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Beneath the Sands: A Comprehensive Study of Groundwater in Tharparkar Region

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Pakistan Council of Research in Water Resources (PCRWR)
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Citation:

Salam, H.A., M. Ashraf, N. Iqbal, N. Gul, S. Memon (2023). Beneath the Sands: A Comprehensive Study of Groundwater in Tharparkar Region. Pakistan Council of Research in Water Resources (PCRWR) Islamabad, pp.33

ISBN: 978-969-8469-95-5

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Executive Summary

Tharparkar District heavily relies on groundwater due to the absence of rivers and canal irrigation network. Groundwater serves as a vital resource for drinking, domestic, livestock and small-scale agriculture purposes. The majority of the people get their water from far-flung dug wells as their primary source of water. People use donkeys or camels to pull buckets of water from deep dug wells. Practically, they spend their entire day for collecting water, especially during the dry season. Women carry the majority of burden because they are the ones who fetch the water. Thari people are in jeopardy due to the severe drought conditions, dwindling water levels, and rising salinity levels. Therefore, the assessment and proper management of groundwater resource is of utmost importance.

This report encompasses the findings of soil texture, depth to water table, water quality data analysis and Electrical Resistivity Survey (ERS) conducted in Tharparkar District of Thar Desert from 2017 to 2020. The soil and water quality samples were collected on a 10 km x 10 km grid. Total 672 soil samples through auger were collected from 0 - 15 cm, 15 - 30 cm, 30 - 45 cm and 45 - 60 cm depth. Overall 168 water samples were collected from dug wells. Moreover, ERS was carried out through a uniform grid of 5 km x 5 km, wherein 576 resistivity probes were conducted up to the depth of 300 m. For mapping purpose, groundwater quality was categorized into four 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 dS/m).

Being desert area, the top soil is predominantly sand up to the depth of 60 cm. In certain patches of Chachro tehsil, sandy clay loam is prevalent covering both the upper (0 - 15 cm) and the middle (15 - 30 cm) layer. In Chachro, the groundwater is relatively deep ranging from 91 to 112 m. In contrast, the groundwater in tehsil Diplo is shallow (about 2 m). The analysis of water samples collected from dug wells having varying depth (2 - 112 m), shows that major part (69% area) of the district is under highly saline groundwater. However, only 6% area falls under useable groundwater quality (EC ≤ 2.5 dS/m) covering southern parts of tehsils Diplo, Islamkot and Nagarparkar.

Furthermore, the analysis of water quality reveals that 10% water samples are contaminated with Arsenic, exceeding the permissible limit (10 ppb) of World Health Organization. This higher concentration of Arsenic is more prevalent in the areas of Chachro tehsil, and some parts of Mithi as well as Diplo tehsils. About 28% groundwater samples are also unfit in terms of Fluoride concentration exceeding the permissible limit. Indeed, these contaminants pose a significant health concern for the population, necessitating urgent measures for mitigation and remediation.

The ERS results show that usable groundwater quality is about 10% (fresh 3%, marginal 7%) at shallow depth (25 m) in southern parts of Diplo, Islamkot and Nagarparkar tehsils. About 31% of the area falls under the saline to highly saline zone. The groundwater quality at depths ranging from 26 to 50 m in Diplo, Islamkot, Nagarparkar, and Dahli tehsils is significantly affected and 51% area falls under the high salinity zone. At 51 - 75 m depth interval, the groundwater quality further deteriorates as about 76% area falls under highly saline zone whereas, remaining 24% area is under marginal to saline quality and unsaturated zone. The groundwater quality at 76-100 m depth, 82% area is highly saline covering Mithi, Chachro, Diplo and Nagarparkar, and remaining 18% area is under saline zone. The groundwater quality deteriorates significantly at depths ranging from 101-150 and 151-200 meters with 85% and 88%, respectively, being classified as highly saline. This indicates a substantial increase in salinity with greater depth, posing challenges for water usability in these deeper aquifers. At depths exceeding 200 m, groundwater quality is consistently highly saline, affecting approximately 99% of the area. The high groundwater salinity in this region is attributed to several factors, including low and erratic rainfall, aridity, high temperature, high evaporation losses and limited groundwater recharge. This study concludes that fresh to useable groundwater is primarily accessible at shallow depths in the areas where, groundwater recharge is available. Therefore, the availability of usable groundwater is closely linked with the effectiveness of recharge mechanisms.

Acknowledgements

The authors would like to express their deep appreciation to the supporting team who have been helpful and worked in the challenging environment of Thar Desert. We are thankful to Mr. Yousuf Abro, Instrument Mechanic and Syed Zohaib Habib, LDC for conducting ERS probes. The authors are also grateful to the officers and officials of Soil and Water Analysis Laboratory, Tandojam for their untiring efforts of soil and water analysis. The work of Mr. Umer Abro and Mr. Zeeshan Munawar is highly appreciated for formatting the report. Special gratitude to the Government of Pakistan for providing necessary funds for undertaking this research through PSDP project titled, "Exploration of Groundwater Potential and Promotion of Interventions for Rainwater Harvesting and Bio-Saline Agriculture in Thar".

1. Introduction

Thar Desert covering Pakistan and India is the 20th largest in the world, spanning over an area of approximately over 200,000 km^2. About 85% area of Thar is in India, while 15% lies in Pakistan (Figure 1). It is one of the densely populated deserts of the world. It is known for its unique but gorgeous rich culture, natural beauty, diverse and rich biodiversity. The livestock farming and agriculture are main sources of income for the local people. The ancient temples, unusually constructed homes of straw and mud locally called "Chaunra," and stunning handicrafts are the heart-warming symbols of the area. The melodious voice of peacock, jingling of bells in the neck or foot of cattle's in the morning, and the tattering of birds in the trees is the prettiness of the region. Flora of this area is composed of tree, shrub and herb species. About 89 plant species from 68 genera and 26 families make up this rich flora.

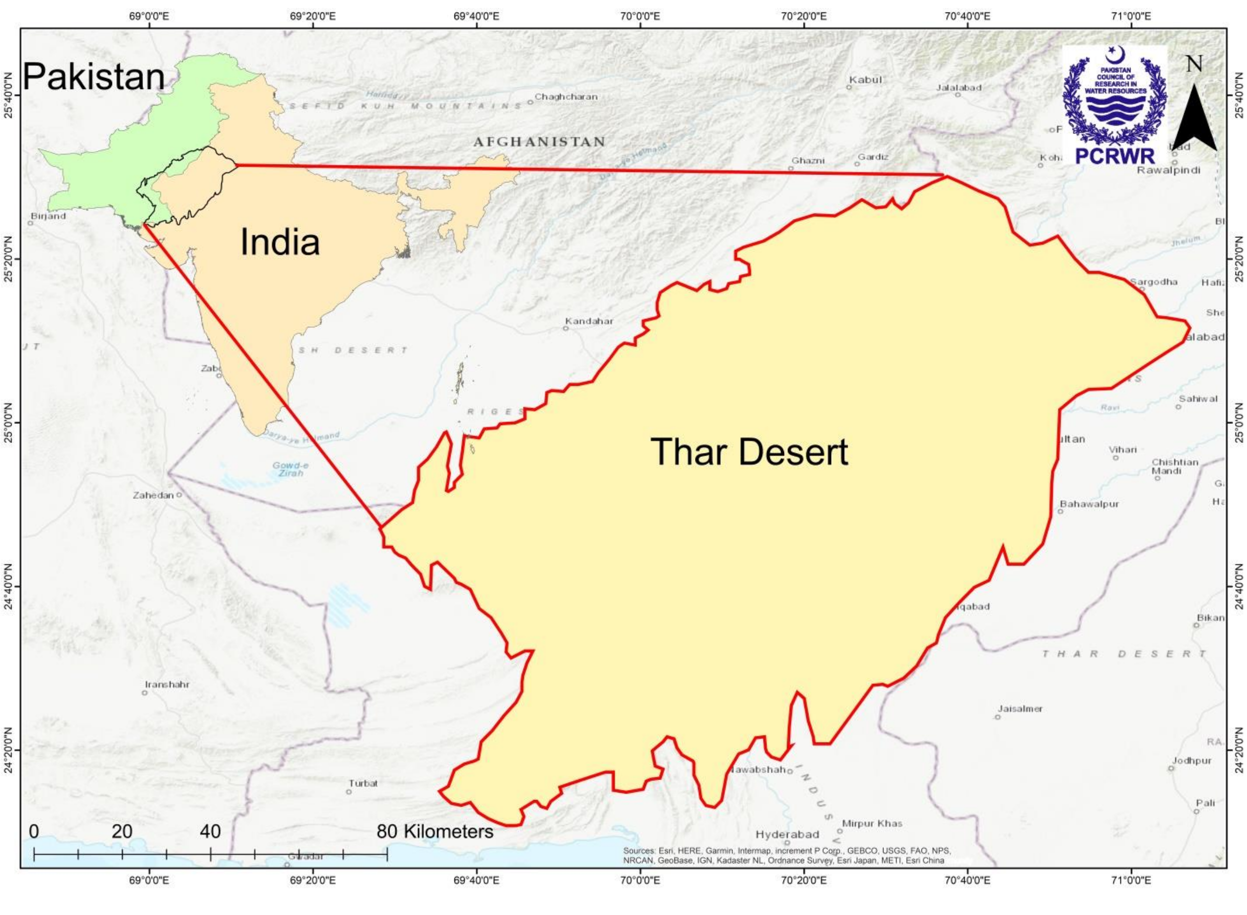

Figure 1: Map showing Thar Desert (Pakistan and India)

This region also contains highly diversified mammalian fauna. The Rann of Kutch is the prime wildlife habitat of Thar Desert. The study area "Tharparkar" originates from the words Thar (referring to Thar Desert), and Parkar means "to cross over". The Tharparkar District (Figure 2) is spread over approximately 19,813 km^2 with population density of about 83 people per km^2.

