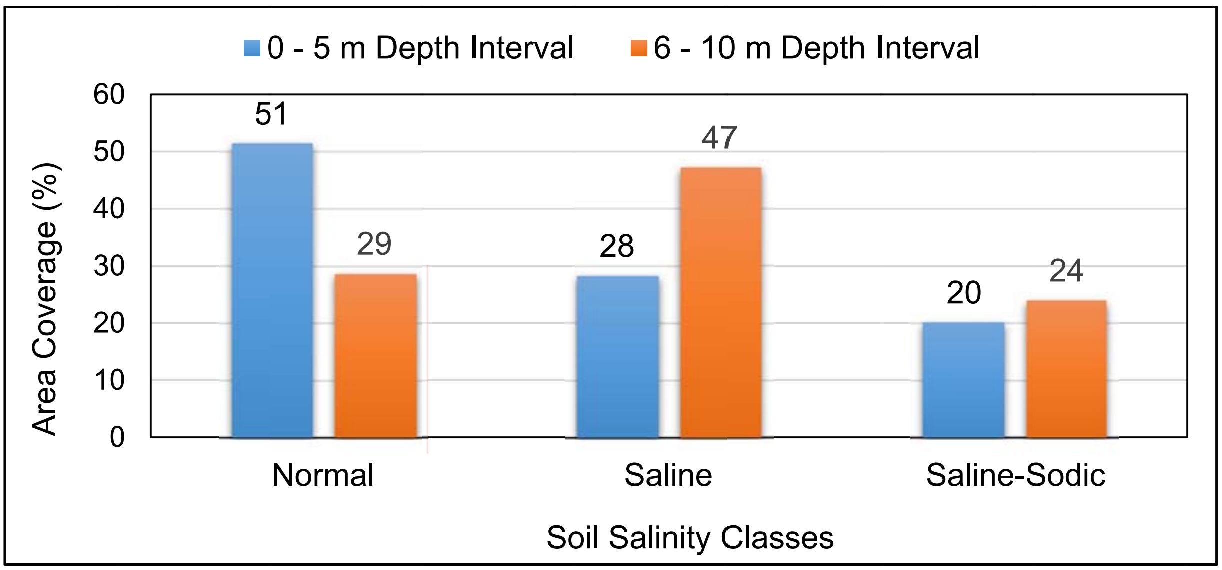

Figure 16: Vertical variation in soil salinity over the LIP, 2014-18

Basharat *et al.,* (2014) has reported the results of earlier studies conducted by IWASRI during 1978-79 and 2001-03 pertaining to the variations in the extent of surface salinity over the LIP. The results of present study have also been incorporated in above results to see the temporal trends. Although these results are not the representation of surface salinity as covers 0-5 m depth interval, the analysis will help to improve the understanding of temporal variations in the LIP. On average, the percentage area coverage under normal soil decreased from 54% (1978-79) to 51% (2014-18). The reason of this area reduction may be associated with saline groundwater pumping in Sindh. Because, there is a very thin lens of fresh groundwater available. Over the time, the continuous pumping has caused saline water up-coning which has increased surface salinity by accumulation of salts in the root zone and decreases crop yield (Ashraf *et al.,* 2012). Resultantly, the area of normal soil decreases gradually. However, an increasing trend is evident in area coverage of saline-sodic as well as saline soils over the period from 1978-79, 2001-03 and 2014-18 (Figure 17). The area under saline-sodic and saline soils varies from 17%, 21%, 20% and 29%, 30%, 28%, respectively.

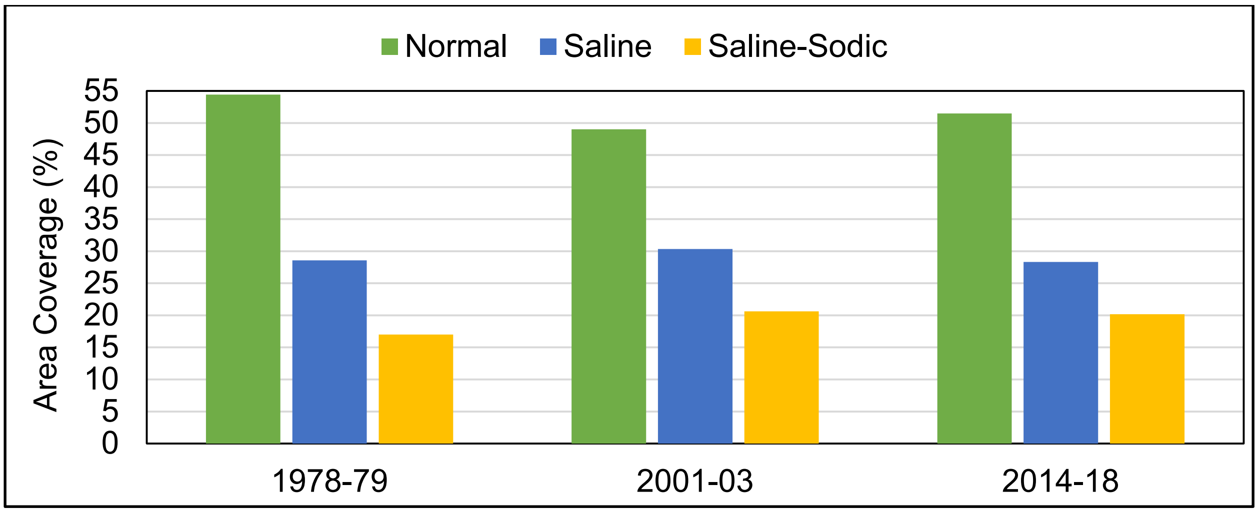

Figure 17: Temporal variations in surface salinity over the LIP from 1978-79 to 2014-18 (Source: Basharat et al., 2014 and updated by the authors)

3.4 Groundwater Quality Mapping

In the Indus Plain Aquifer, the behavior of hydro-salinity is dynamic and varies over space and time (Saeed *et al.,* 2003). Especially in the LIP, the groundwater quality at deeper depths is highly saline and a layer of fresh quality prevails with varying thickness in the aquifer in the areas of favorable lithologies where sources of groundwater recharge are available. The evaluation of groundwater quality and monitoring of groundwater usage are important for sustainable groundwater management.

Figures 18 and 19 show that groundwater of the major area has a high EC ranged from 2.6 to 30.0 dS/m at 15 m and 25 m depths. Both the laboratory results of EC (Figure 15) and groundwater quality (GWQ) derived through ERS (Figure 16) show an agreement that only the areas along the River Indus in the upper part of Sindh province have pockets of fresh groundwater. The EC increases towards lower parts of Sindh, especially in the Indus Delta where at 15 m depth; it reaches up to 97 dS/m.

Interestingly, the analysis indicates that there is more salinity at the depth of 10-15 m as compared to 20-25 m depth. Generally, the salinity increases with depth due to the decrease in recharge induced by freshwater through different sources. The reason for high salinity at shallow depth (10-15 m) may be due to compound effect of the existence of native salinity in the soil and increase in salinity through capillary rise.

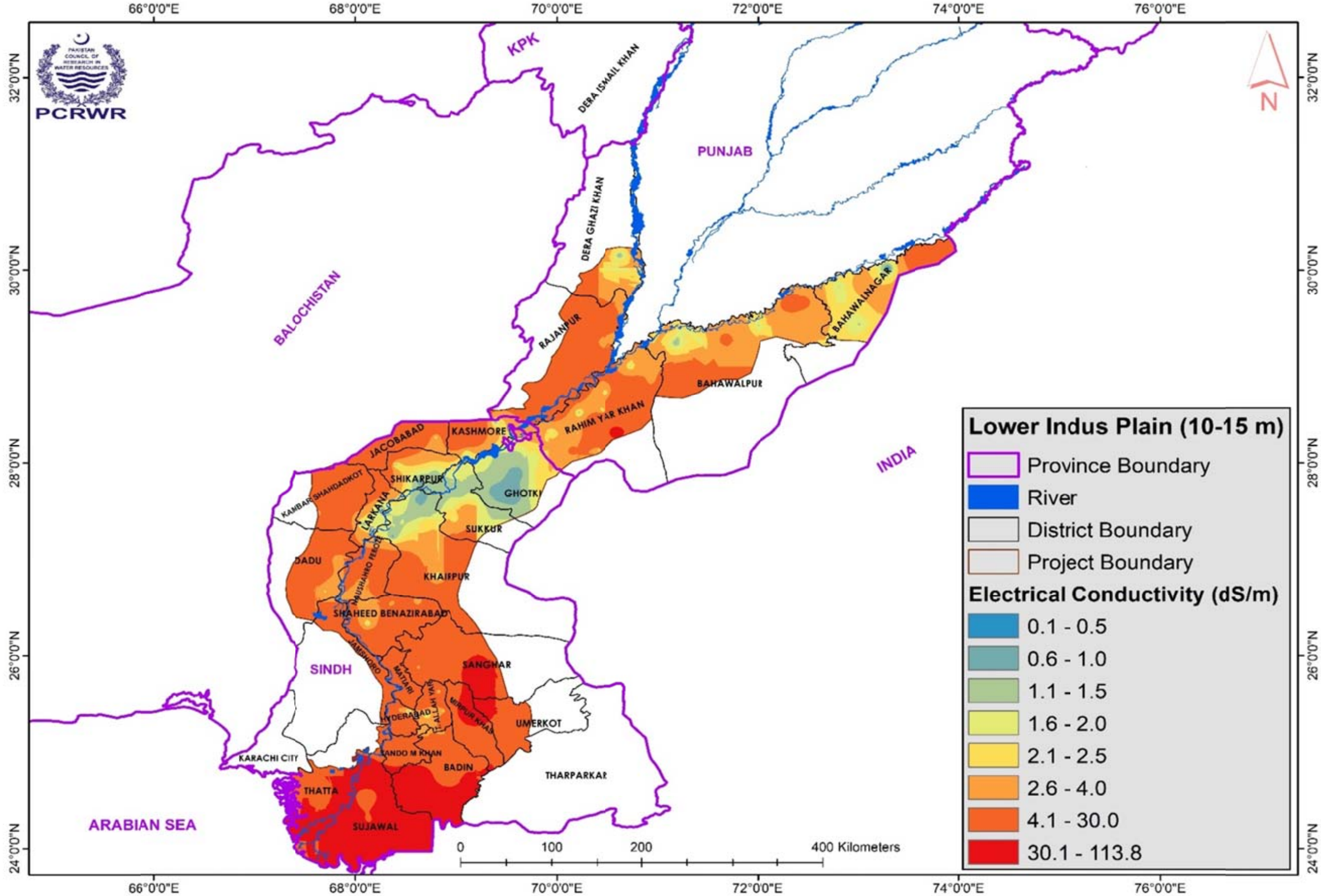

Figure 18: Spatial variations of EC in the groundwater at 10-15 m depth

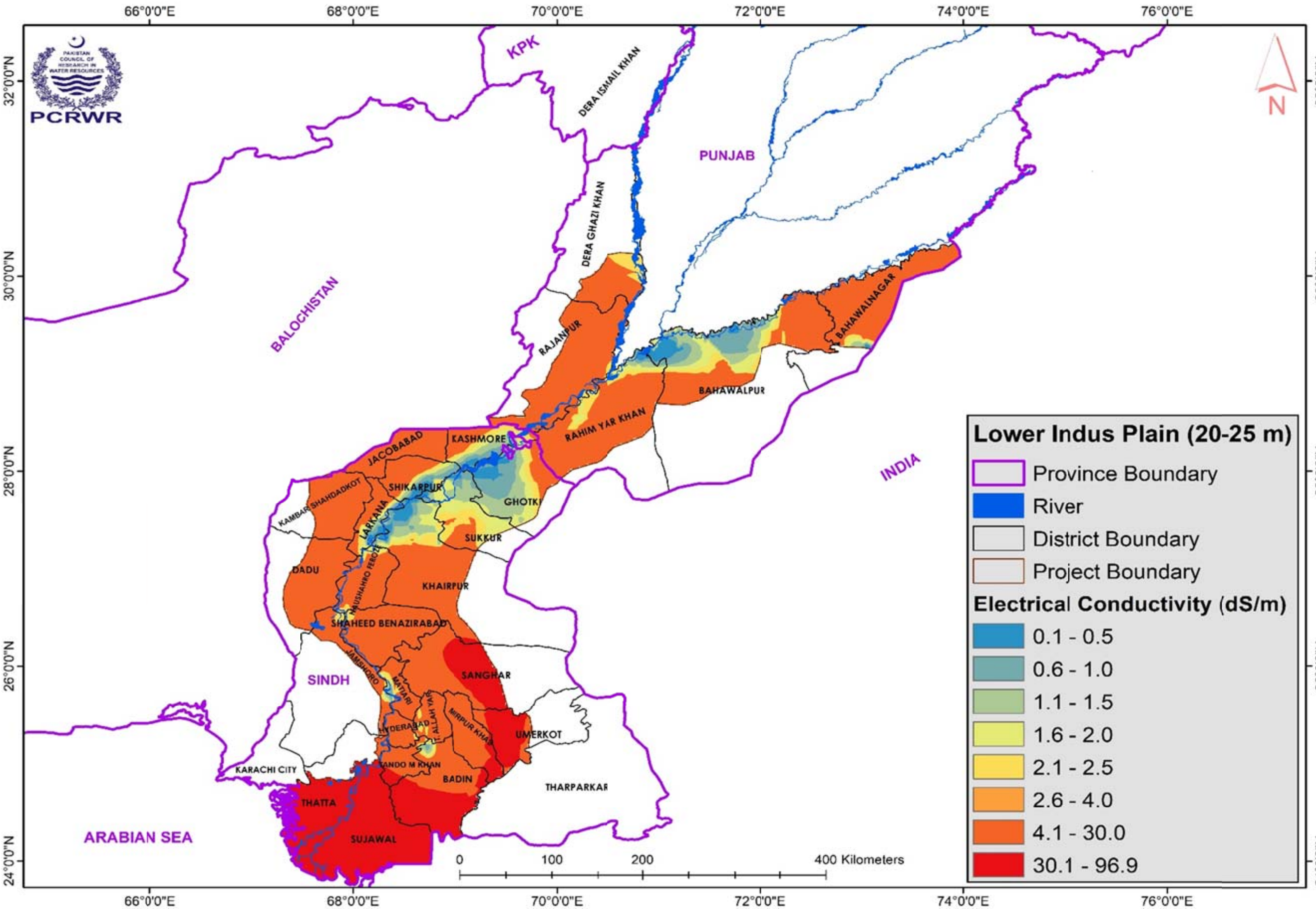

Figure 19: Spatial variations of EC in the groundwater at 20-25 m depth

The extent of groundwater salinity further increases as well as intensifies below Hyderabad towards the Indus Delta may be due to sea-water intrusion and prevalence of more fine strata (loam and clay). The groundwater of usable quality is found in shallow pockets in parts of districts Kashmore, Shikarpur, Ghotki, Sukkur, Khairpur, Naushero Feroz and Shaheed Benazirabad. The extent and intensity of hydro-salinity further increases with depth (Figures 20 to 27).