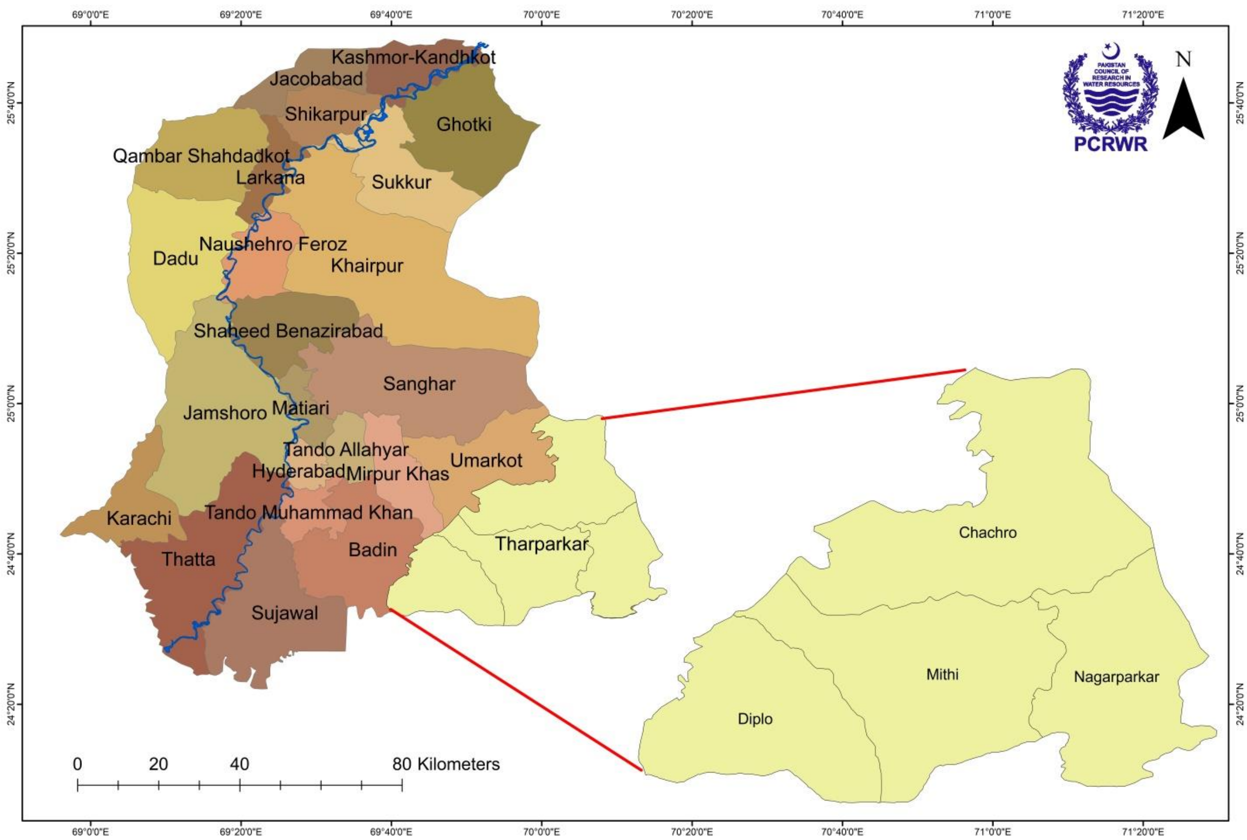

Figure 2: Map of Tharparkar District

Tharparkar is mostly arid and only 1.6% of the district's cultivated land is irrigated, mostly in Diplo tehsil by a tributary of the Naukot branch of Nara canal. The communities mainly depend upon rain fed agriculture and livestock. The natives adopt subsistence farming on small patches of land. The Kharif season crops are mainly grown in the summer season, sown in June/July and harvested during September and October. The main crops are wheat, beans, barley (Jau), pearl millet (bajra), pulses, cluster bean (guar), Sorghum (Jowar), maize, and sesame. They also keep livestock and exchange the surplus crops with livestock in hard times.

The soil of this area remains dry for most of the year and is prone to wind erosion. High velocity winds affect the neighboring fertile lands, and causes shifting of sand dunes within the desert. The district is predominantly a rural area with 96% of the population residing outside of urban areas. The main food source and economic base comes from livestock management and farming. The whole area is covered with extensive and thick cover of sand dunes extending vertically to an average height of 80

m. According to Pakistan Bureau of Statistics (2017), population of Tharparkar District has increased from 0.914 million (1998) to 1.65 million (2017). This shows increase in population by 44.58% (Nawaz-ul-Huda and Burke, 2017) with an annual growth rate of 2.34% (SPDC, 2018).

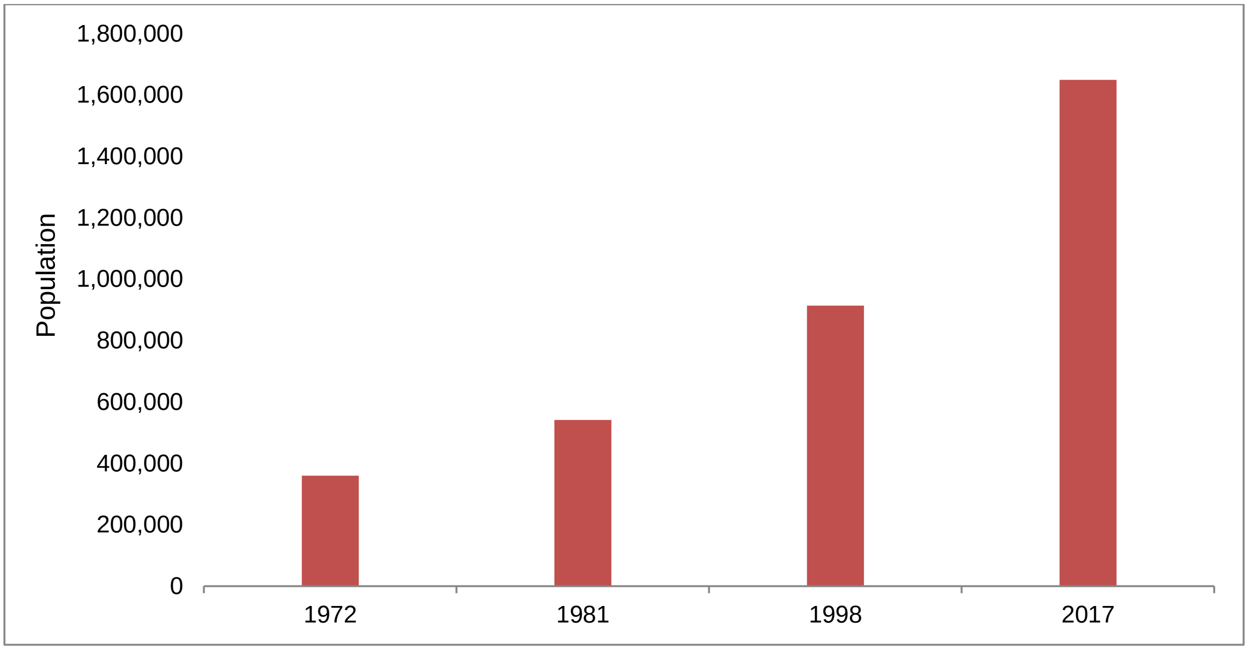

Figure 3: Population of Tharparkar District

Being major source of livelihood, the local people raise goats, sheep's, cattle's, buffaloes, donkeys, and camels. Besides livestock, they also practice agriculture on limited scale (Table 1).

Table 1: Livestock in Tharparkar

Livestock	**Population**
Cattle	752,265
Buffalo	46,328
Sheep	1,185,122
Goat	2,217,876
Camel	135,356
Horse	8,519
Mule	1,475
Donkey	246,657
Domestic Poultry	263,431

Source: PESA, (2014)

According to the Rapid Need Assessment Report on Drought in District Tharparkar (2018), 90% of households possess livestock, upon which their livelihoods depend. On an average, the small livestock size is about 8 animal heads per household. The high population growth has increased demand for food and water to meet the drinking water requirements of humans, livestock as well as small-scale irrigation.

The district has a tropical desert climate with very low rainfall. About 87% of annual precipitation occurs during monsoon season between June and September and varies between 50 to 300 mm (Beran and Rodier, 1985; Shaikh, 2003; Chaudhry, 2017). In summers, days are extremely hot, but nights are cooler. April, May and June are the hottest months and December, January and February are the coldest months. The 17 years data of mean monthly maximum and minimum temperature are showing the increasing trend (Figures 4 & 5). The mean maximum and minimum temperature during winter is 35°C and, 5°C respectively. The mean maximum and minimum temperature during summer is as 43°C and, 10°C, respectively.