It is important to note that depth to bedrock is shallow in the LIP as compared to the UIP. Due to financial constraints and time limitations, the exploratory well drilling was conducted only up to the depth of 100 m. Although, the resistivity survey was carried out upto a depth of 300 m, the results do not show the existence of bedrock. This was the main limitation of resistivity method. Similarly, the results of Induced Polarization (IP) survey that was conducted upto 1000 m depth do not help for the delineation of aquifer thickness. The main reason is the presence of high concentration of salts in the groundwater. Under such a scenario, the results of ERS are considered more valid upto the depth of 200 m and the maps beyond this depth have been developed just to see the trend of groundwater quality.

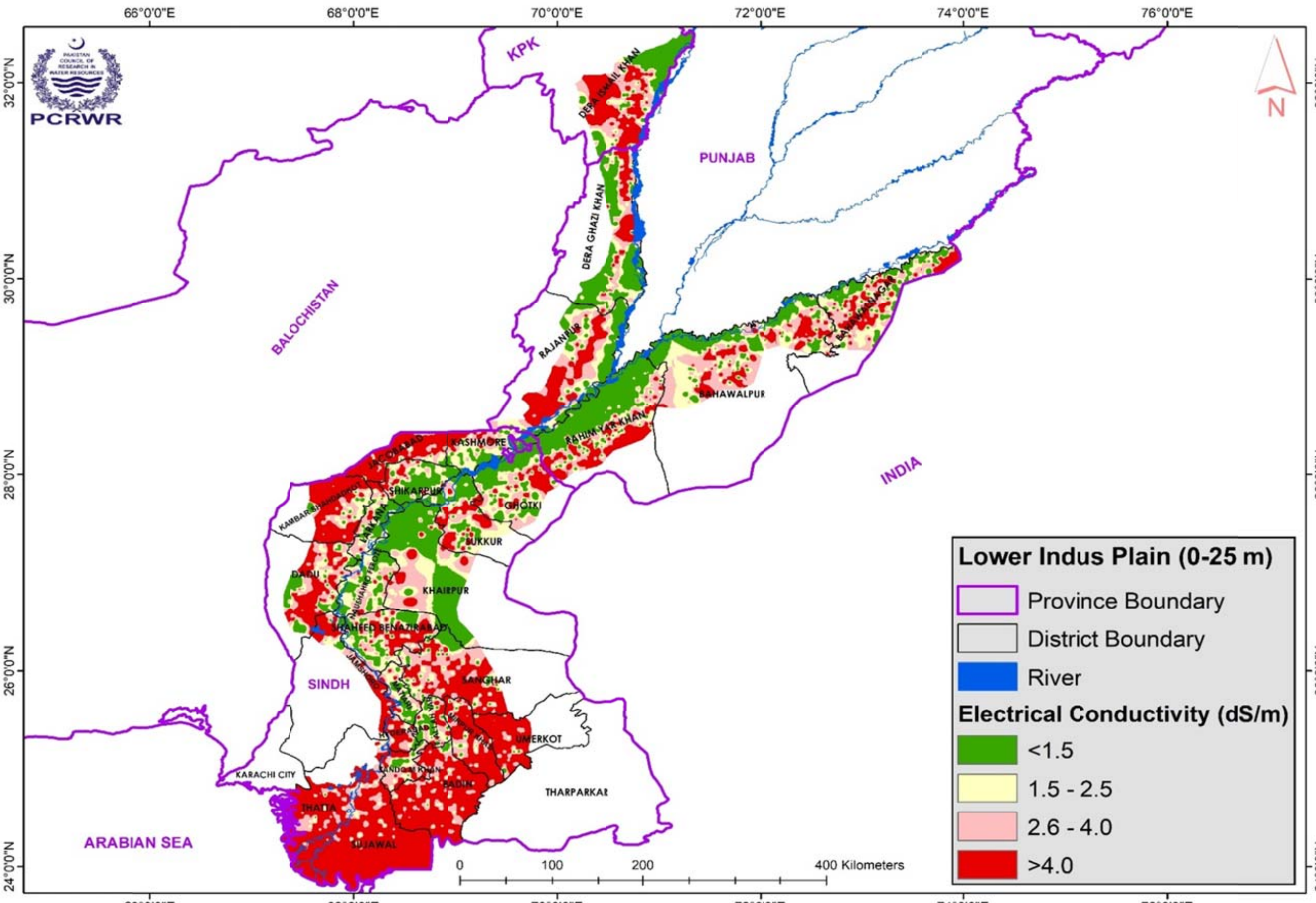

Figure 20: Groundwater quality at 0-25 m depth

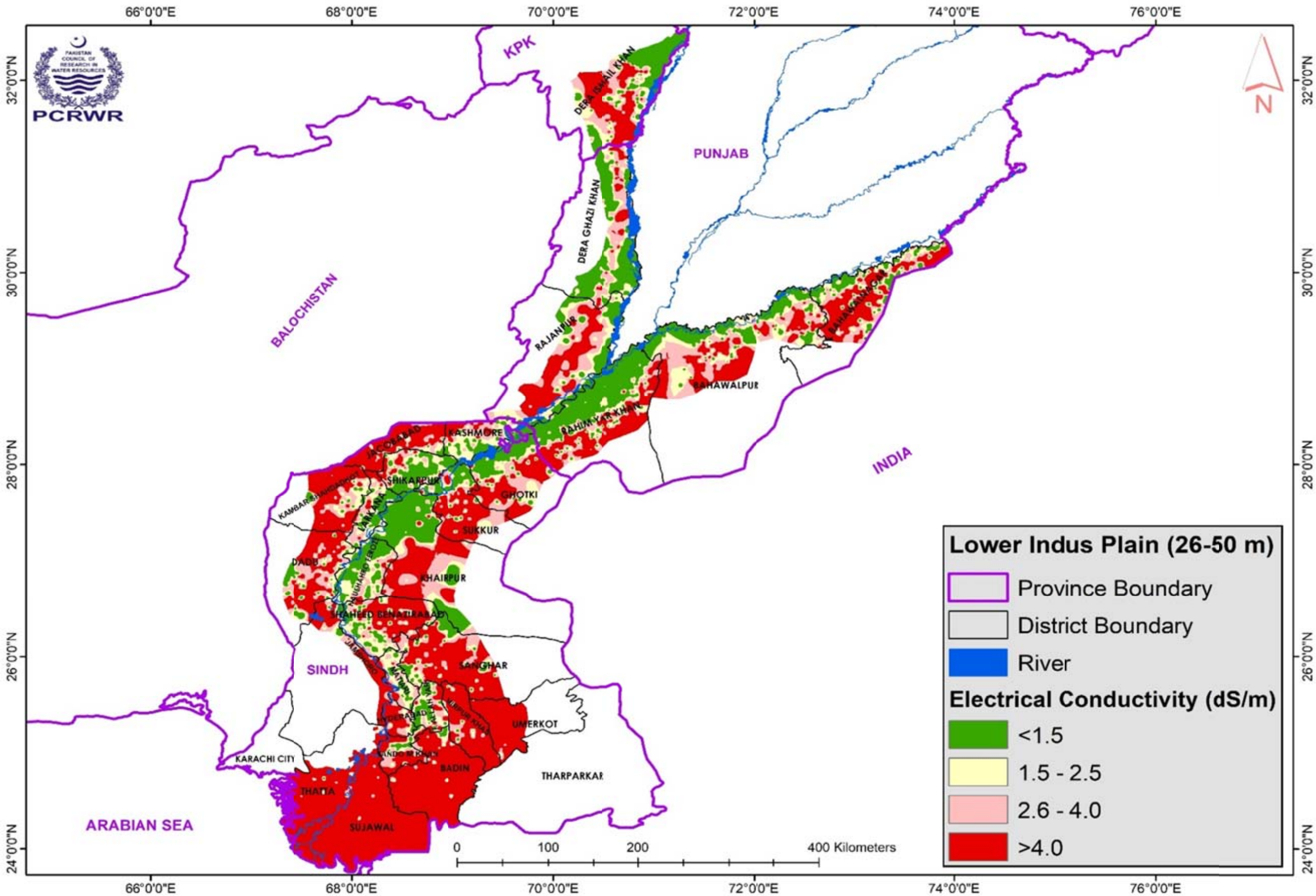

Figure 21: Groundwater quality at 26-50 m depth

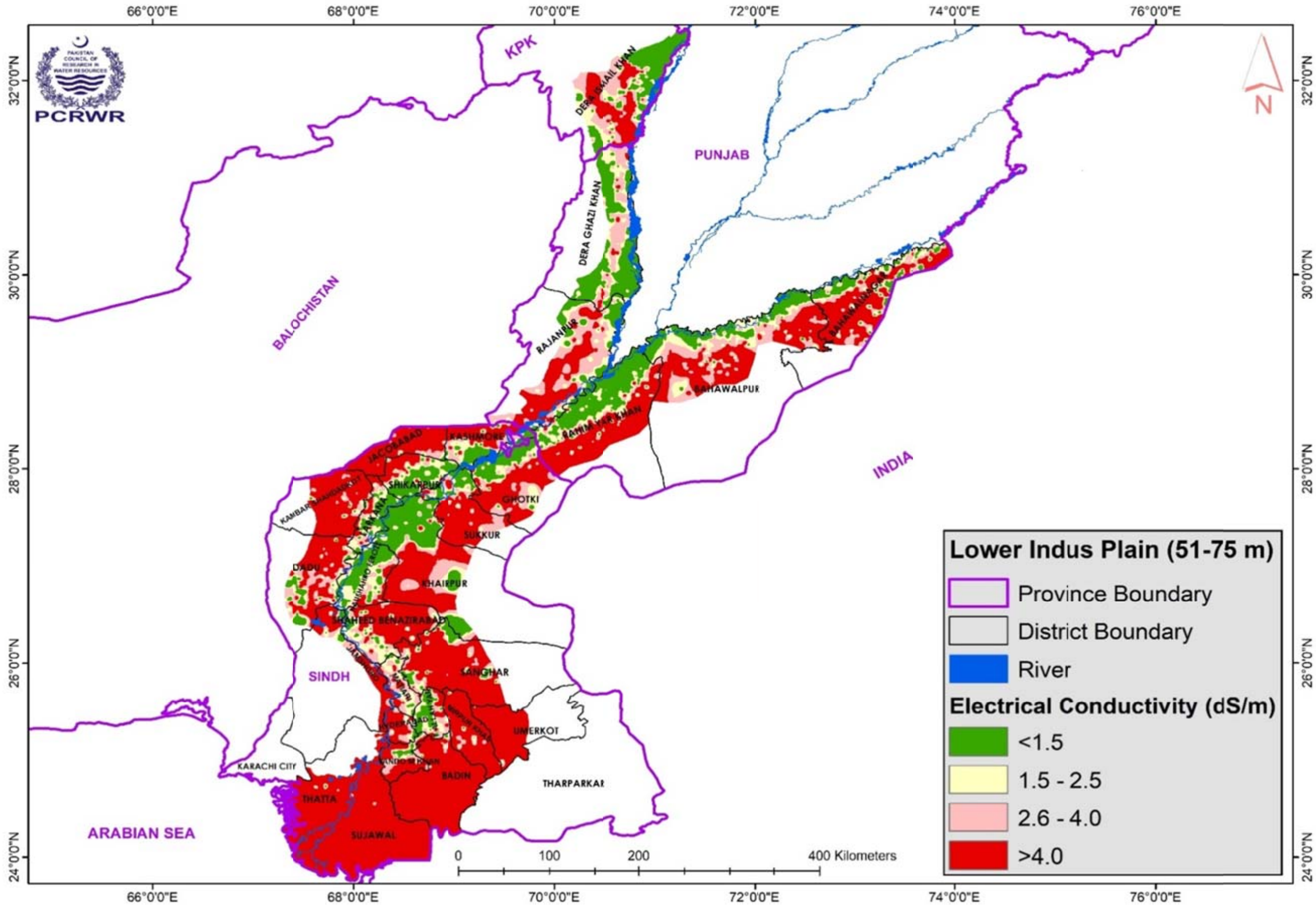

Figure 22: Groundwater quality at 51-75 m depth

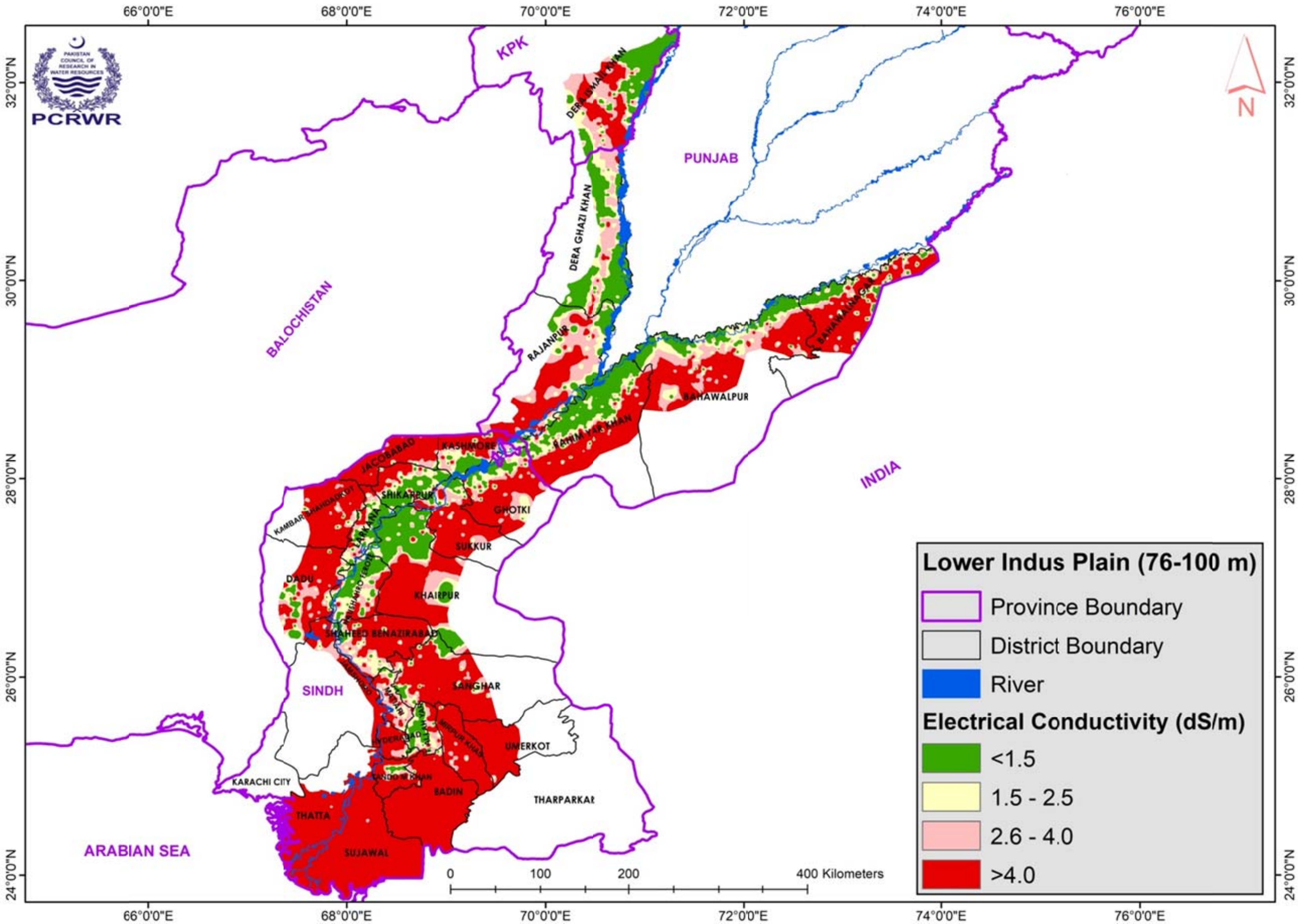

Figure 23: Groundwater quality at 76-100 m depth

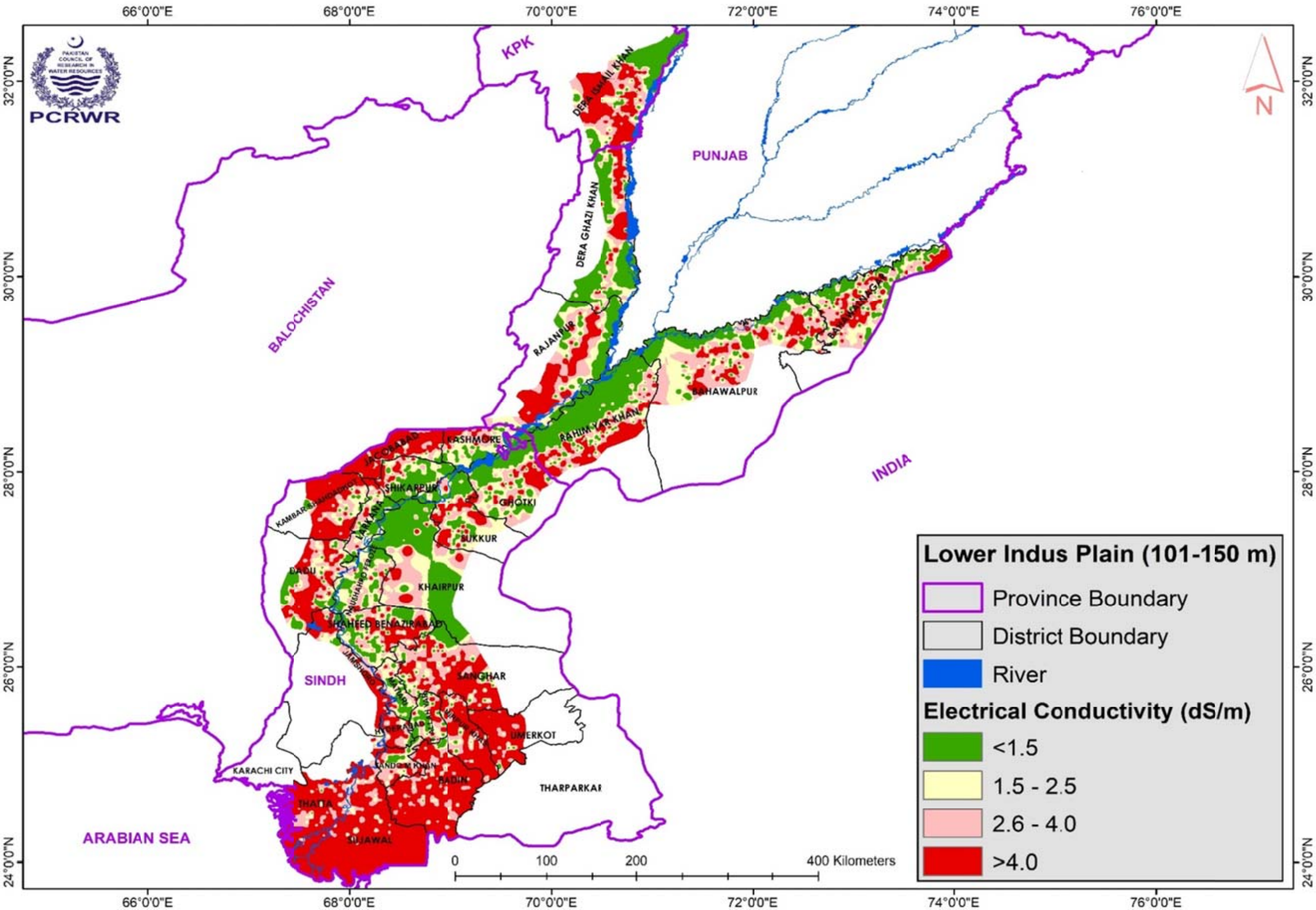

Figure 24: Groundwater quality at 101-150 m depth

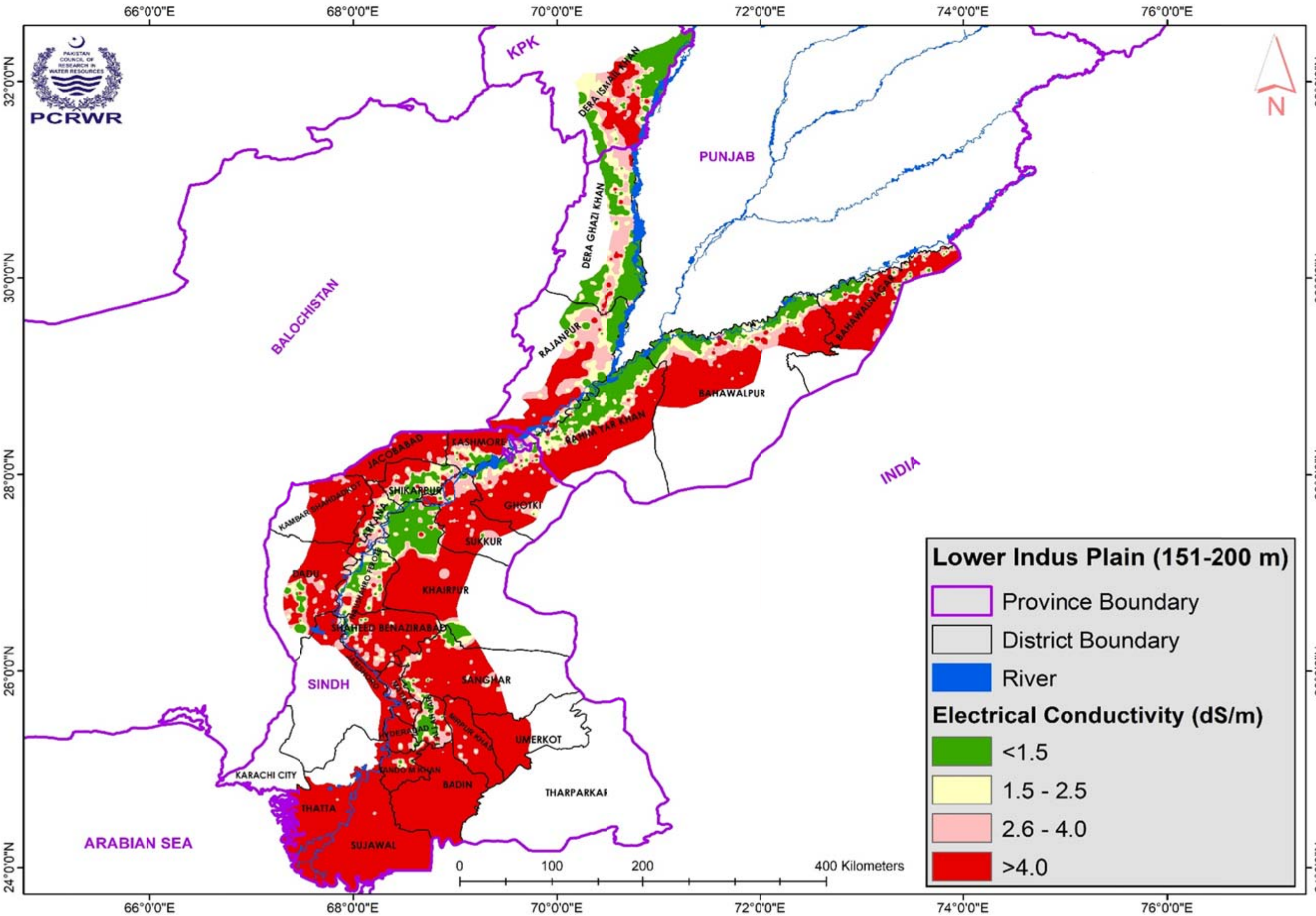

Figure 25: Groundwater quality at 151-200 m depth

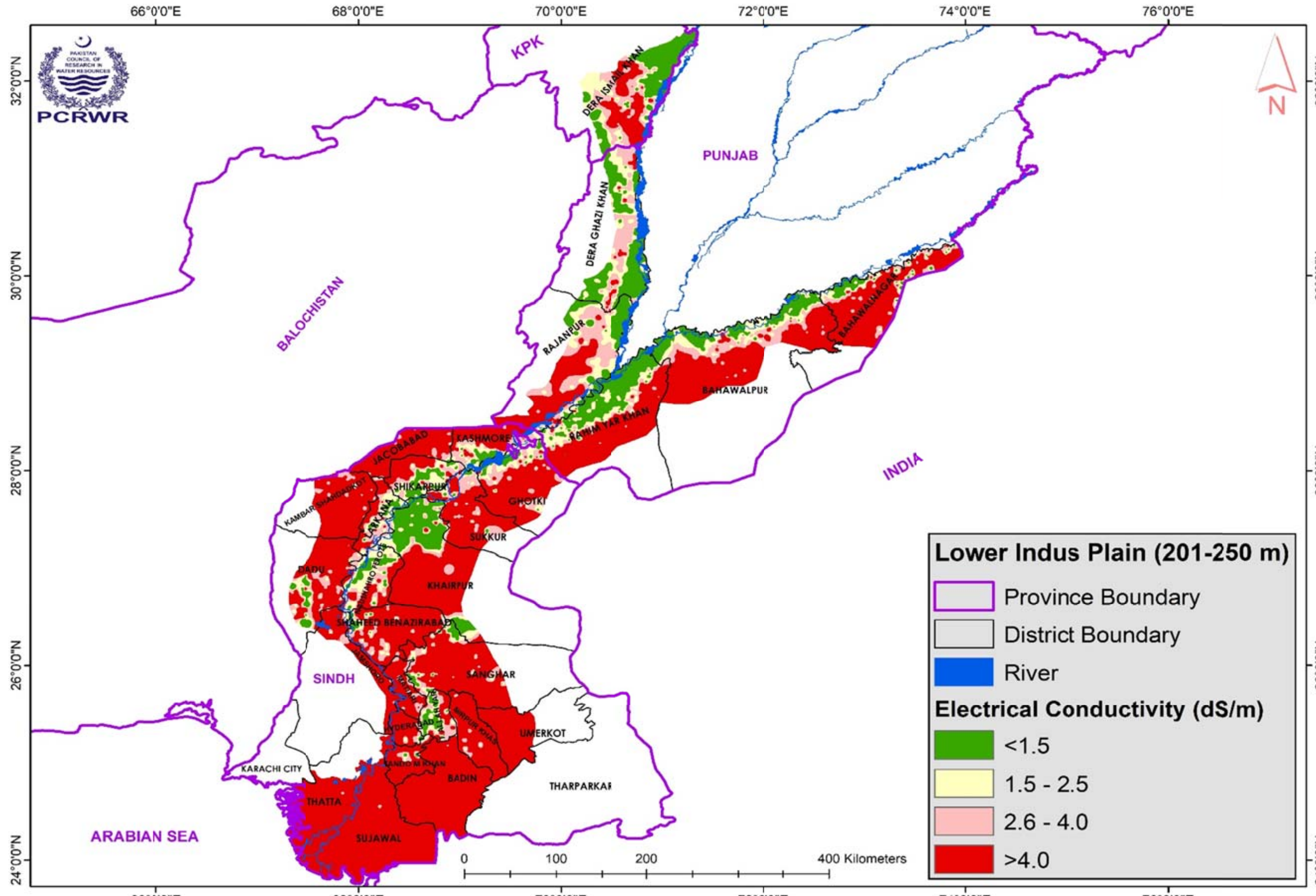

Figure 26: Groundwater quality at 201-250 m depth

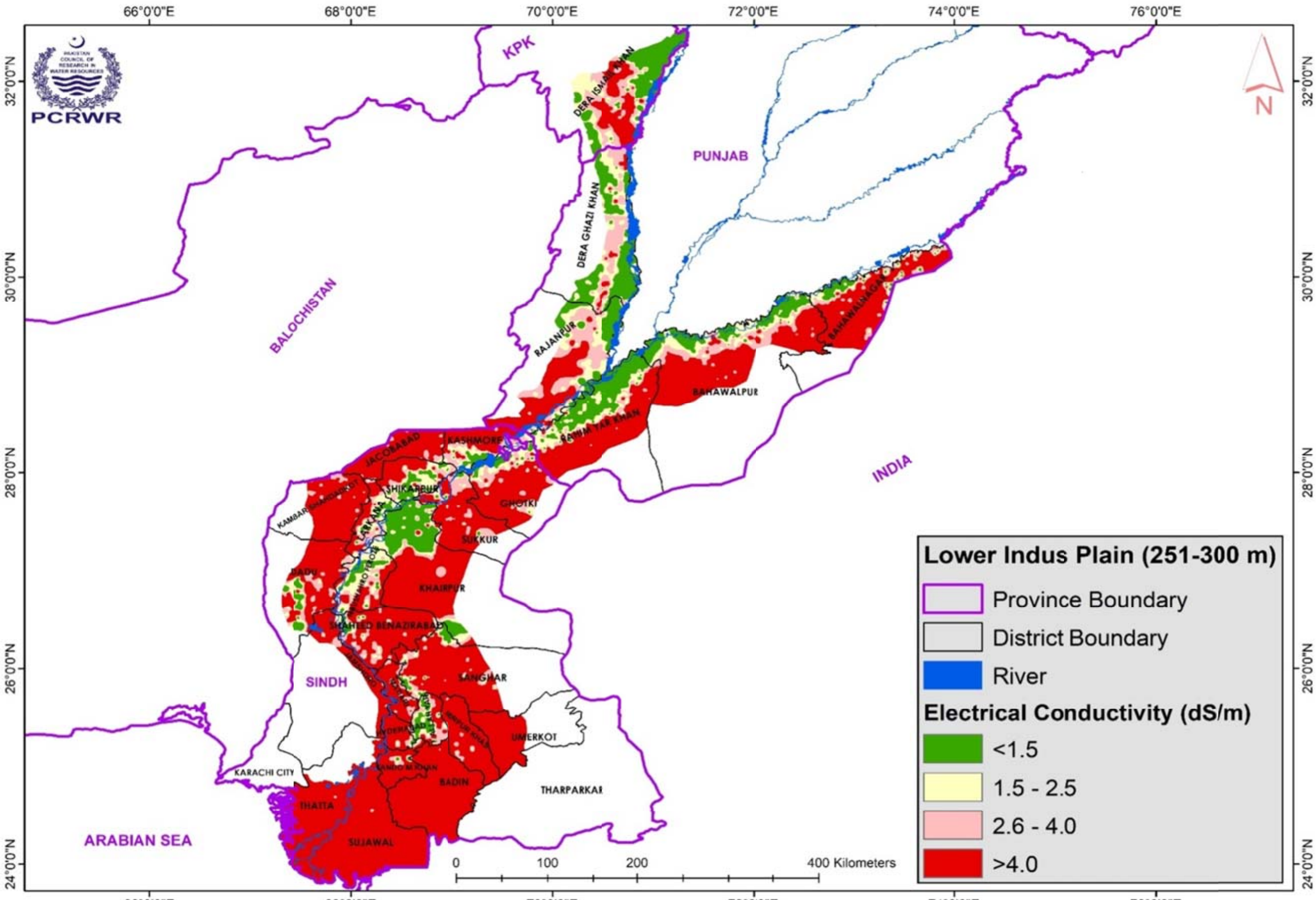

Figure 27: Groundwater quality at 251-300 m depth

3.5 Usable Groundwater Resources

For the quantification of groundwater resources, the groundwater quality has been divided into four major categories; freshwater (0-1.5 dS/m), marginal water (1.6-2.5 dS/m), saline water (2.6-4.0 dS/m) and highly saline water (>4.0dS/m). For this purpose, the area under each class has been calculated against different depths using ArcGIS software. The analysis was further focused on two areas i.e; Lower Indus Plain Aquifer (LIPA) referring Sindh Province and parts of the UIPA referring districts of Punjab Province including plain area of D. I. Khan district along the River Indus. The comparison in both areas (LIPA and UIPA region) shows that the deterioration of groundwater quality with respect to depth is more in the LIPA than the UIPA (Figures 28 and 29). In LIPA, the area under freshwater (0-1.5 dS/m) decreases gradually whereas; a dramatic increase in the area under highly saline water with depth can be seen (Figure 28).