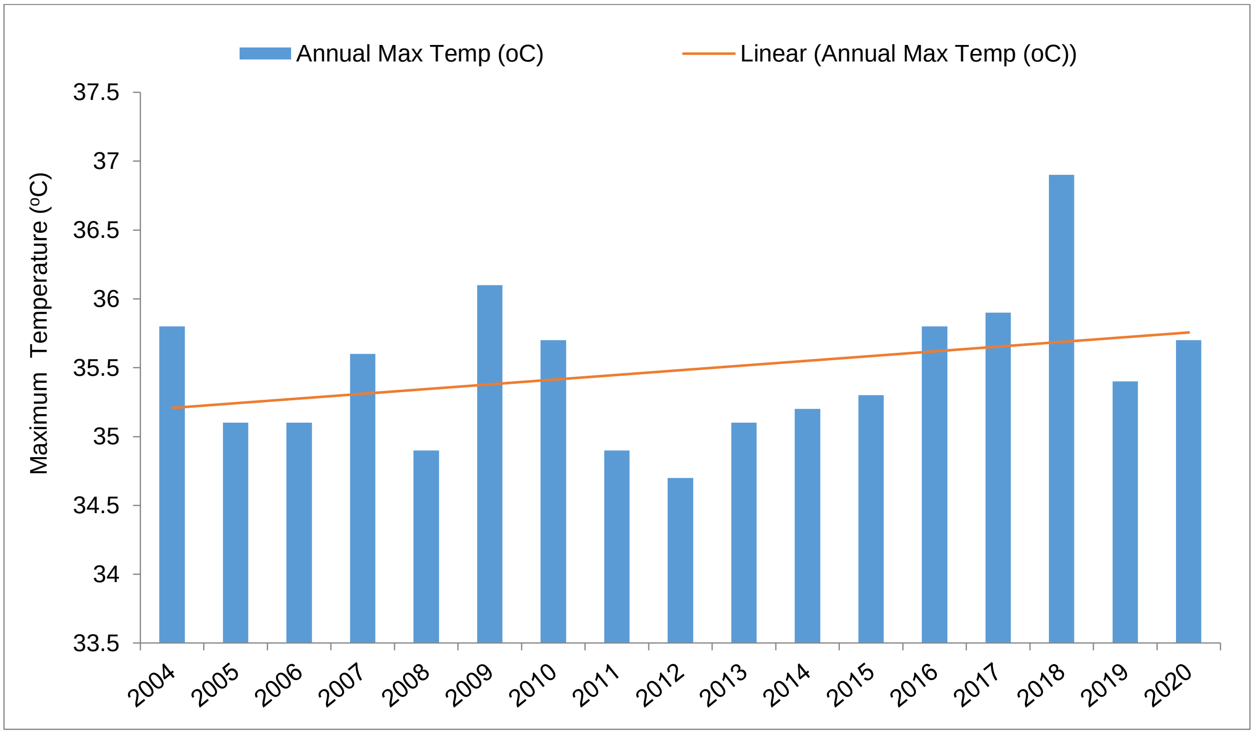

Figure 4: Mean annual maximum temperature at Mithi, Tharparkar

Climate change has now become a reality that has intensified the sufferings of people living in Tharparkar. Rise in temperature and increase in the frequency of extreme events are some of the changes observed during the last decade.

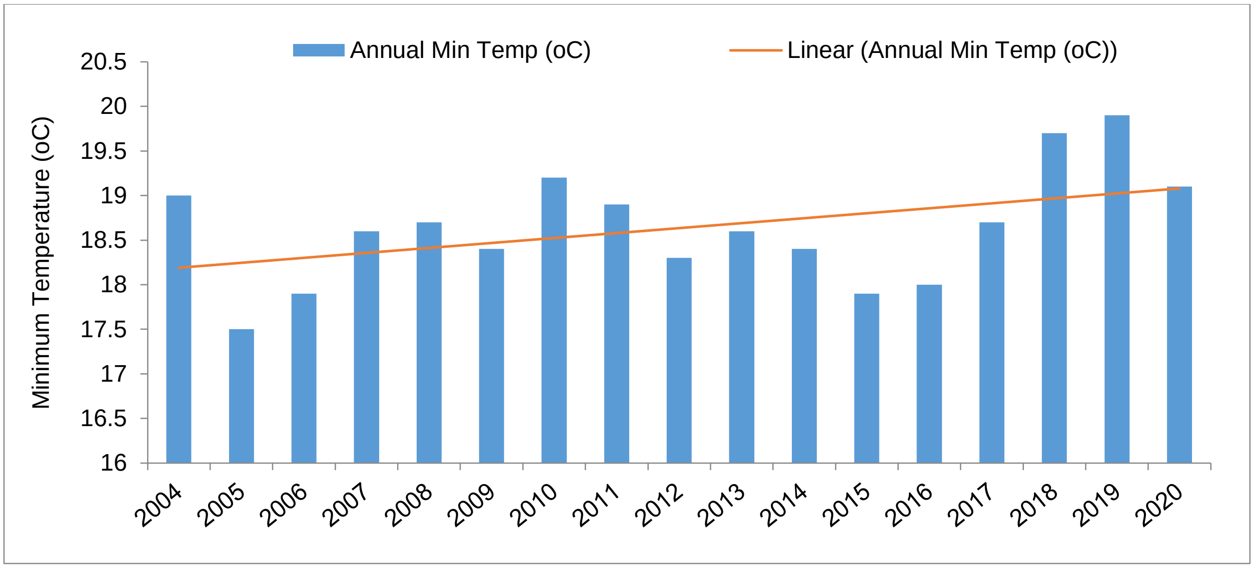

Figure 5: Mean annual minimum temperature at Mithi, Tharparkar

Based on the analysis of 17 years data (2004-2020), maximum rainfall of 1,361 mm recorded during the month of August - September, 2011 at Mithi station during monsoon season (Figure 6).

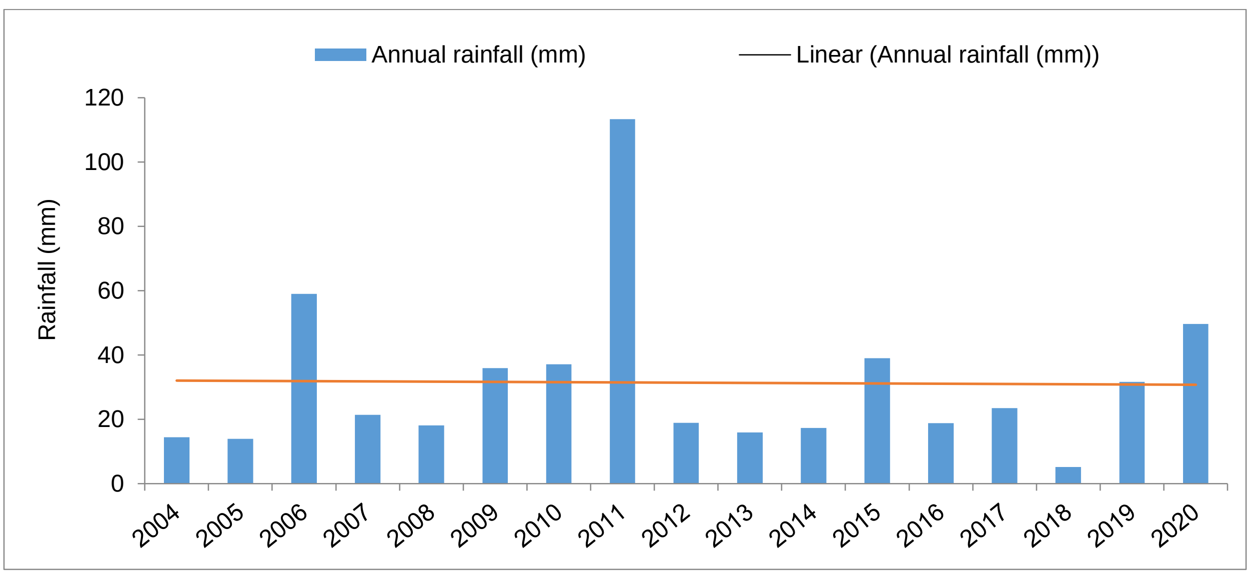

Figure 6: Mean annual rainfall at Mithi, Tharparkar

For thousands of years, people of this region are coping with drought and aridity of the land by using indigenous and climate smart interventions. However, global changes in climatic pattern and deterioration of social and economic conditions have pushed the inhabitants of this region into extreme vulnerable situation. Tharparkar has been suffering from drought for several decades and the Provincial Government has declared it as a drought - affected area. In 2014, it was vigorously struck by drought, causing devastation at a massive scale. Deaths of 128 children and 105 adults were reported accompanied with epidemics, dehydration, malnutrition, diarrhea and fever/ malaria. Furthermore, 2069 livestock deaths were also recorded including sheep, goats and cows or big domestic animals in result of this disaster (PESA, 2014). Due to drinking water scarcity, natives had to dig wells and use brackish water to meet human and livestock needs. The agriculture is totally dependent on rainfall and global warming has further put share in making the situation more critical.

Rainfall is scanty and groundwater is saline in most of the areas. The masses rely on rain-fed agriculture and livestock for their livelihoods. The consistent droughts in this area have hit a severe blow to both the agriculture and livestock. This has led to seasonal migration of local residents along with livestock to the irrigated areas. Access to the drinking water is so poor, only 47% of the population has access to drinking water. The data collected by Thar Deep Rural Development Program (TRDP) shows that 60% of the households wait more than one hour for their turn to fetch drinking water from dug wells (Figure 7).

Figure 7: Women fetching water from a dug well

Thirty percent of the households spend 30 rupees for 2 rubber buckets of water. About 85% households meet their water demand through camel/donkey support. Twenty Five percent households fetch water even after 2 days in some areas. Women fetch water for 75% of families. On an average, these women have to travel 3 km daily which consumes their 52% of the working hours that can be spent in any other economic or household activity. The health of the women is also affected when they travel continuously for hours to get water.

Generally, the groundwater quality is saline to highly saline. The groundwater tapped by 83% of dug wells has an EC ranging from 2.5 dS/m to more than 50 dS/m. The quality of groundwater is an important factor for limiting its potential for drinking, agricultural and industrial usages. In the past, a number of studies have been carried out in bits and pieces by different organizations to explore the potential of groundwater resources. The status of drinking water quality in the western parts of the Thar Desert has been investigated by Ploethner (1992); and Danishwar *et al.,* (1995). They observed that primary source of drinking water was dug well but suspected to be unfit for drinking. The data like anions, cations and trace metals indicated higher levels than permissible limits with possible hazardous effects on human health when used for drinking purpose.

Geyh and Ploethner (1995) have conducted a study during 1986 to 1991 to explore fresh groundwater resources in the deserts of Pakistan. They reported that low rainfall, high rates of evapotranspiration, low groundwater recharge and absence of perennial streams are general reasons for the scarcity of water in Cholistan, Tharparkar and upper Nara areas of their study. Rafique *et al.,* (2008) examined fluoride ion contamination in the groundwater of Mithi. They collected groundwater samples from different locations of Mithi and analyzed for fluoride ion together with other chemical parameters. The results indicated that collected water samples were contaminated with fluoride ion having higher concentration than permissible limits of WHO (1.5 mg/L) for drinking water. The fluoride ion concentration ranged between 0.09 to 11.63 mg/L with mean value of 3.64 mg/L. Brahman *et al.,* (2013) found that the groundwater of Diplo and Chachro tehsils were severely contaminated with arsenic (0.1 - 3.83 mg/L) and fluoride ions (13.8 - 49.3 mg/L), which were higher than WHO provisional guideline values (0.01 mg/L and 1.5 mg/L).