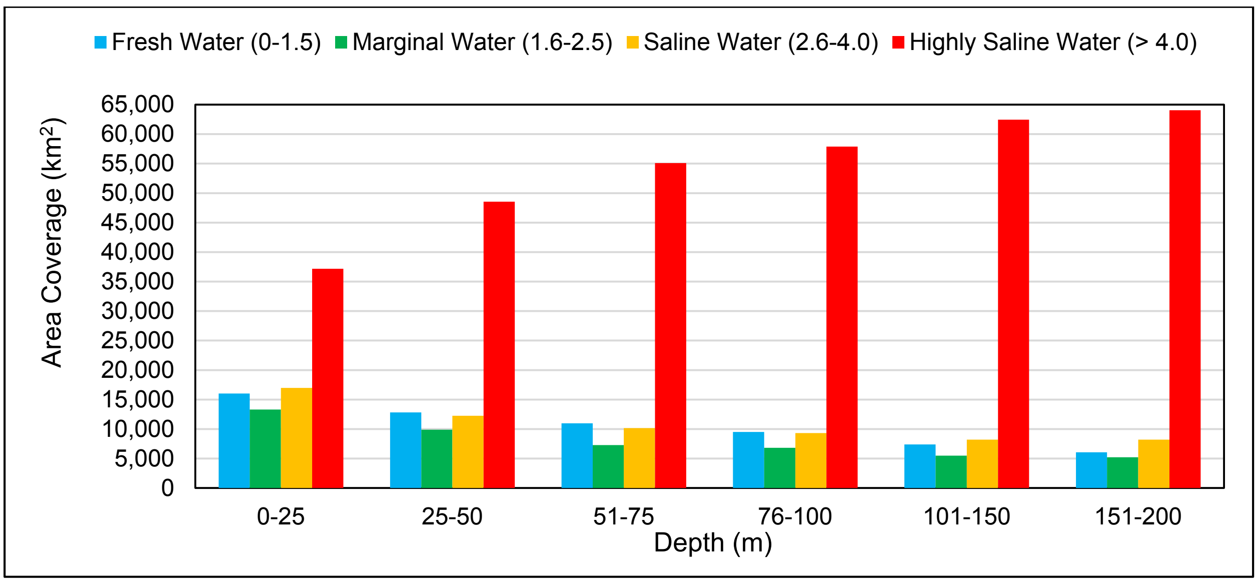

Figure 28: Changes in area coverage under different groundwater quality classes in the LIPA

Due to relatively better recharge from irrigation system and rainfall, the groundwater salinity is relatively low in most of the districts of the UIPA covered in this study. The area under freshwater quality decreases with depth with a moderate increasing trend of salinity (Figure 29).

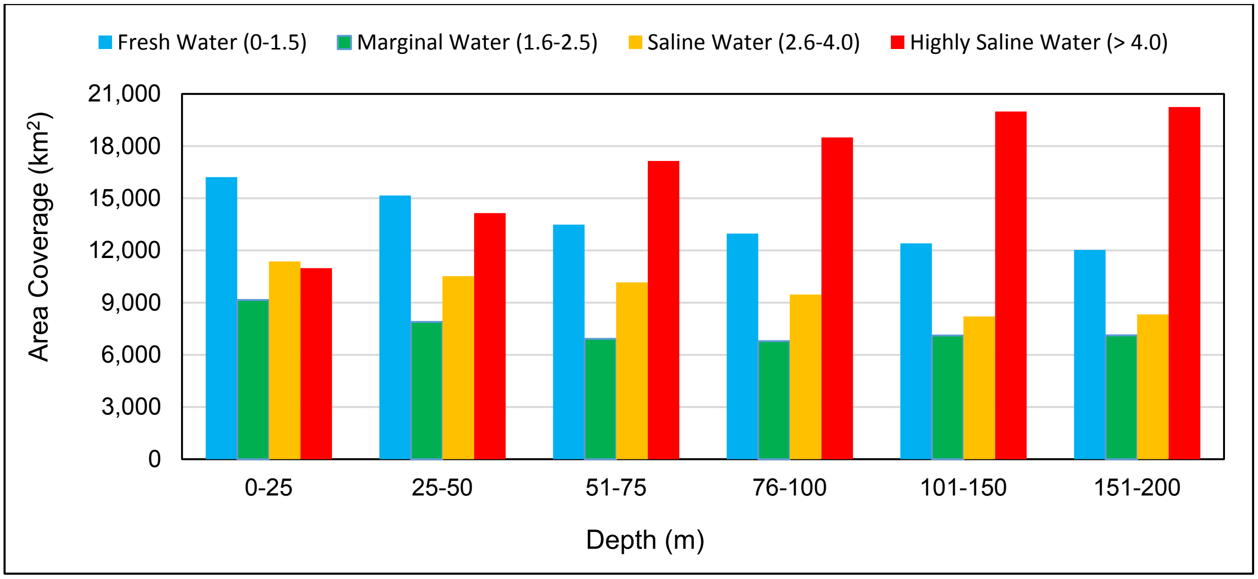

Figure 29: Changes in area coverage under different groundwater quality classes in the remaining areas of the UIPA

Table 4 shows the variations in area coverage under each groundwater quality class over the LIPA and the UIPA regions. About 20% area of LIPA falls under useable groundwater quality. Contrary to the LIPA, the groundwater salinity in the regions of the UIPA is moderate where about 43% area falls under useable groundwater quality. The active storage is estimated as 217 BCM and 335 BCM for the LIPA and the UIPA regions, respectively. The active storage has been calculated based on specific yield of 0.12% and 0.14% for LIPA and UIPA remaining areas, respectively. Therefore, the remaining areas of the UIPA constitute about 36% (335 BCM) of active storage in comparison with four doabs (800 BCM) (Khan *et al.,* 2016). The active storage is the volume of usable groundwater, which is available for pumping from the aquifer.

Table 4: Details of area coverage under different groundwater quality zones alongwith the active storage

Sr. No	Area	Groundwater Quality (dS/m)	Area Coverage (km^2)								Percentage of Total Area		Active Storage (BCM)
			Depth Interval (m)										
			0-25	25-50	51-75	76-100	101-150	151-200	201-250	251-300	0-300		0-300
1	Remaining Areas of UIPA	Fresh Water (<1.5)	16,219	15,154	13,481	12,967	12,413	12,028	11,896	11,884	28	43	335
		Marginal Water (1.6-2.5)	9,151	7,894	6,920	6,786	7,109	7,117	7,171	7,182	16		
		Saline Water (2.6-4.0)	11,365	10,524	10,168	9,468	8,207	8,327	8,301	8,302	20	57	
		Highly Saline Water (> 4.0)	10,979	14,143	17,145	18,494	19,986	20,243	20,347	20,347	37		
2	LIPA	Fresh water (<1.5)	16,035	12,822	10,973	9,503	7,384	6,055	5,796	5,732	11	20	217
		Marginal Water (1.6-2.5)	13,318	9,883	7,281	6,811	5,490	5,212	5,271	5,313	9		
		Saline Water (2.6-4.0)	16,980	12,246	10,160	9,,313	8,196	8,202	8,162	8,167	12	80	
		Highly Saline Water (> 4.0)	37,179	48,560	55,098	57,885	62,442	64,042	64,282	64,299	68		

Figures 30 and 31 show the variations in groundwater quality covering both the Upper and the Lower Indus Plains. Generally, more fresh groundwater is available in the UIP than the LIP. In the UIP, the groundwater quality is more deteriorated in the center and towards the tail of the doabs. However, in case of the LIP, the fresh groundwater is only available along the River Indus. On average, an area of about 80% is underlain by fresh groundwater in the UIP whereas it is 20% in the LIP. However, the groundwater quality estimated in October 2010 indicates that about 30% area is under usable groundwater quality in the LIP (Basharat *et al.,* 2014). Generally, fresh quality groundwater is available at shallow depths. Furthermore, the groundwater quality varies at canal command scale depending upon the availability of canal discharges at head, middle and tail reaches as well as sub-surface lithological conditions. The major reason of fresh groundwater availability in the UIP is the groundwater recharge induced through seepage from rivers, irrigation system and rainfall and presence of mainly coarse sand (alluvial fans). The inter-connected system of link canals and tributaries of the River Indus play an important role in the replenishment of groundwater system in the UIP.

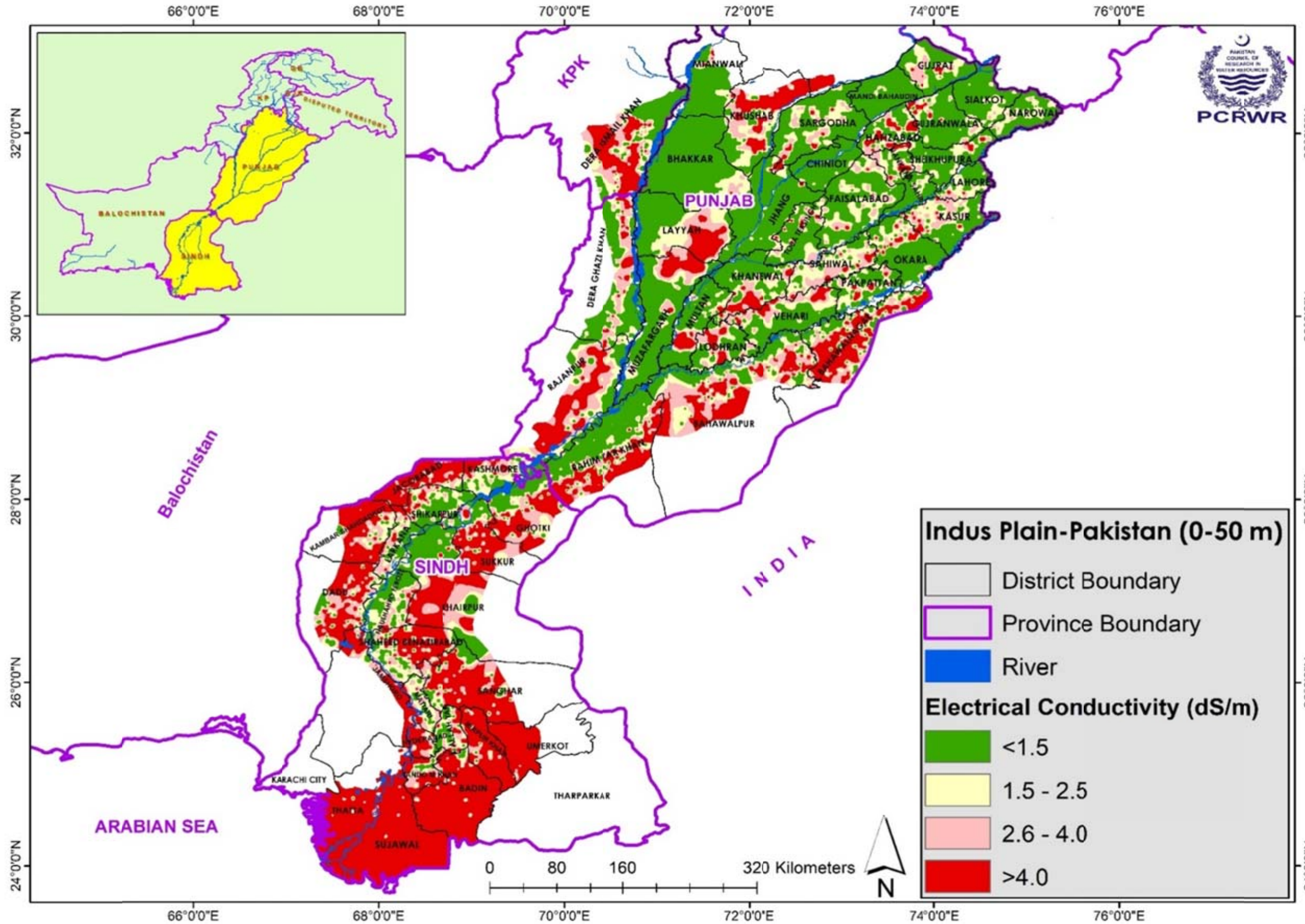

Figure 30: Groundwater quality variations in the Indus Plain at 0-50 m depth

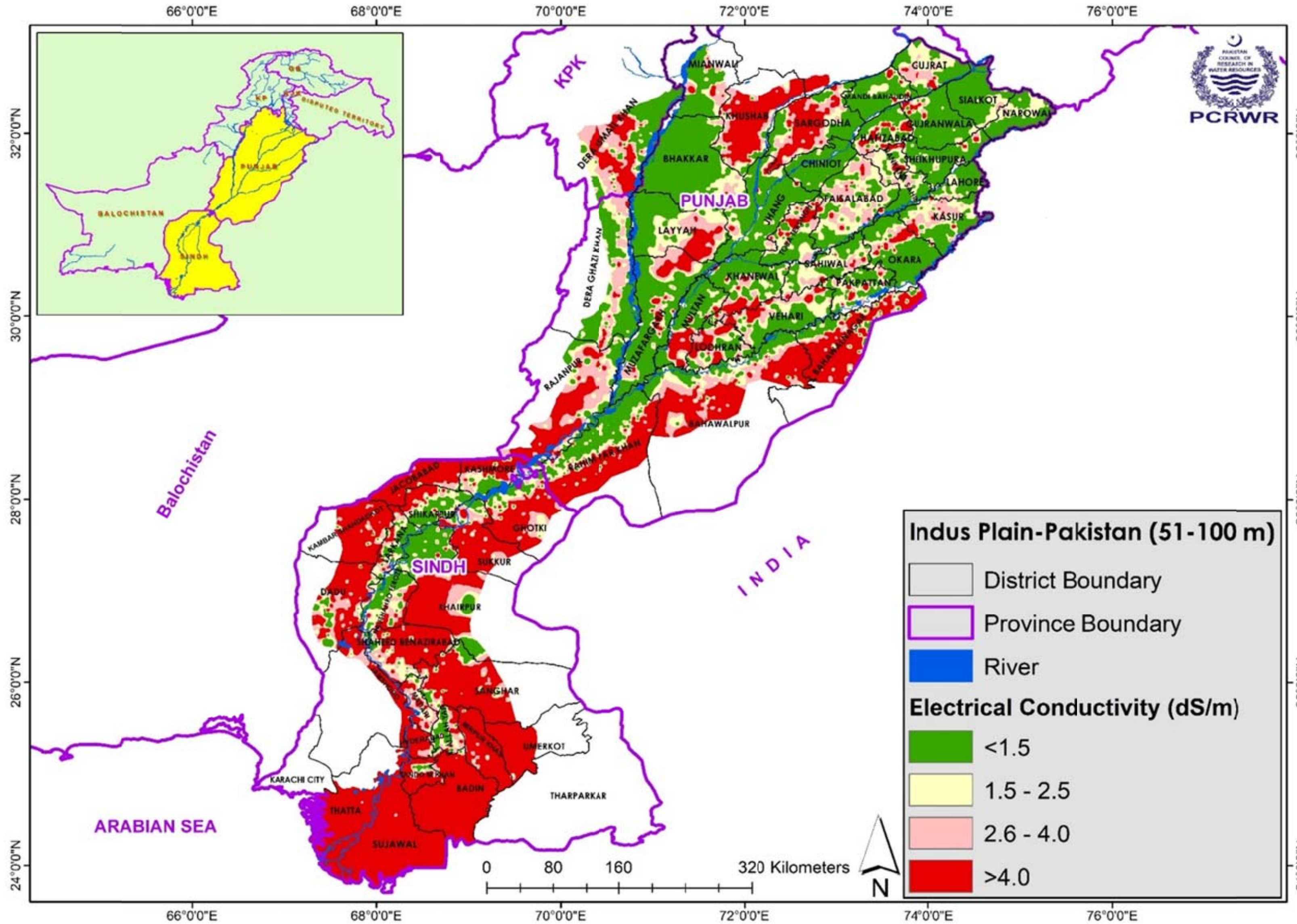

Figure 31: Groundwater quality variations in the Indus Plain at 51-100 m depth

3.6 Isotopic Analysis

The isotopic analyses of groundwater samples collected from shallow (hand pumps) and deep (tubewells) indicate that seepage from river and irrigation network constitutes the major groundwater recharge whereas, the contribution from rainfall is small (Figures 32 and 33). At shallow depth (<15 m), the major recharge is through River Indus and irrigation system with minor contribution from rainfall. However, the recharge from rainfall gradually decreases in the LIP at deeper depth (20-50 m). The areas of the UIP falling along the left side of the River Sutlej (Bahawalnagar and Bahawalpur districts) receive major recharge through rainfall and almost the same trend prevails throughout the aquifer except some pockets, which are being recharged from the river. However, the right side of the River Indus in the UIP covering the areas of Mianwali, Dera Ismail Khan, Dera Ghazi Khan and Rajanpur districts receive a mix of river and rainfall recharge whereas the contribution from the rainfall increases with depth.

There are different techniques used for groundwater dating. However, the applicability of a specific technique depends on the various factors where groundwater quality plays a major role. The tritium is one of widely used technique for the dating of groundwater of young age. The presence of tritium concentration in groundwater provides estimation of age of water, which has recharged through different sources. In the LIP, the results of groundwater sampling show that the concentration of tritium varies from 1.6-13.7 tritium unit (TU) and 1.5-11.6 TU at shallow and deep depths. The higher concentration indicates more recent recharge or young water whereas, very low concentration is representative of old water. The results of tritium analysis reveals that usable groundwater in the irrigated areas of the LIP is <50 years old (Figure 34 and 35). Groundwater having tritium in the range of 4-8 TU (<50 years) is relatively young and contains major fraction of post-1960s water. Areas with groundwater having tritium in this range are related to recent recharge and groundwater is of 20-30 years. However, the combination of tritium alongwith chlorofluorocarbons (CFCs), stable isotopes and noble gases may be used to model more precise estimation of groundwater dating.