The socio-economic development of Tharparkar is dependent on water resources and it is of fundamental importance. The groundwater is available but not of require quality to meet drinking and irrigation requirements. Many substantial development initiatives have been taken intending for the development of groundwater resources. These development initiatives include construction of rainwater harvesting through ponds and tankas, construction of new and renovation of old dug wells, installation of Reverse Osmosis (RO) plants and hand pumps. However, the problem of water-crisis has yet not been resolved mainly because of lack of knowledge about the groundwater table, quality and aquifer thickness. As a result, during the hydrological drought, community has to migrate towards the irrigated areas.

PCRWR has conducted a study with the aim to identify fresh groundwater pockets in Tharparkar by applying an integrated methodology consisting of a number of techniques and tools.

2. Methodology

Groundwater investigation and evaluation is a tedious and lengthy process, which starts from data collection for resource assessment and involves sophisticated computer modeling for various management scenarios. The complication in dealing with groundwater evaluation lies in the fact that it is dynamic resource and occurs in different types of formations. Groundwater investigation techniques can be grouped in three main categories: aerial remote sensing, geophysical techniques and subsurface investigations including exploratory well drilling.

Under this study, soil samples, measurements of the depth to the water table, and water quality samples were collected at a 10 km x 10 km grid in Tharparkar District. In this context, 168 dug wells were surveyed and nearby soil samples were collected. Overall, 672 soil samples were collected at 0 - 15 cm, 15 - 30 cm, 30 - 45 cm and 45 - 60 cm depth. The soil samples were used to assess soil texture and Electrical Conductivity. The water samples were analyzed at water quality laboratory of DRIP, Tandojam for detailed physio-chemical analysis including heavy metals such as; Arsenic and Fluoride.

To identify the fresh groundwater pockets, Electrical Resistivity Survey (ERS) was used as main geophysical technique for investigation up to the depth of 300 m at a grid of 5 km x 5 km and 576 ERS probes were conducted with ABEM Terra Meter SAS 4000 instrument by using Schlumberger configuration. These resistivity values were modeled through Interpex (IX1D) software and converted into true earth resistivities, which were further converted into electrical conductivity by developing a regression between resistivity and EC values of water samples analyzed in the laboratory. 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 results of soil and water quality assessments, along with ERS data, are mapped using ArcGIS software. The analysis process included overlaying different parameters at various depth intervals.

3. Results and Discussion

3.1 Soil Lithology

Soil texture plays a significant role in replenishing the groundwater system with precipitation induced recharge, and seepage from canal network. The study area is mostly covered by sand and sandy clay-loam texture. Such types of soils are categorized as coarse-textured and they usually store less moisture contents and their intake and drain rate is high as compared to fine-textured soils. The interpolated GIS map for soil texture is shown in Figure 8.

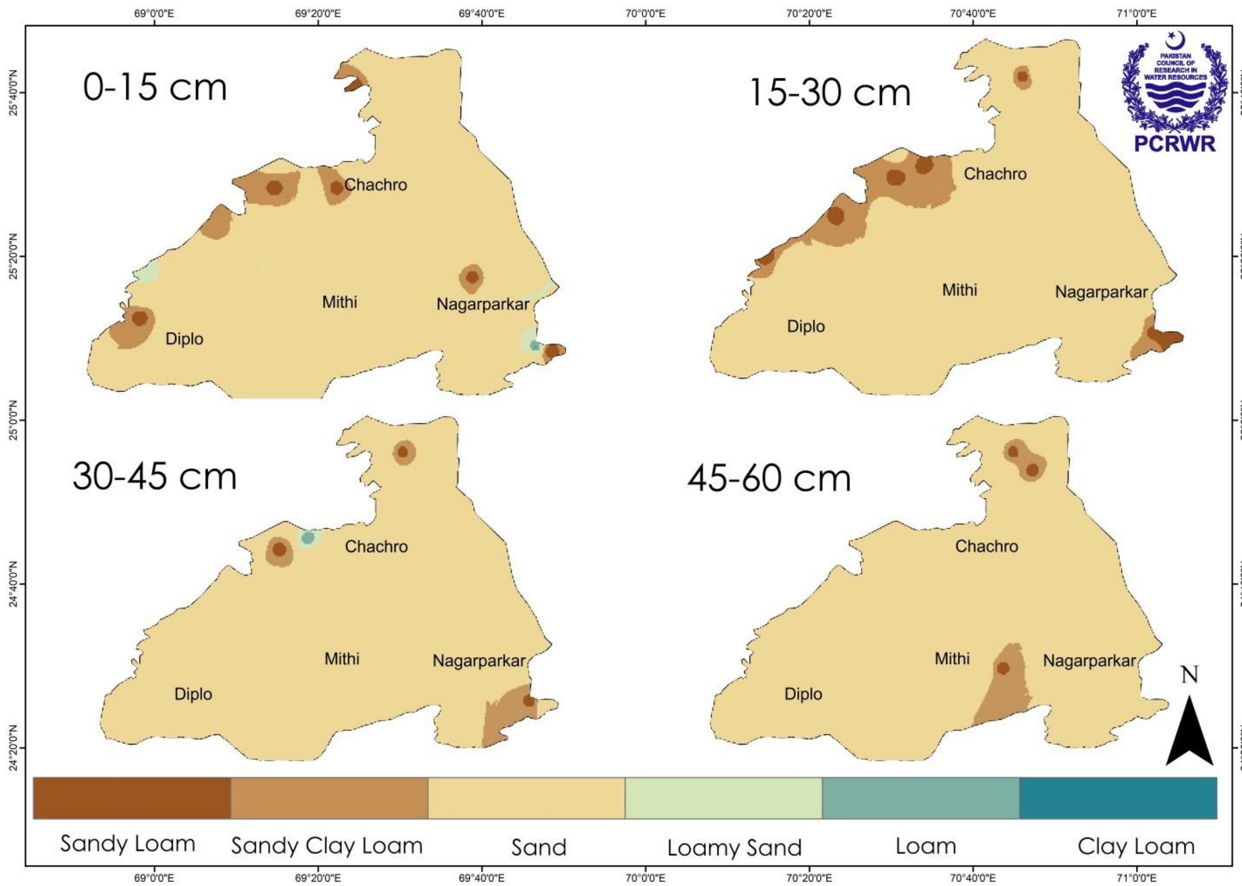

Figure 8: Spatial variation in soil texture at different depths in Tharparkar

The analysis of soil texture shows that sand is dominant at all investigative depths. The sandy soil has high infiltration rate, and low runoff potential. Though, these types of soil allow the water to recharge but due to deep water table, low rainfall and non-existence of irrigation network, water could not become part of the aquifer and remained in the soil profile. The upper (0 - 15 cm) and middle (15 - 30 cm) soil layers in some parts of Chachro tehsil have a sandy clay loam texture. This type of soils improves moisture retention while the sand minimizes compaction and improves drainage.

Furthermore, the soils samples were analyzed for soil salinity (ECe). The soil salinity refers to the amount of salt present in the soil, which has a negative impact on crop growth and yield. The analytical results of soil samples for the assessment of salinity are presented in Figure 9.

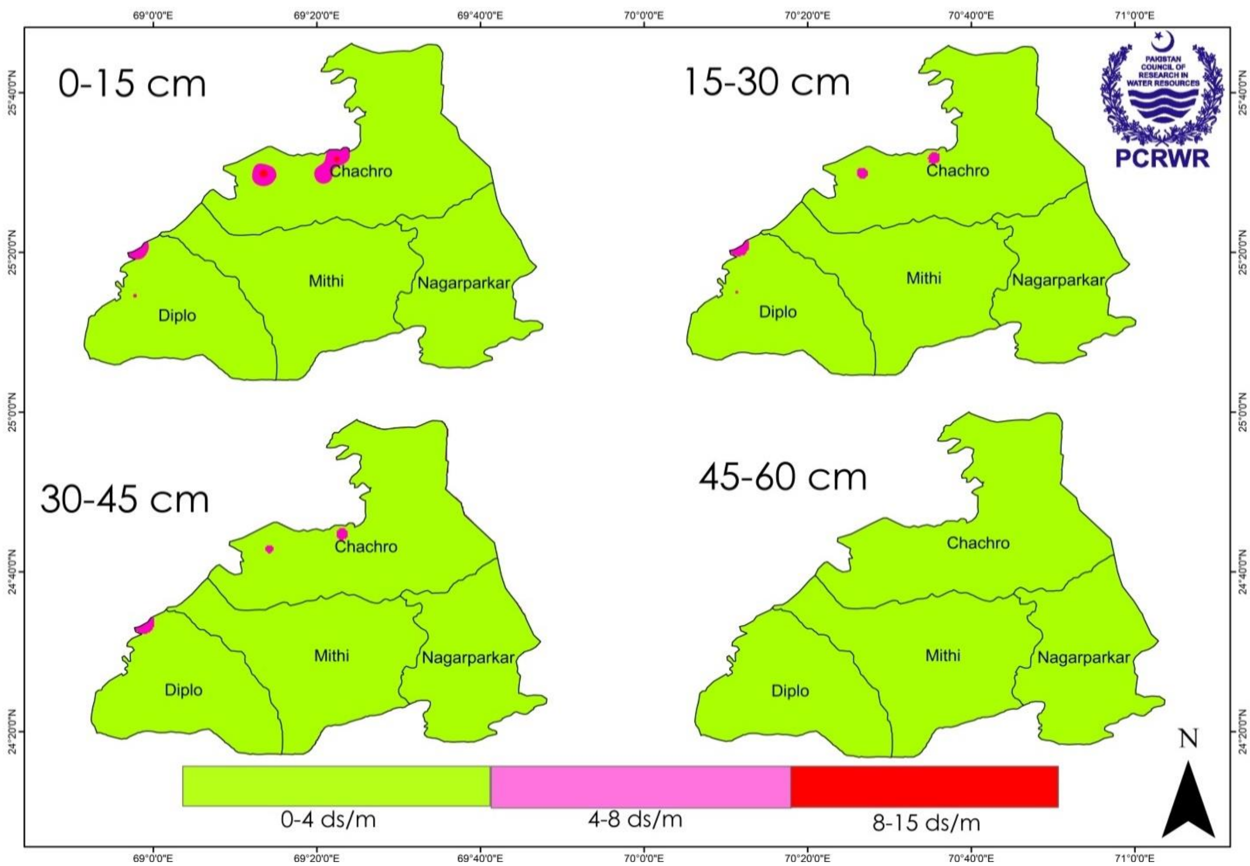

Figure 9: Spatial variation in soil salinity (ECe) at different depths in Tharparkar

Most of the area of the district lies under non-saline (ECe < 4.0 dS/m) category at all measured depth. It shows that up to investigative depth, soil is non saline and suitable for plant growth. It is a fact that soil of the area is fertile as compared to Cholistan Desert and after rainfall in monsoon season; land becomes green improving the biodiversity.