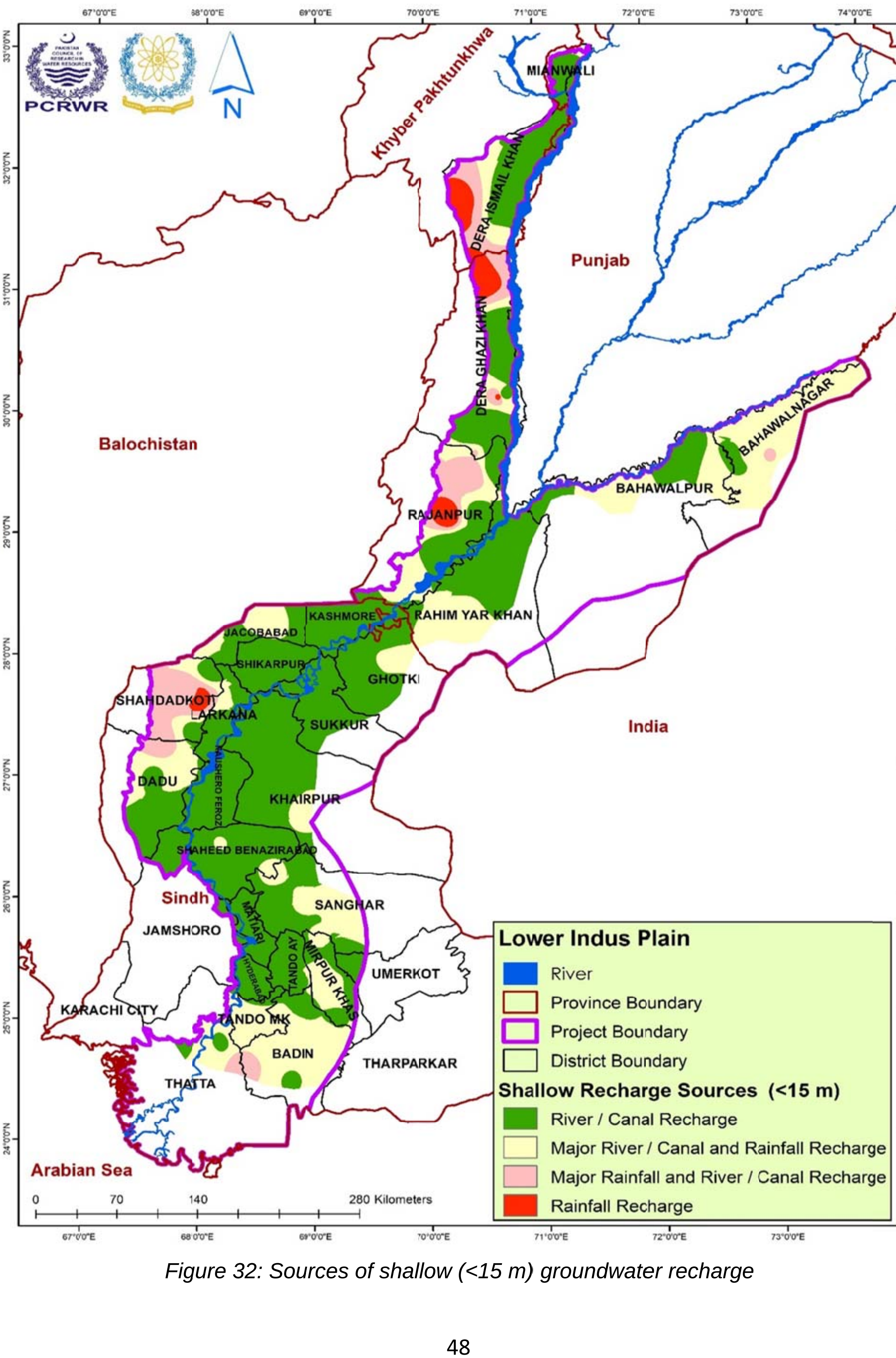

Figure 32: Sources of shallow (<15 m) groundwater recharge

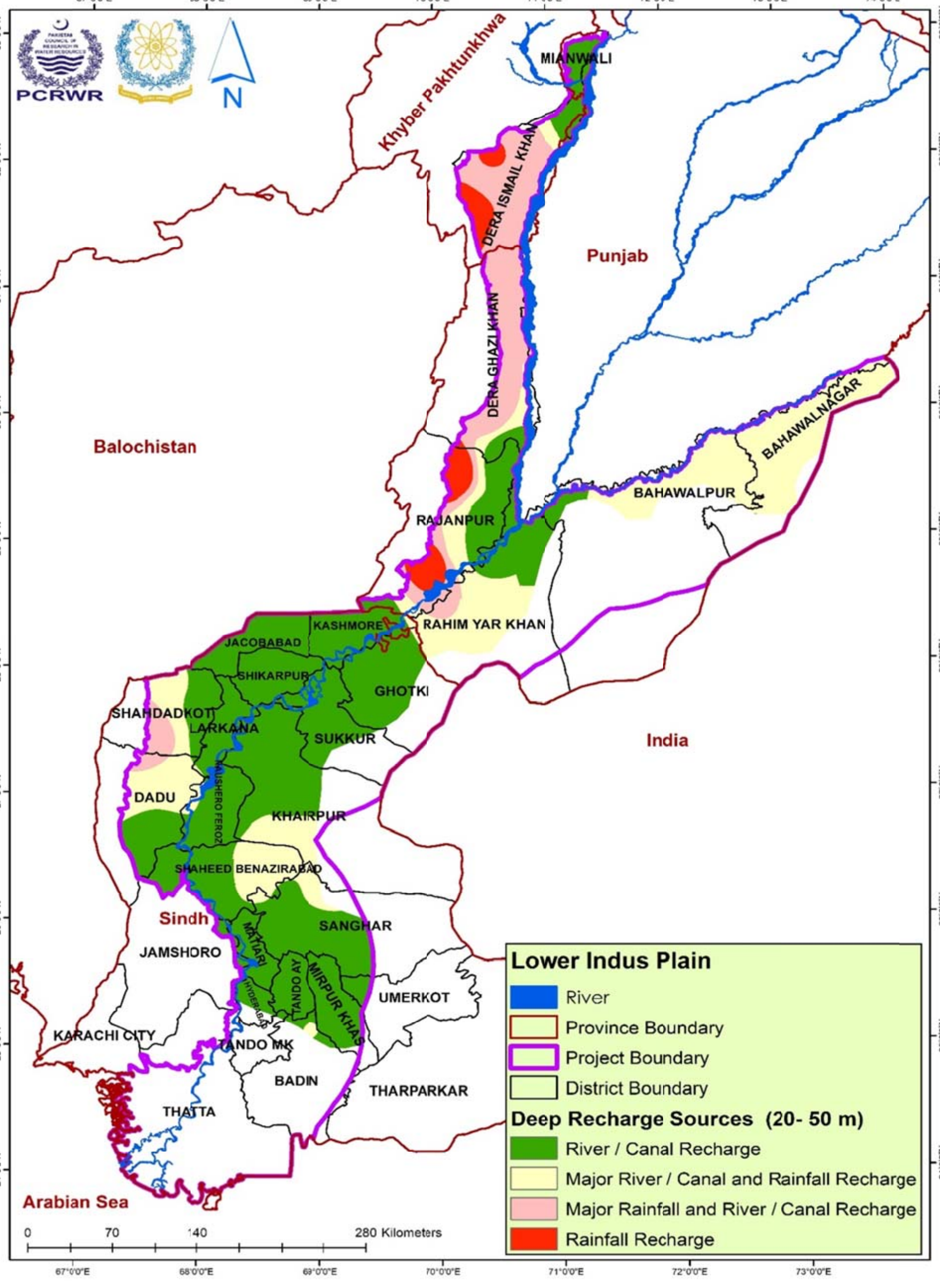

Figure 33: Sources of deep (20-50 m) groundwater recharge

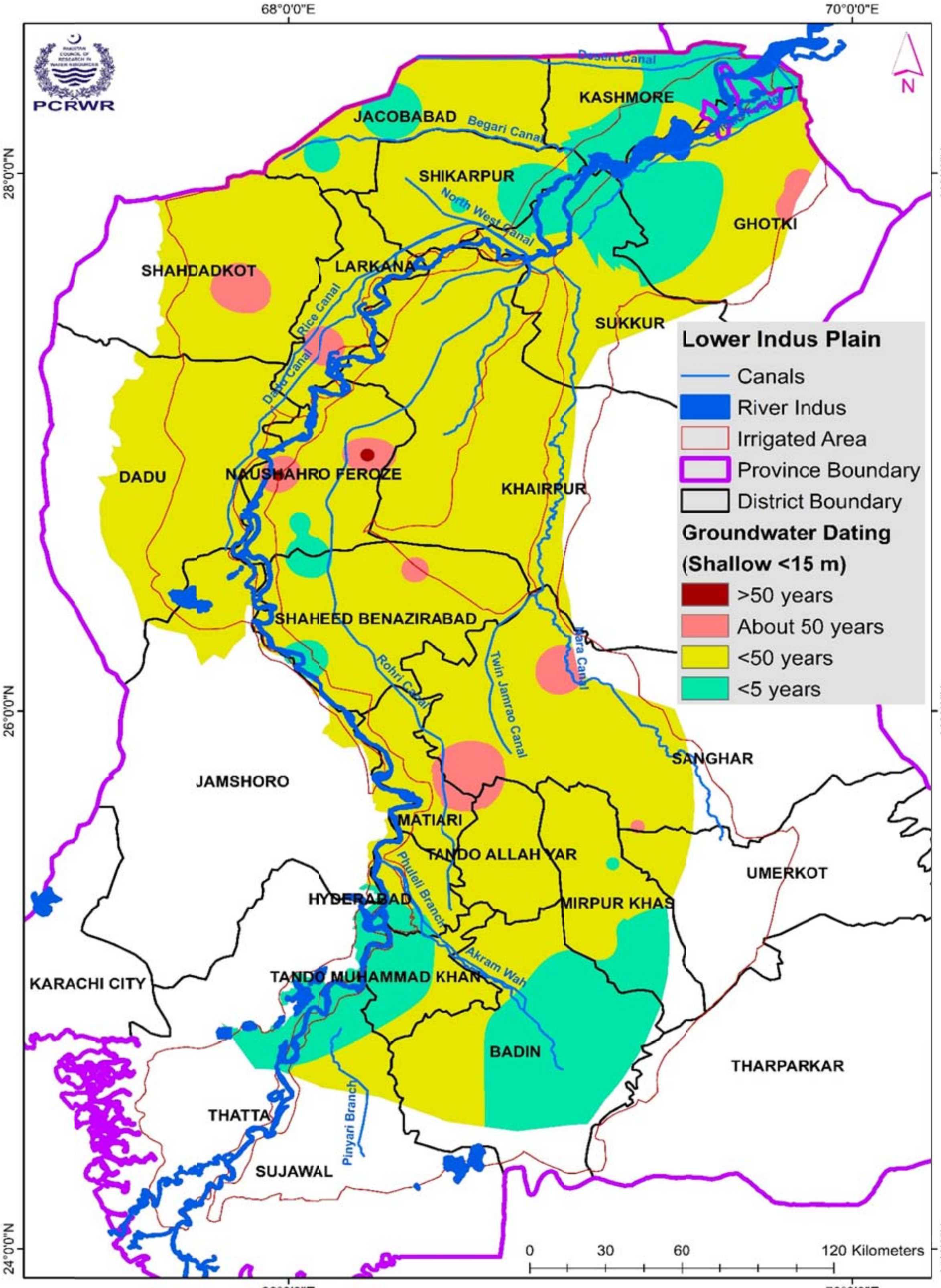

Figure 34: Shallow (<15 m) groundwater dating in the LIPA

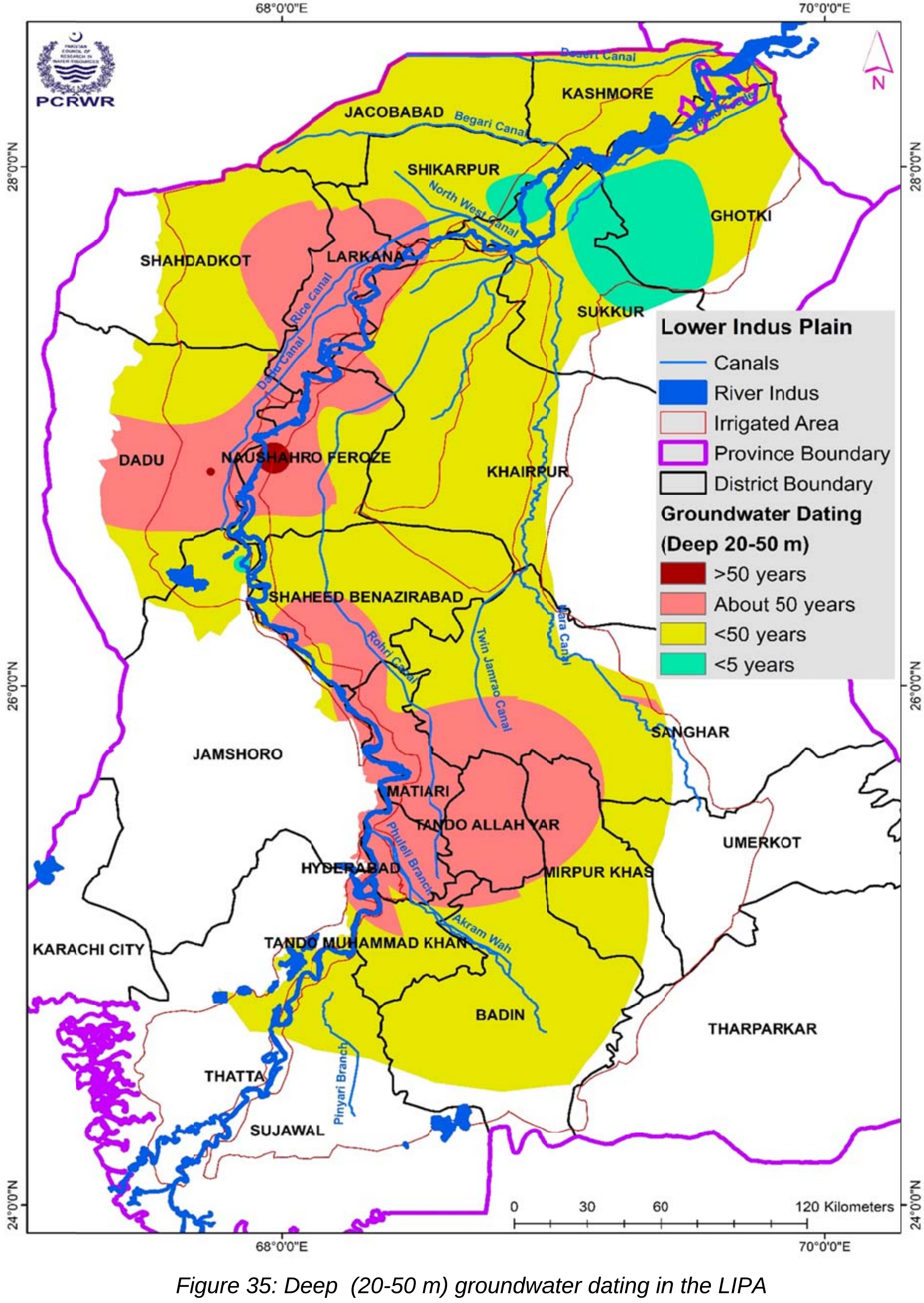

Figure 35: Deep (20-50 m) groundwater dating in the LIPA

3.7 Groundwater Balance

Sustainable groundwater requires that there should be a balance between recharge and abstraction (Ashraf and Sheikh, 2017). The determination of safe yield is a key parameter for the planning of groundwater resource on sustainable basis. For this purpose, the groundwater models are applied to simulate the dynamics of groundwater system.

The Visual Modflow has been used for the modeling of the Lower Indus Plain Aquifer (LIPA). The LIPA model is conceptualized as a large continuous alluvium aquifer having length of 660 km and average width of about 109 km. The vertical model layers were defined based on pumping depths rather than geology. The geological formation of the area is alluvium consisting of very fine to medium sand, silt and clay lenses having irregular patterns. Therefore, the model was developed based on three vertical layers. The first layer consists of aquifer part, which extends from ground surface to 50 m deep. Almost entire pumping in the Lower Indus Plain falls under this layer excepts some deep wells. The second layer is set from 51–201 m depth. The maximum depth of pumping in the near future could be expected from this part of the aquifer. The third layer extends right upto the bed rock and its thickness varies from place to place based on topography and depth to the bed rock.

By considering the available data and purpose of modeling, the model grid of 2.5 km x 2.5 km was used in the simulation. In this way, the finite difference grid consisted of 160 columns and 269 rows. Out of total 42,240 cells, 16,671 cells were considered as active. The river boundary was set on the central part of the aquifer and the data of river stage and width was collected from Federal Flood Commission (FFC). The FFC have modeled all major streams and rivers for stage-discharge relationship at different gauging points. The surface recharge was calculated as combined effects of percolation through precipitation, seepage form irrigation canals, water courses and return flow from pumping. The different evapotranspiration zones were established based on the variations in evapotranspiration in the study area. The long-term piezometric depth to water table fluctuation data collected from IWASRI-WAPDA, Lahore was used for flow simulation. Resultantly, seven zones were identified on the basis of aquifer characteristics. A single value of each hydraulic parameter was assigned by taking simple average of all tests falling in a particular zone.

After proper characterization of the field condition, the model was calibrated manually where the steady state or pre-development simulation was calibrated for the year 1984. The transient simulations were calibrated against varying pumping rates during different time periods which caused changes in storage as well as hydraulic heads. The model was calibrated through comparisons between model-simulated conditions and field conditions by analyzing variations in hydraulic heads, groundwater-flow direction, hydraulic-head gradient and water balance as minimum requirements for flow for the calibration (Figure 36).

The transient model was calibrated for five stress periods; 1985 to 1991, 1992 to 1996, 1997 to 2004, 2005 to 2009 and for the year 2015. After successful calibration, the predictive scenario was also generated for the year 2025. The groundwater flow is governed by the topography and hydrology, which is generally described at three levels; regional, intermediate (sub-regional) and local. The Lower Indus Plain is elongated triangular S-type (North–South) area. The maximum hydraulic head in the extreme north is 210 m and minimum of 0 m at the sea. Figure 37 shows the equi-potential lines.

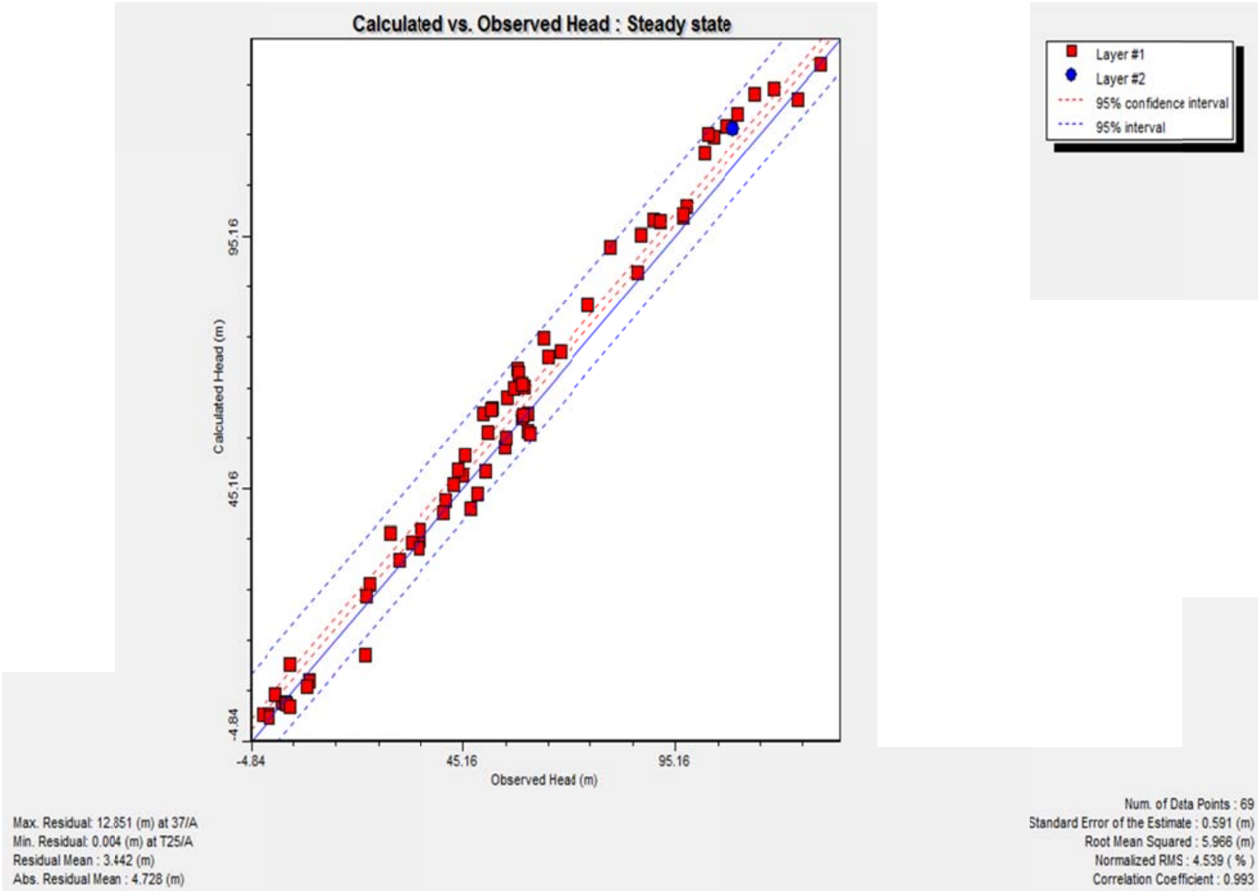

Figure 36: Calibration statistics during steady-state condition

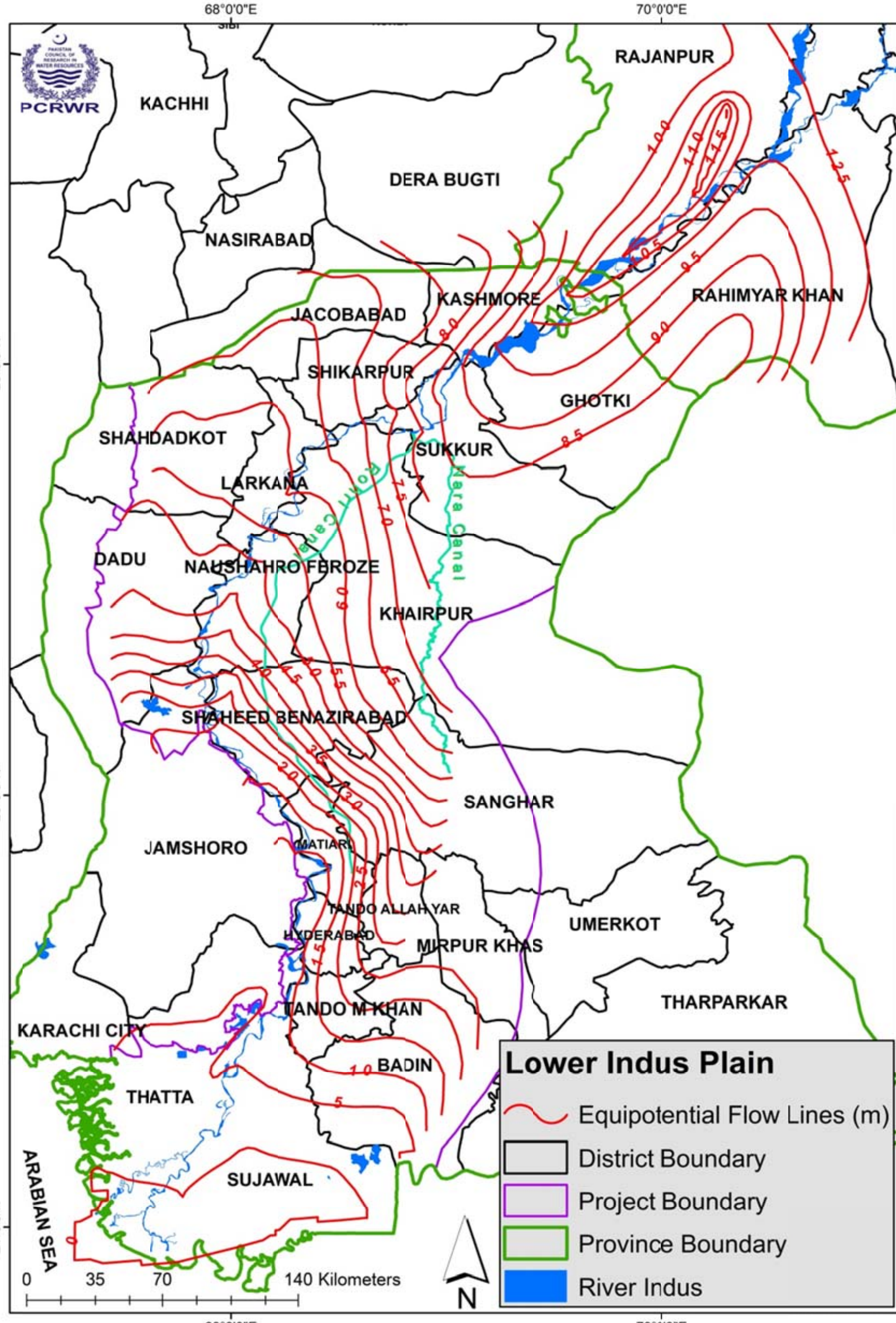

Figure 37: Equi-potential lines showing groundwater flow direction

This difference of head over 660 km indicates low velocity. The lower part of the aquifer forms the Indus Delta where groundwater flow is along the River Indus with very low or almost no flow towards sea. This is because of poor drainage and effect of seawater intrusion, which restricts the groundwater flow towards the sea. Locally, there are changes in the direction of flow. In the upper part of the LIPA, the flow direction is more westwards whereas; in the middle and lower parts, the flow direction is more towards the River Indus. The hydraulic heads in the lower reaches in the Indus Delta are almost constant because of poor drainage and absence of pumping and recharge mechanism. For better understanding, the area was sub-divided as upper, middle and lower reaches. Figure 38 shows the simulation results as well as predictive scenarios.