3.2 Depth to Water Table

Due to desert environment; the native groundwater is mostly saline and deep. The people have relied for centuries on the aquifers of saline groundwater due to non-availability of surface water. The reason for saline aquifer may be sporadic monsoon rains, low recharge, periods of drought and high temperature and evaporation rate.

The Depth to Water Table (DTW) was measured and groundwater samples (168) were collected at 10 km x 10 km grid (Figure 10). In tehsil Diplo, DTW is minimum (2.4 m), whereas it is maximum in tehsil Chachro (112 m). The DTW is shallow upto 15 m in southern parts of tehsils Diplo, Islamakot, Nagarparkar and upper parts of Dalhi (Figure 11). The reason for shallow DTW may be low elevated plains and geographical location of the areas close to sea. The water table in Nagarparkar at shallow depth (3.7 m) may be due to the small dams situated in the vicinity and Rann of Kutch (water logged & saline) areas close to the Arabian Sea. The water table in Mithi and Chachro tehsils is deep as compared to Nagarparkar and Diplo tehsils. The area coverage under different water table depths is given in Figure 12.

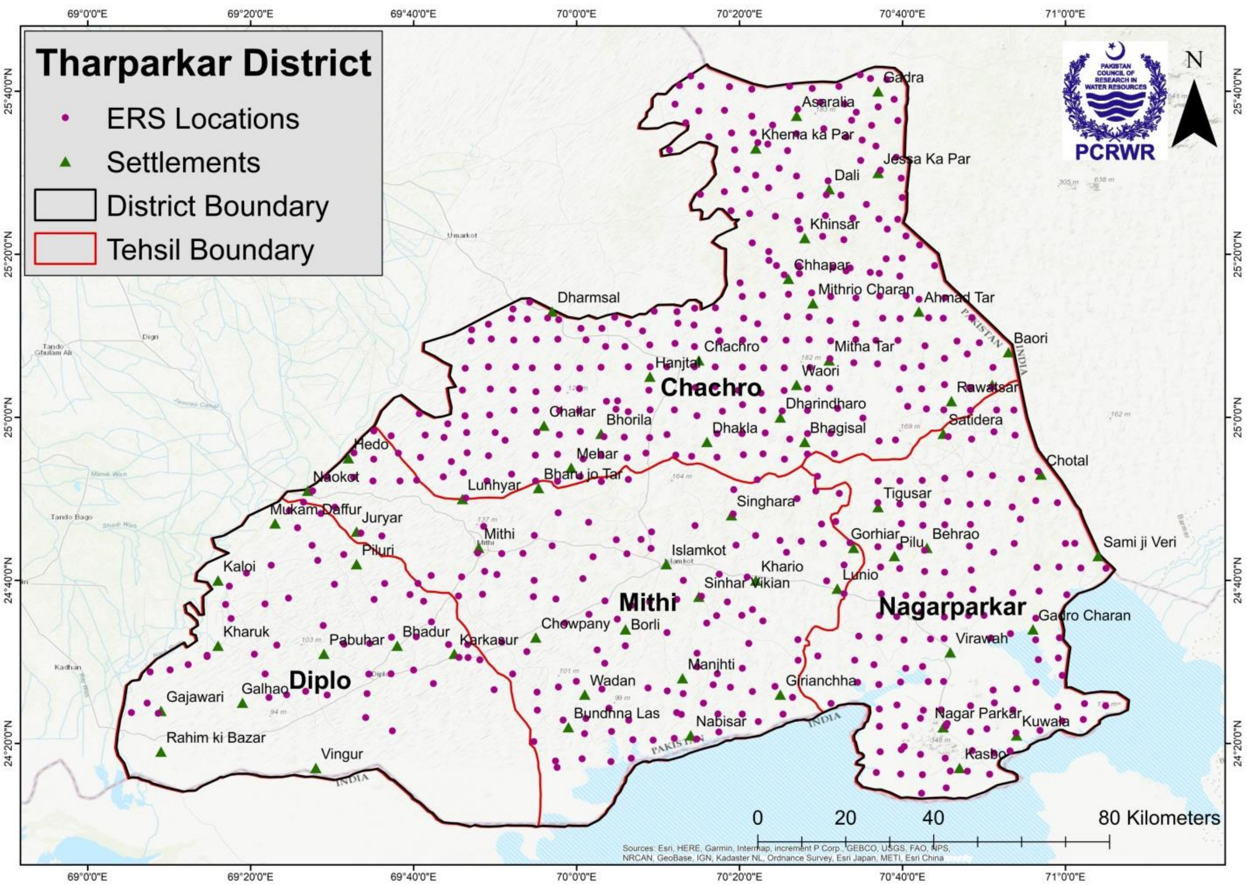

Figure 10: Locations of dug wells

It is observed that 26% (5,151 km^2) area is at shallow (2 - 15 m) depth in southern low elevated areas of Diplo, Islamkot, Nagarparkar and Dahli tehsils may be due to recharge of canal in Diplo and dams located in Nagarparkar areas. The adjacent to above mentioned locations, 23% area (4,557 km^2) falls under 16 - 30 m. The DTW in 19% (3,764 km^2) area is in the range of 61 - 90 m in mostly central part of Chachro and upper Mithi area. The water table is deep in Chachro tehsil may be due to native groundwater or less recharge. Water table remains in the range of 46 - 60 m in upper part of Mithi and Chachro tehsils at 16% (3,170 km^2) area of Tharparkar.

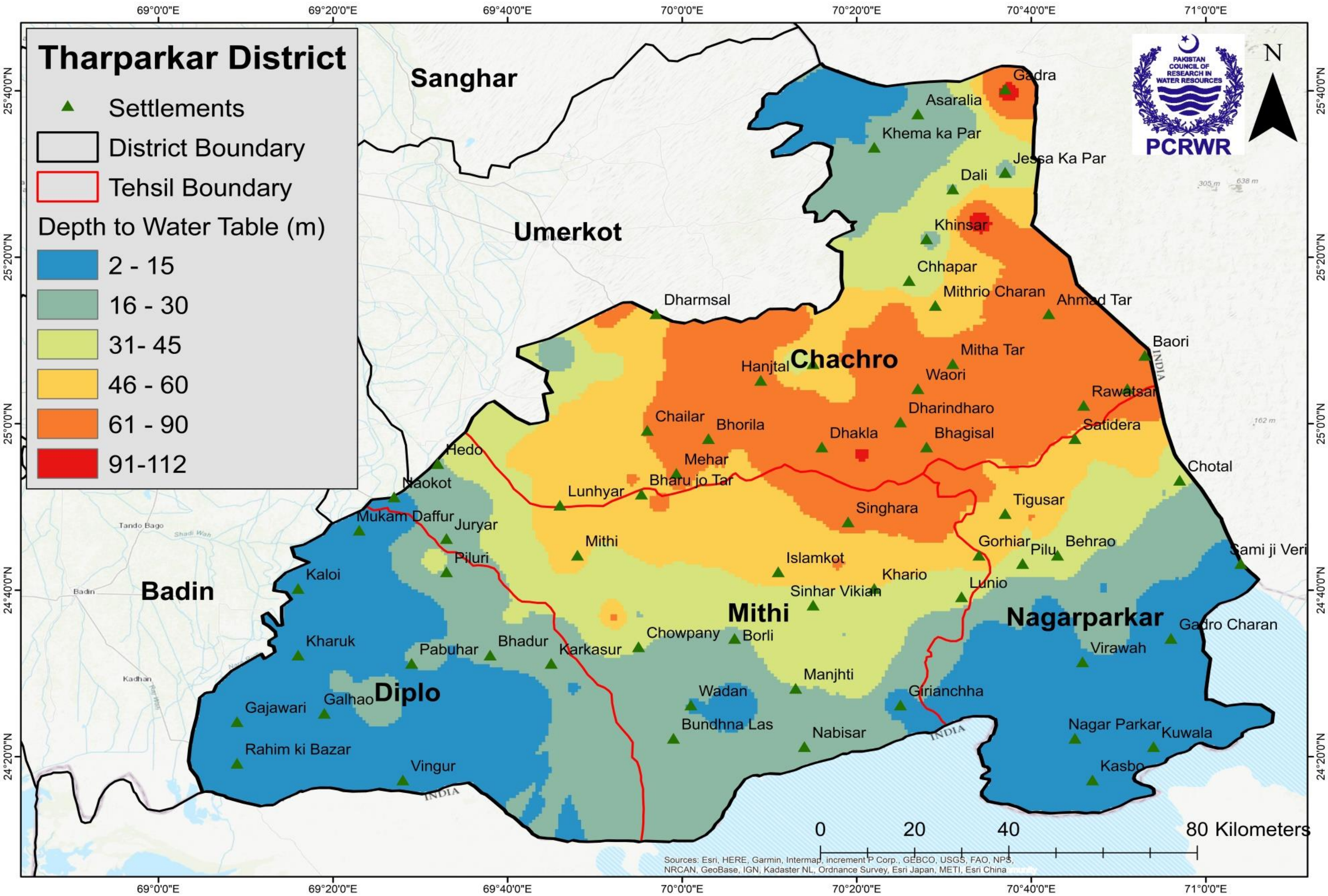

Figure 11: Spatial variations in depth to water table in Tharparkar

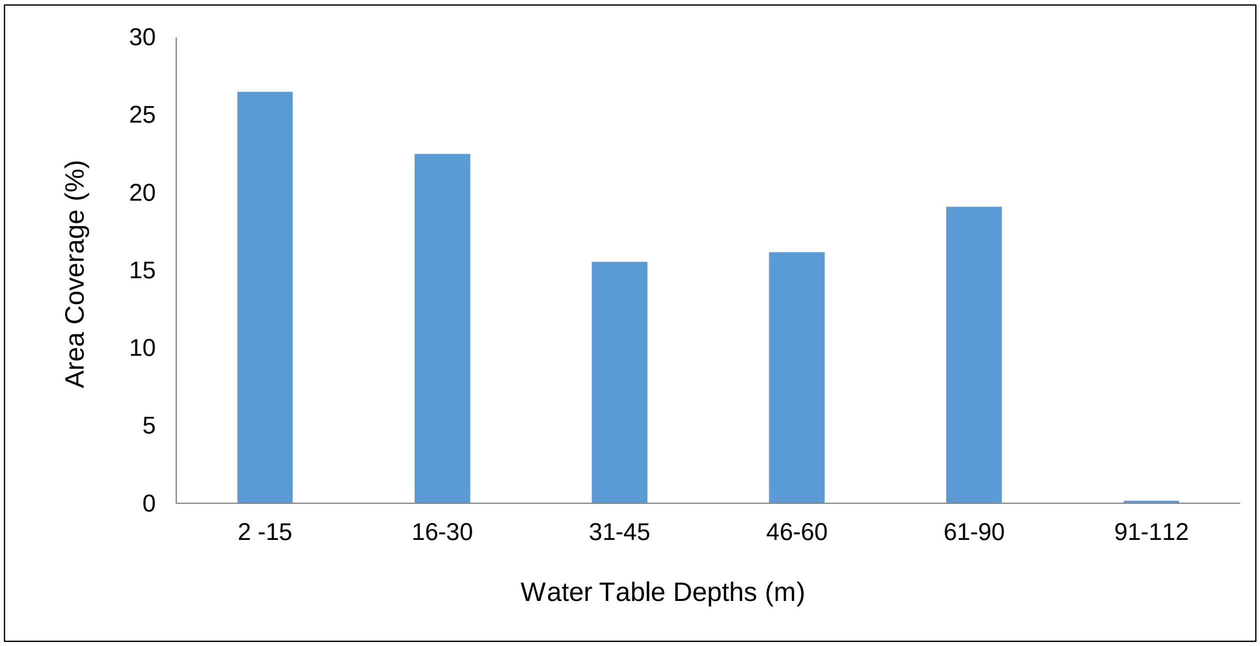

Figure 12: Area coverage under different water table depths

3.3 Groundwater Quality Analysis

The groundwater samples were examined for water quality analysis. The electrical conductivity (dS/m) was measured and divided into four water quality zones (Table 2).

Table 2: Water quality zoning

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

Source: Iqbal *et al.,* 2020

The groundwater quality (EC) was evaluated through DRIP, PCRWR Laboratory, Tando Jam. It shows that 69% area (13,671 km^2) is under highly saline water (4.1 - 35.9 dS/m). Whereas, 1% and 5% area is fresh and marginal, respectively in pockets of southern parts of tehsils Diplo, Islamkot and Nagarparkar having EC ranging from 0.18 - 2.50 dS/m. This is useable quality water and can be used for irrigation purpose (Figure 13). The area coverage of EC is shown in Figure 14.

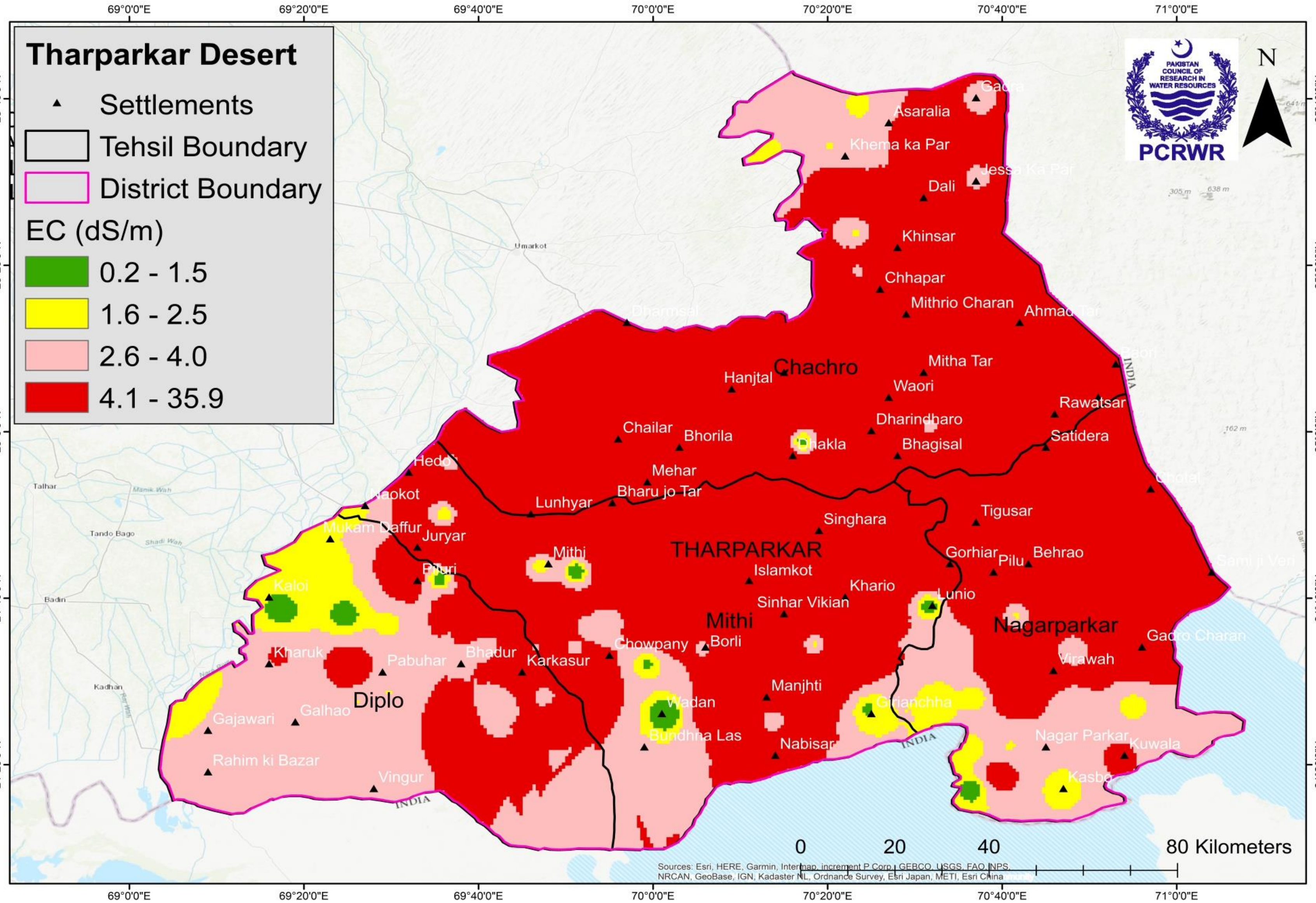

Figure 13: Groundwater quality in Tharparkar at variable depths (2 - 112 m)

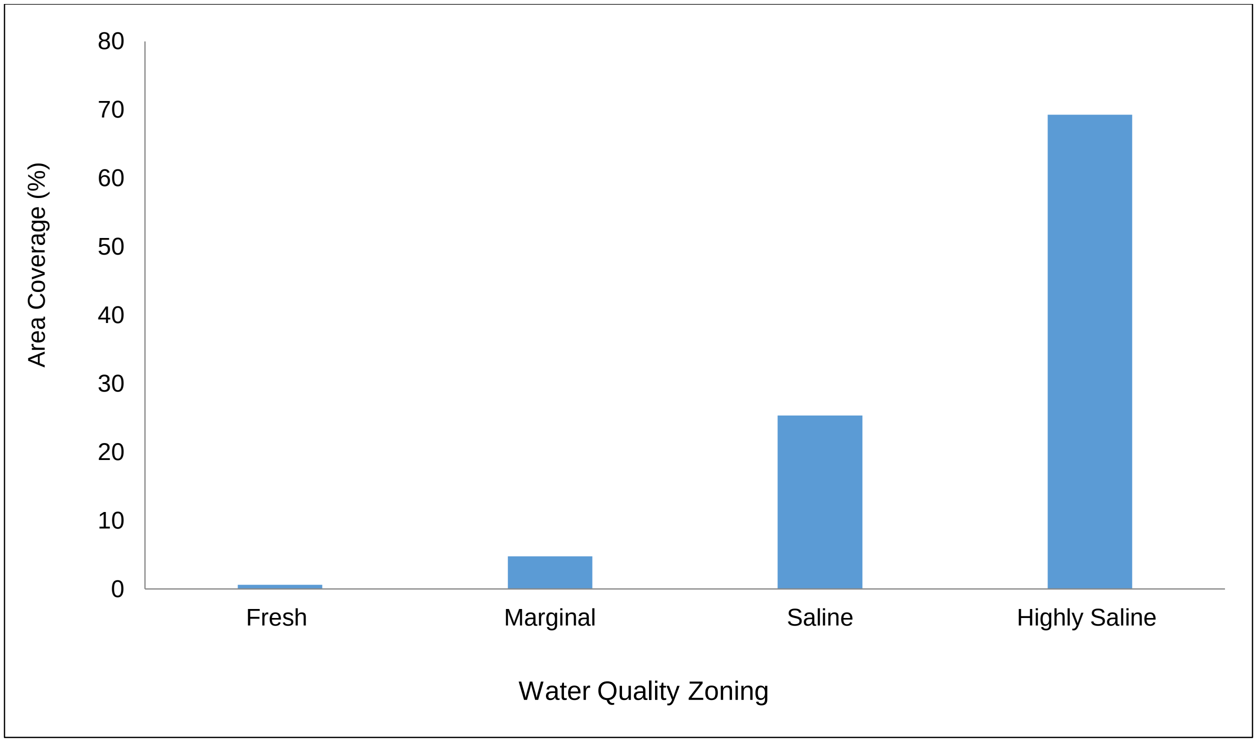

Figure 14: Area coverage under different water quality zones at variable depths (2 - 112 m)

The groundwater quality of tehsil Chachro is highly saline may be due to high water table depth and low recharge. The water quality of samples taken from varying depths in southern parts of Diplo, Mithi and Nagarparkar are saline (≤ 4 .0 dS/m) and under hard conditions of Thar, same water can be used for livestock and irrigation purpose.