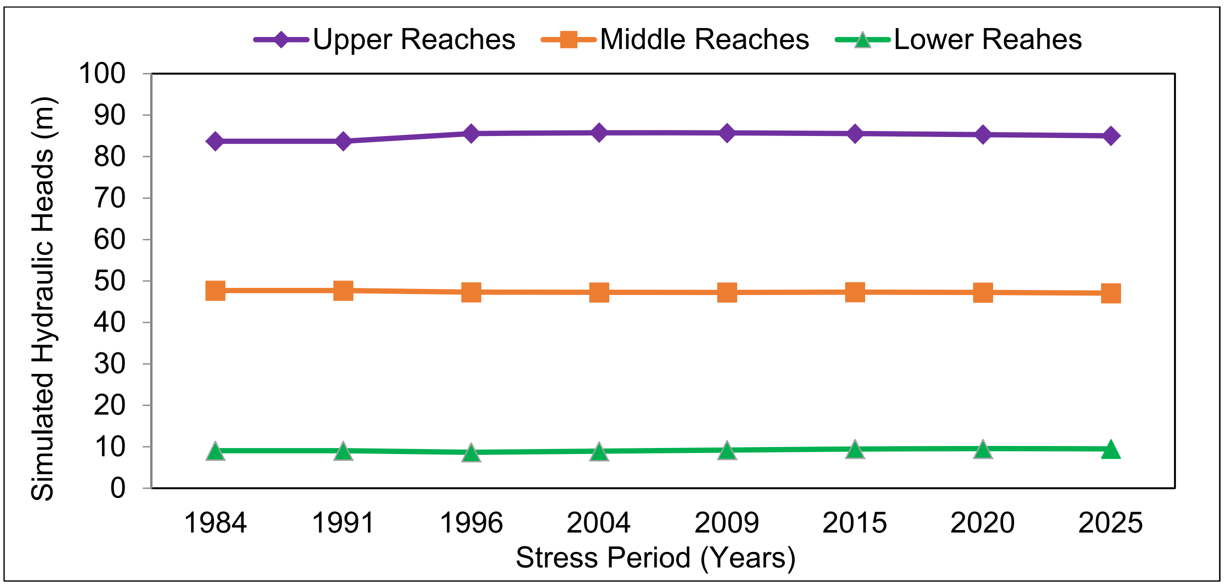

Figure 38: Visual Modflow simulated average annual variations in hydraulic heads over the LIPA

In the Upper Reaches, out of 13 observation wells, 9 wells showed increase in heads whereas the remaining 4 wells indicated decreasing trend. This indicates that groundwater system of the LIPA is active in the Upper Reaches. On an average, the rise in hydraulic heads was found to be 1.80m during transient simulation for the period from 1984 (83.7 m) to 2015 (85.5 m). A drop of about 0.4 m is also noticed in heads during predictive scenario (2016-2025). An overall decline in simulated hydraulic head is noticed in the Middle Reaches. Out of 23 observation wells, 19 has indicated decline in hydraulic heads. In the Middle Reaches, the drop of 0.35 m was found during transient simulation period from 1984 (47.6 m) to 2015 (47.3 m) and subsequently, further decline of 0.24 m from 2015 to 2025. The simulation results indicate a minor decline in the hydraulic heads. Overall, the Middle Reaches remained waterlogged, which will continue even during the predictive periods of 2025. The simulated hydraulic heads data of 15 observation wells was processed in the Lower reaches. Only 5 wells indicated decline whereas 10 wells indicated increasing trend in the hydraulic head. On an average, the hydraulic heads increased by 0.42 m in 31 years ranging from 9.06 m (1984) to 9.48 m (2015). The hydraulic heads will remain almost the same for future predictive scenarios (2016-2025). The groundwater system in the LIPA is almost at equilibrium as there are no significant changes in the hydraulic heads. Therefore, the waterlogging will remain an issue in the LIPA.

3.8 Annual Average Mass Balance

In Sindh, on an average, tubewells pump water for about 2.14 hours daily throughout the year (Qureshi *et al.,* 2003). Although, the average per day tubewells operating hours in Sindh (9 hrs) are higher than Punjab (6 hrs), the cropping period is short due to high evapotranspiration. Therefore, 87 days have been worked out for effective tubewells operation to meet the irrigational requirements of crops in Sindh whereas; in Punjab, it reaches up to 139 days (Qureshi *et al.,* 2003). Due to high evaporation losses, the surface water allocation per acre foot in Sindh is about 1.8 times higher than Punjab (Qureshi and Ashraf, 2019). The simulation results indicate that pumping has increased from 1.6 BCM per year to 19 BCM per year during the transient period of 31 years (1984-2015).

There are about 230,390 tubewells in Sindh (GoP, 2018). Most of the tubewells pump saline water, further increasing the secondary salinization. The simulation results of first layer (50 m depth) indicate that surface recharge and evapotranspiration (ET) are two major active components of the mass balance. The ET has increased from 59 BCM to 66 BCM from 1994 to 2015 and it would reduce to 64 BCM by 2025. The surface recharge has decreased from 109 BCM to 83 BCM during the period from 1894 to 2015 (Table 5). The reduction in ET by 2025 would be due to increase in water-table depth and increased pumping.

There are two possible reasons of this reduction in recharge. The first reason may be attributed to the efficient utilization of water resources, which includes; canal and watercourse lining, laser land levelling (Ashraf *et al.,* 2017). The ET component of the water balance has also increased associated with increased cropping intensity (Ashraf *et al.,* 2018), which has now reached upto 162% in Sindh Province (GoP, 2012). More cropping intensity means more ET and less percolation losses. The potential evaporation (ETo) in the Lower Indus is almost 25% higher as compared to Central Punjab (Rao *et al.,* 2016; Soomro *et al.,* 2018). Secondly, the reduction in recharge may be attributed to variations in canal flows (Figure 39). However, Figure 40 shows that the canals in the LIP are getting almost the same flows annually with some variations in seasonal flows (GoS, 2017). The reduction in recharge may also be attributed to the confinement of the river sections due to construction of flood protection dikes.

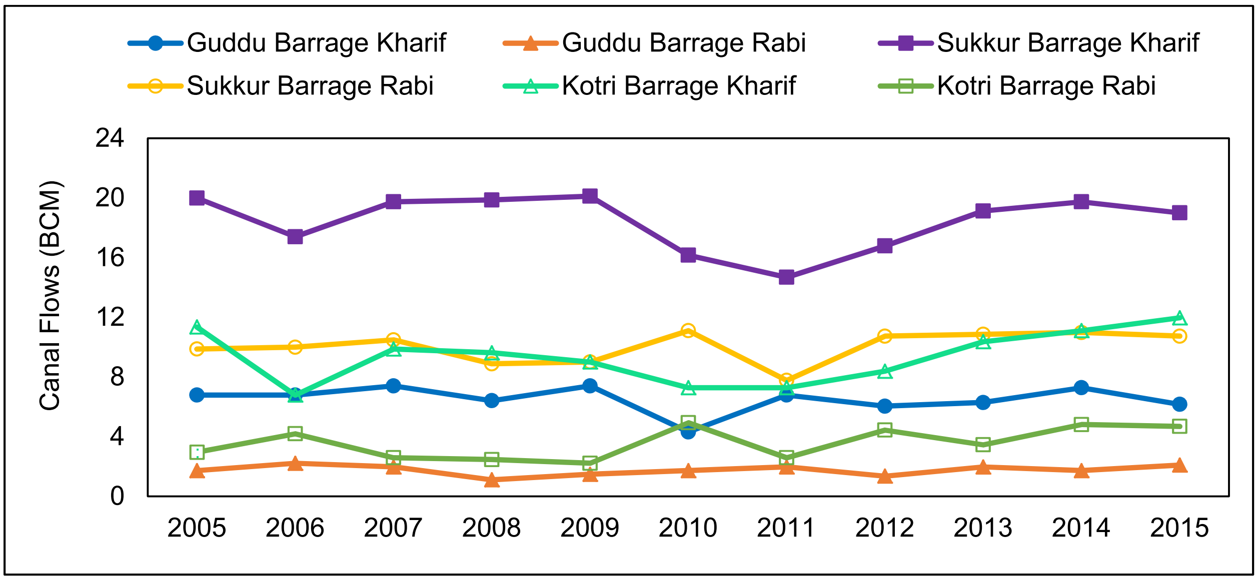

Figure 39: Seasonal variations in canals flows from 2005-2015 in Sindh

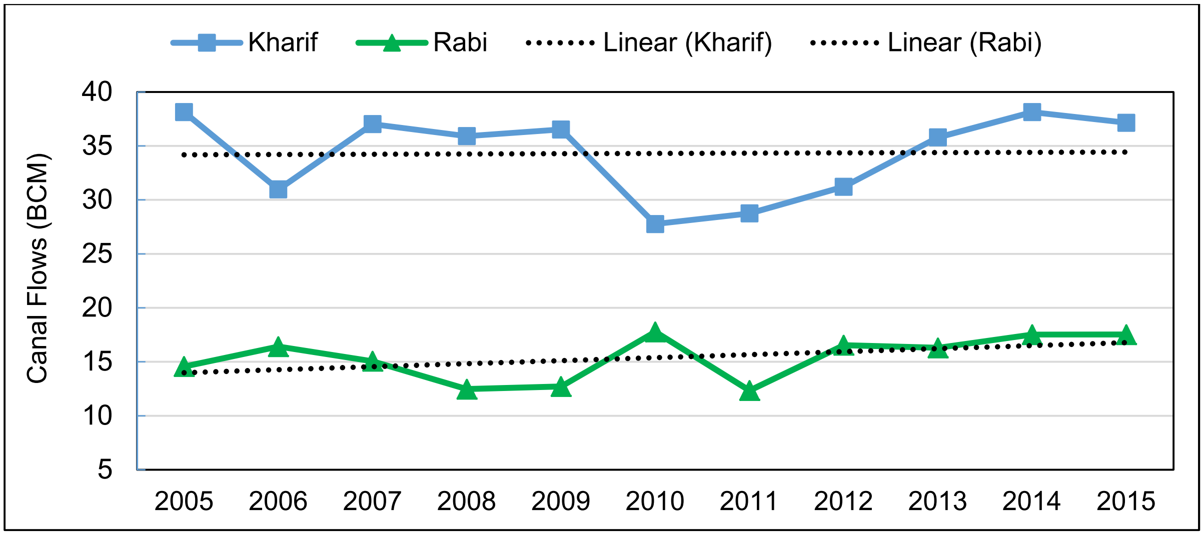

Figure 40: Trend lines showing seasonal variations in canals flows in Sindh (2005-2015)

The model has reported an increasing trend in groundwater pumping after 1994. In 2015, 19 BCM groundwater was pumped which is predicted to further increase upto 24 BCM by 2025. The historic trend of tubewells growth in Sindh shows a major increase during the period 1998-1999 and 2012-2013 (Figure 41). This is the result of prevalence of drought event as well as increase in cropping intensity. The effect of long-term drought conditions is evident from the fact that both recharge and ET remained lowest in 2004 (Figure 42).

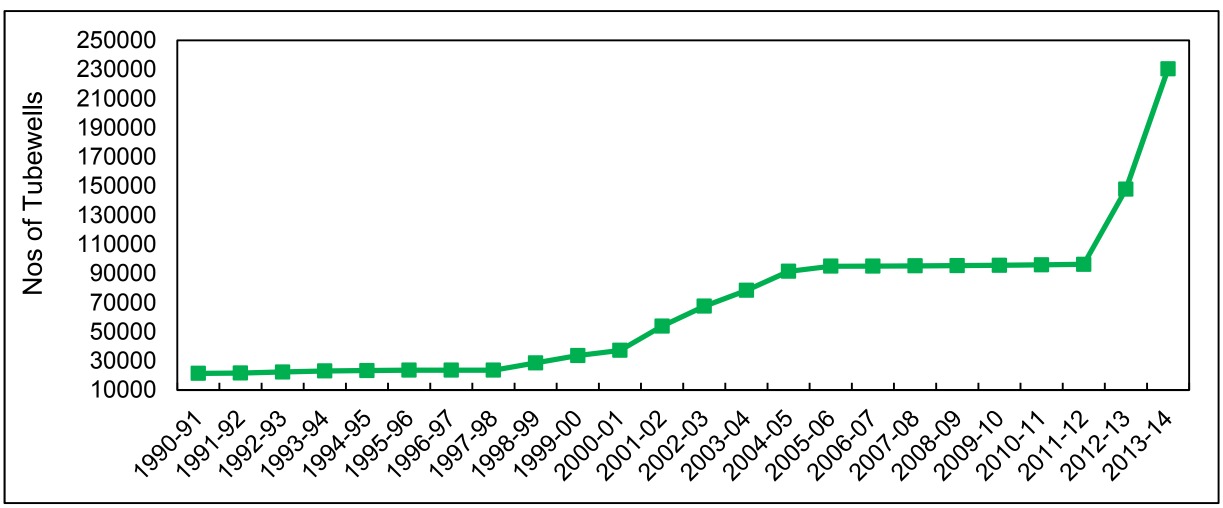

Figure 41: Temporal trend in tubewells growth from 1990-2014 in Sindh (Source: GoP, 2018)

Due to increased pumping, the seepage from the River Indus has increased from 11.5 BCM to 13.7 BCM from 1991-2015. Although groundwater pumping has increased over the time however, it has affected water-table depths in certain fresh groundwater pockets without significant changes in major areas of Sindh. As a result, there is no appreciable decline in hydraulic heads especially in the lower reaches.

Table 5: Summary of simulated components of mass balance

Simulated Annual Average Components of Water Balance (BCM)		1984	1991	1994	2004	2009	2015	2025
System IN	Change in Storage	11.0	1.3	0.3	0.1	0.1	0.4	1.0
	River Leakage (Flow from River to Aquifer)	25.2	11.6	9.4	7.4	12.1	13.7	15.9
	Recharge	109.0	85.4	82.5	51.9	83.4	83.4	83.4
	Total	145.2	98.2	92.2	59.4	95.6	97.5	100.3
System OUT	Change in Storage	75.0	29.5	17.6	4.6	2.9	1.7	1.3
	Pumping	1.6	2.7	4.1	8.8	15.2	19.0	24.0
	River Leakage (Flow from Aquifer to River)	9.4	8.7	9.7	5.1	10.9	10.8	10.8
	ET	59.2	57.4	60.9	40.9	66.6	66.0	64.2
	Total	145.2	98.2	92.2	59.4	95.6	97.5	100.3

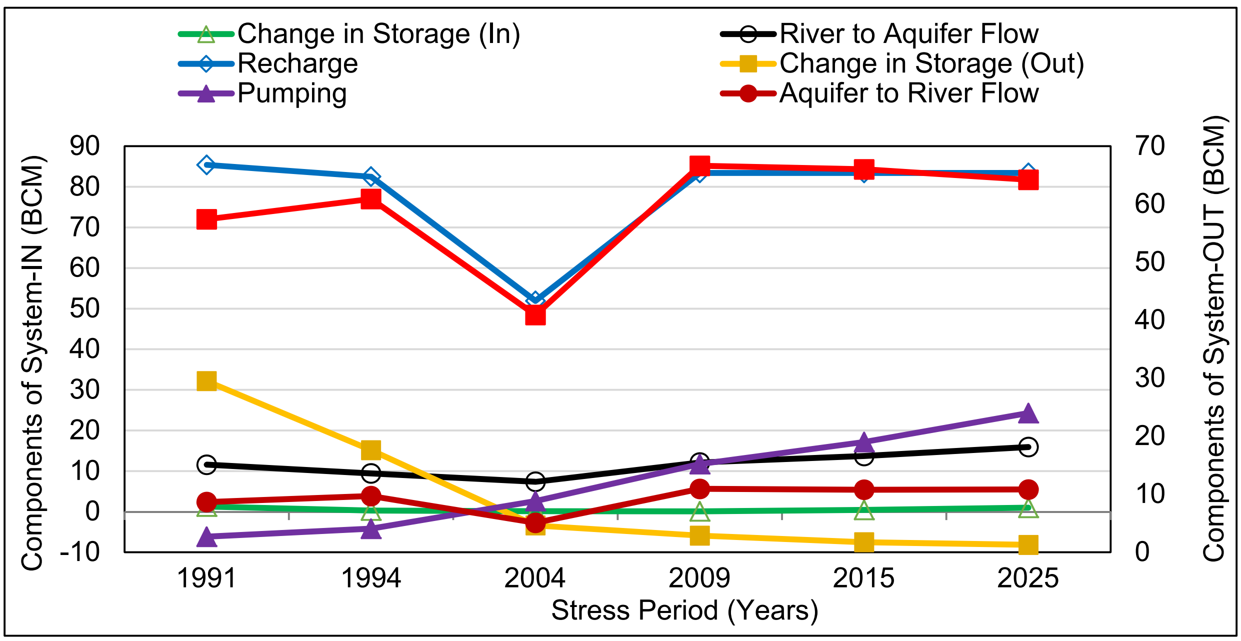

Figure 42: Variation in average annual simulated components of mass balance

The seepage from the River Indus as the part of the groundwater system varies widely with the discharge and river stage (Figure 42 and Table 5). When the river flow increases, the seepage helps to replenish the groundwater aquifer. The spatial mapping of groundwater quality demarcates that most of the fresh water pockets exists along the River Indus. Resultantly, the groundwater pumping increases in those pockets to supplement irrigational requirements. However, when river flow decreases, the aquifer helps to regulate the river flows in the form of base flow. The recharge has a direct relationship with river flows as well as flows in the canals. When river stage or canal discharge increases, there is more recharge into the groundwater system and vice versa. This is supported by the model that the recharge has decreased significantly from 82.5 to 52 BCM from 1994 to 2004 due to the happing of drought event (Table 5). However, the model simulation shows that the flooding event of 2010 has played a key role in the replenishment of the LIPA rather it has facilitated waterlogging (Figure 7). Figure 43 shows the average annual variations in the flows of River Indus downstream of Panjnad.

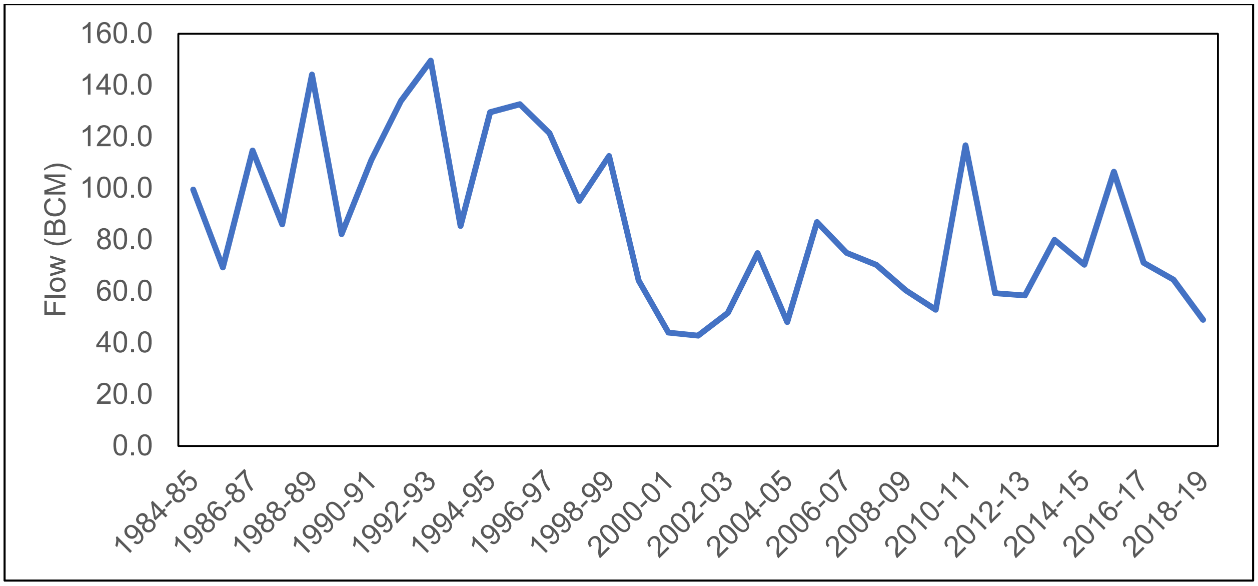

Figure 43: Temporal variation in the flows of River Indus downstream Guddu from 1984-2018 (Source: IRSA unpublished data)

The predictive scenarios indicate that major part of the aquifer will remain under shallow water tables till 2025. There is no major changes in groundwater regimes of the LIPA during the simulation and prediction periods and the aquifer pumping at the present rate is essential to avoid waterlogging. However, the indiscriminate pumping may cause saline water up-coning as the groundwater is saline at the deeper layers. Therefore, controlled abstraction alongwith establishment of effective groundwater monitoring mechanism is imperative. The installation of properly designed skimming wells and adoption of appropriate operational strategies could help minimize the chances of saline water up-coning (Ashraf *et al.,* 2012). The surface recharge, ET and groundwater pumping would remain major active components of the water balance (Figure 42).

4 Conclusions and Recommendations

4.1 Conclusions

1. The synthesis of soil texture derived from samples collected from 0-5 m depth shows that sandy loam, loam, silty loam and clay are the four major soil types, which cover about 70% area. The clay content gradually decreases with depth and becomes negligible after 50 m depth.
2. The clayey strata is more prominent in the areas below Hyderabad particularly in the Indus Delta alongwith some parts of Bahawalpur, Rajanpur, Dadu, Kashmore, Shikarpur, Kambar and Shahdadkot districts.
3. About 32% of canal commands of Sindh province have shallow water tables (1.6 m to 3 m depth) during the period of post monsoon 2014. About 61% area is under waterlogging conditions (0.25-1.5 m depth). This waterlogging condition is found more pronounced in the upper and lower reaches of LIPA especially in the Indus Delta.
4. In some areas, depth to water table has increased up to 16 m due to groundwater pumping. These are the pockets of fresh groundwater which falls in the districts of Shaheed Benazirabad (Nawabshah), Matiari and Tando Allah Yar.
5. The soil salinization and sodification increase with depth as the area under normal soil reduces to half (51% to 29%) while moving from 0-5 m to 6-10 m depth in the LIP. Similarly, the area under saline and saline-sodic soils increase from 28% to 47% and 20% to 24% with depths of 0-5 m and 6-10 m, respectively.
6. The soil salinization and sodification further intensify with depth especially in the Indus delta.
7. The groundwater quality at deeper depths is highly saline. However, a layer of fresh water exists with varying thickness in the areas of favorable lithologies

and where sources of groundwater recharge are available. The extraction of freshwater layer needs special care to avoid saline water up-coning.

8. About 20% area of Sindh Province has useable groundwater quality whereas the reaming 80% area is saline to highly saline.

9. The isotopic analysis shows that seepage from the River Indus and irrigation network mainly constitutes the groundwater recharge whereas, the contribution of induced recharge from rainfall is small.

10. The groundwater modeling has estimated that evapotranspiration is very high and is a major component of the water balance in the LIPA. This is mainly due to high temperature, wind speed, shallow water table and high cropping intensity.

11. An overall decline in simulated hydraulic head is noticed in the Upper and Middle Reaches whereas, heads in the Lower Reaches increases. Therefore, waterlogging will persist in future especially in the Lower Reaches.

12. There is no major change observed in groundwater regime of the LIPA during the simulation period. The careful groundwater pumping at the present rate is essential to control waterlogging. However; the increased pumping in future can cause saline water up-coning as the groundwater is saline at the deeper layers.

4.2 Recommendations

1. The controlled abstraction alongwith establishment of effective groundwater monitoring mechanism is imperative for sustainable groundwater management in the LIPA.
2. To overcome the issue of saline water up-coning, skimming well techniques may be adopted to minimize the detrimental environmental impacts associated with aquifer depletion.
3. To ensure the aquifer sustainability, the enforcement of groundwater regulation is critical and groundwater pumping should be allowed as per safe yield of the aquifer.

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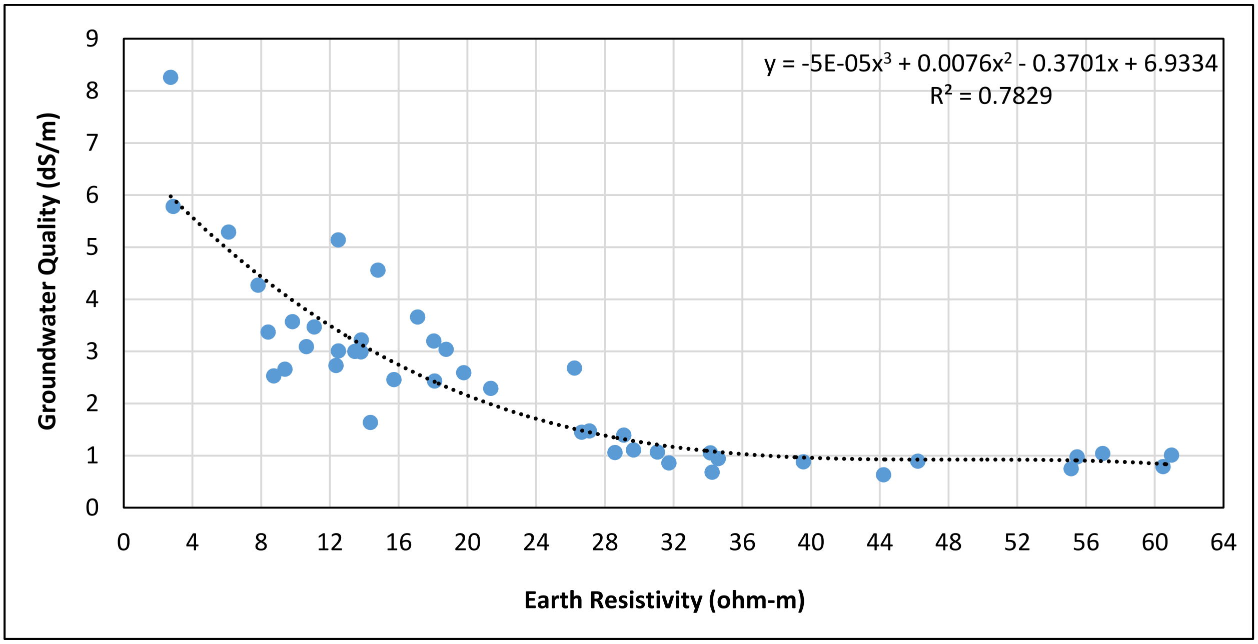
Annexure I

Regression between Earth Resistivity and Groundwater Quality for LIPA



Annexure II

Some Important Conversion Units

Area	1 ha	2.47 acres	
	1 km^2	100 ha	
Length	1 mile	1.609 km	
	1 m	3.28 feet	100 cm
	1 inch	2.54 cm	
Volume	1 m^3	35.28 ft^3	1000 liters
	1 m^3	264 US gallons	
	1 m^3	220 Imp gallons	
	1 m^3	0.0008 acre foot	1 acre foot = 1233 m^3
	1 billion cubic meter (BCM)	0.81 million acre foot (MAF)	1 MAF = 1.234 BCM
Discharge	1 m^3/s	35.32 ft^3/s (cusecs)	28.32 l/s
Weight	1 metric ton	1000 kg	
Water quality	1 EC mg/l	0.64 TDS parts per million (ppm)	

About PCRWR

PCRWR is an apex body of the Ministry of Science and Technology and is mandated to conduct, organize, coordinate and promote research on all aspects of water resources including irrigation (surface and groundwater), drainage, soil reclamation, drinking water and wastewater. It has eight regional offices located at different agro-ecological zones and each centre conducts research on water-related issues of the respective zones. These Regional Offices are located at Lahore, Bahawalpur, Tandojam, Quetta, Peshawar, Karachi, Gilgit and Muzaffarabad. Besides these eight Regional Offices, PCRWR has a setup of 18 water testing laboratories in major cities of the country. It has all types of infrastructure such as soil and water testing laboratories, groundwater assessment equipment, research farms to conduct and disseminate the research. It is the only organization in Pakistan that owns drainage type lysimeters in Lahore, Tandojam, Quetta and Peshawar. PCRWR has done considerable work on crop water requirements, tile drainage, soil reclamation, on-farm water management technologies, rainwater harvesting, artificial recharge, groundwater assessment and management, skimming wells, drinking water, and indigenous development of salinity and moisture sensors.

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