3.3.1 Arsenic in Groundwater

The presence of Arsenic (As) in water derived from anthropogenic and geological sources has disastrous and life-threatening consequences (Brahman *et al.,* 2013). The consumption of Arsenic contaminated drinking water may adversely affect human health worldwide. Arsenic can be absorbed readily in the gastrointestinal tract where it can lead to cardiovascular diseases, diabetes, cancer, and mental health issues (Bhowmick *et al.,* 2018 and Karim, 2000). Pakistan is also facing severe public health adversities due to arsenic-contaminated water. According to WHO drinking water safety standards, Arsenic value should not be more than 10 (ppb). Under this study groundwater samples (168) were analyzed for Arsenic and results are shown in Figure 15.

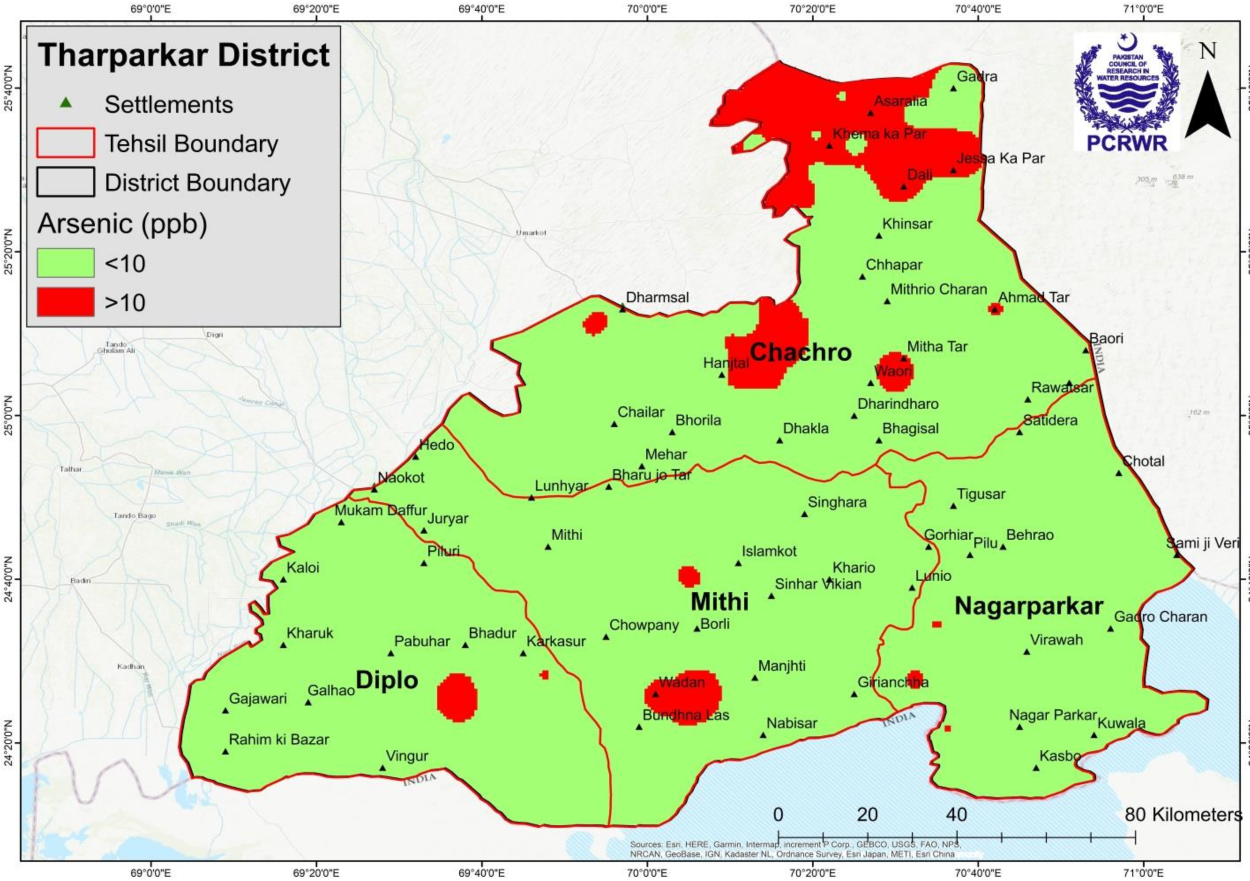

Figure 15: Arsenic concentration in groundwater of Tharparkar

The arsenic results indicate that the majority of the area adheres to the permissible limit set by the World Health Organization (<10 ppb). It shows that 90% groundwater samples are fit (Arsenic free) for consumption, and only 10% (contaminated with Arsenic) are unfit. Tehsil Chachro and some parts of Mithi and Diplo contain significant presence of Arsenic. The main anthropogenic sources for contamination of groundwater with Arsenic are mining, burning of fossil fuels, use of arsenical fungicides, herbicides and insecticides in agriculture, and wood preservatives. Khuhawar *et al.,* (2019) reported that 29% samples were found unfit and indicated Arsenic contents more than permissible limit of WHO (10 ppb) for human consumption in Tharparakar. The presence of Arsenic in water poses health hazards to humans, creates non-cancer effects such as hyperand hypo-pigmentation, keratosis, black foot disease, hypertension, cardiovascular diseases and diabetes (Milton *et al.,* 2004).

3.3.2 Fluoride in Groundwater

Drinking water containing fluoride is recognized as worldwide problem that impacts the health of millions of people (Meenakshi, 2006). Fluoride is an essential micronutrient for human beings, serving to strengthen the apatite matrix of skeleton tissues and teeth at the concentration less than 1 mg/L. On the other hand, high Fluoride concentration greater than 1.5 mg/L results into dental and skeletal fluorosis, renal, and neuronal disorders along with myopathy (Ayoob and Gupta, 2006). Fluoride in excess can cause fluorosis, a condition of yellowing teeth and other gum diseases (Srivastava, 2020).

Fluoride is abundantly found in phosphates, and minerals included within the earth's crust (950 mg/l in its ionic form) (Kumar *et al*., 2022). The groundwater samples were analyzed for Fluoride and results are presented in Figure 16.

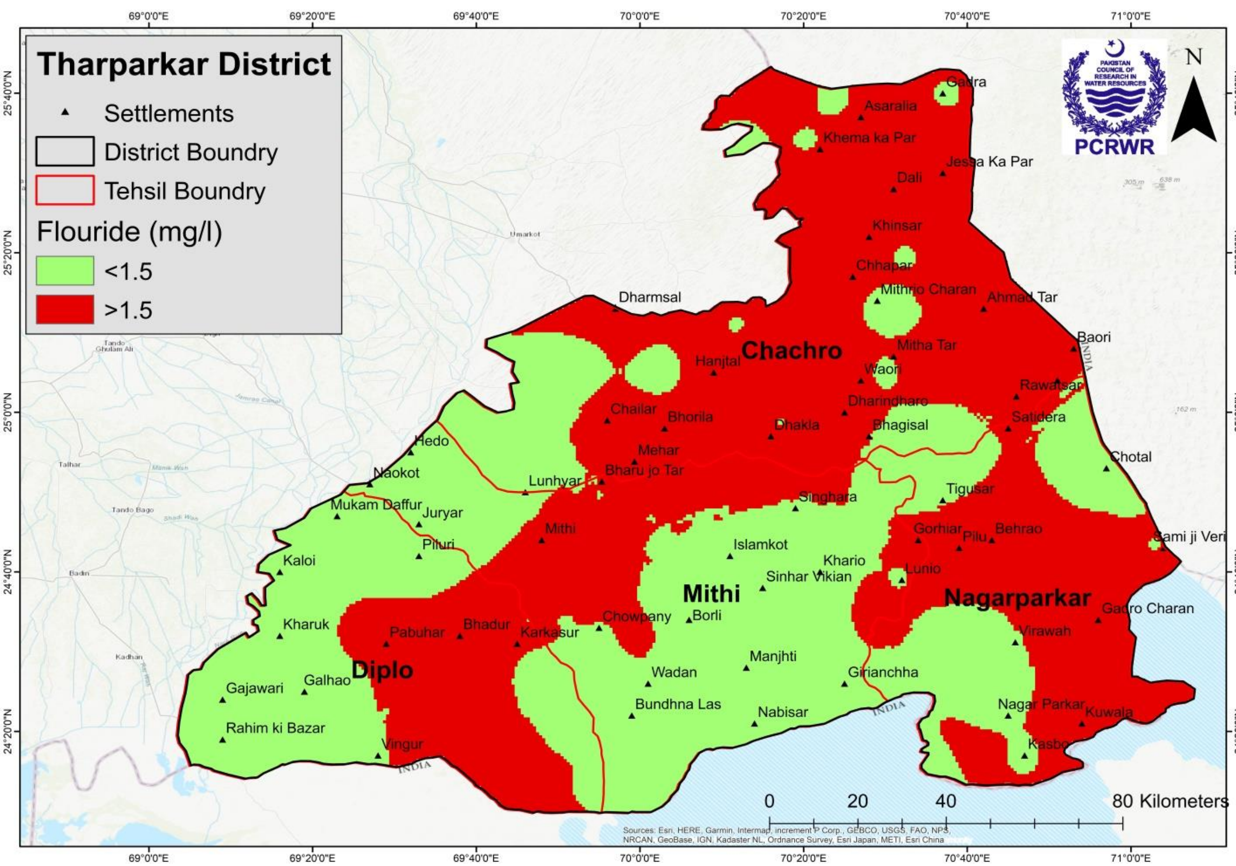

Figure 16: Fluoride concentration in groundwater of Tharparkar

High concentrations of Fluoride in groundwater are therefore expected in areas where Fluoride bearing minerals are abundant in geologic substrate (Naseem *et al.,* 2010). As per WHO guidelines, range of Fluoride concentration in drinking water is 1.5 mg/l. The results expressed that 72% groundwater samples are fit for consumption in terms of Fluoride concentration and 28% are unfit. Fluoride levels are higher than allowed permissible limit in all four tehsils. The occurrence of Fluoride in groundwater is due to weathering and leaching of fluoride-bearing minerals from rocks and sediments. Khuhawar *et al.,* (2019) also reported similar finding that 28% crossed the permissible level of 1.5 mg/L and 8% crossed the hazardous level of 3.0 mg/L of Fluoride in drinking water. Kumar *et al.,* (2022) concluded that concentration of Fluoride in areas of Mithi, Dharar, Harmar and Satar was found above the permissible limits. Long-term groundwater usage with high levels of Fluoride, and Arsenic can result in waterborne diseases, including bone disorders, skin diseases, and asthma.

3.4 Groundwater Quality Mapping through ERS

To delineate the quality of usable groundwater, 576 Electrical Resistivity Survey (ERS) probes were conducted upto a depth of 300 meters. The interpretation of the ERS data indicates that sandy stratum dominates the study area. The location map of ERS probes conducted is given in Figure 17.

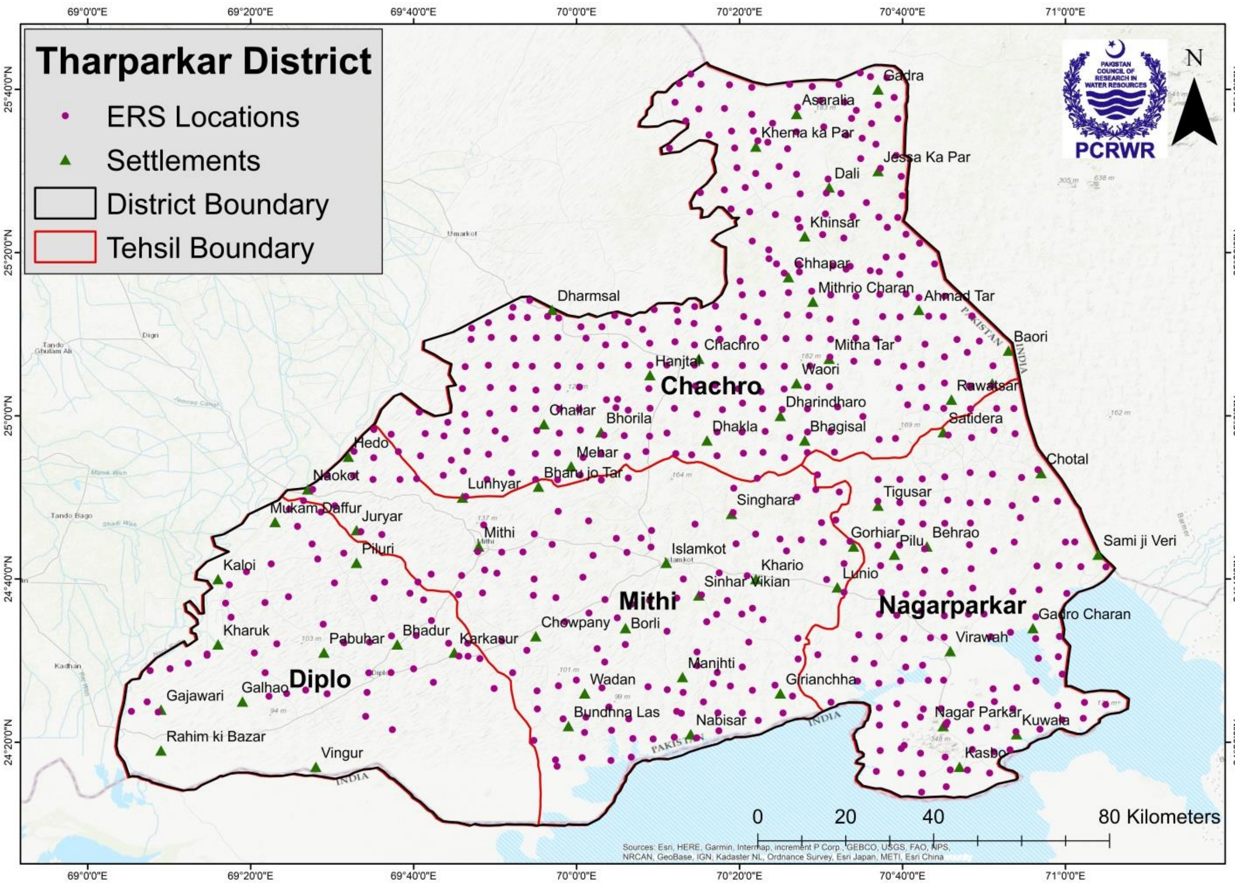

Figure 17: Location of ERS in Tharparkar

The rural population comprises scattered villages mostly around the source of water in the form of dug wells. The groundwater quality in terms of EC at 25 m depth is given in Figure 18 which indicates that groundwater quality in southern areas of Diplo, Islmakot, and Nagarparkar is fresh (3%) to marginal (7%). The area coverage (%) at 25 m depth is given in Figure 19.

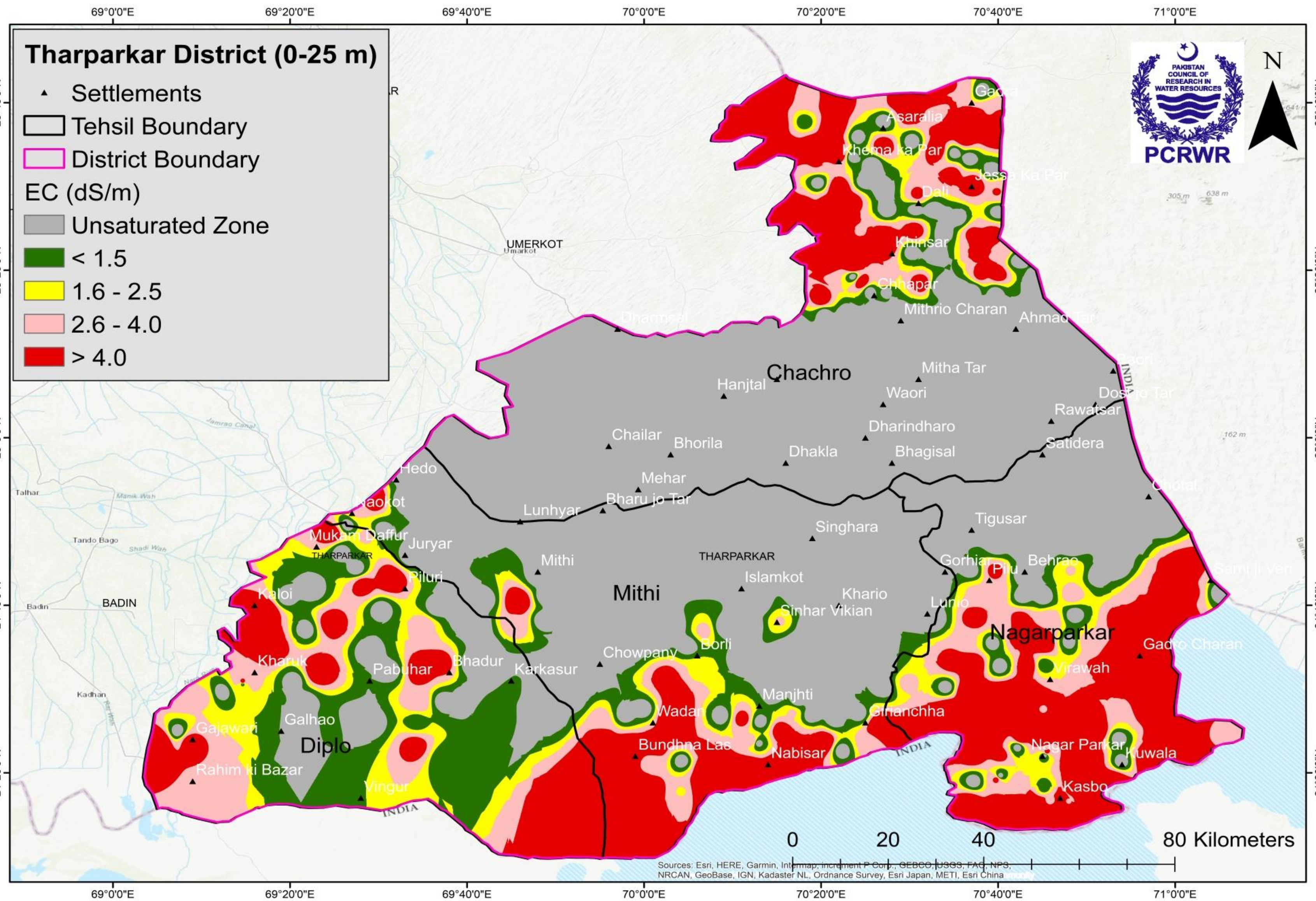

Figure 18: Spatial variations in EC at 25 m depth in Tharparkar

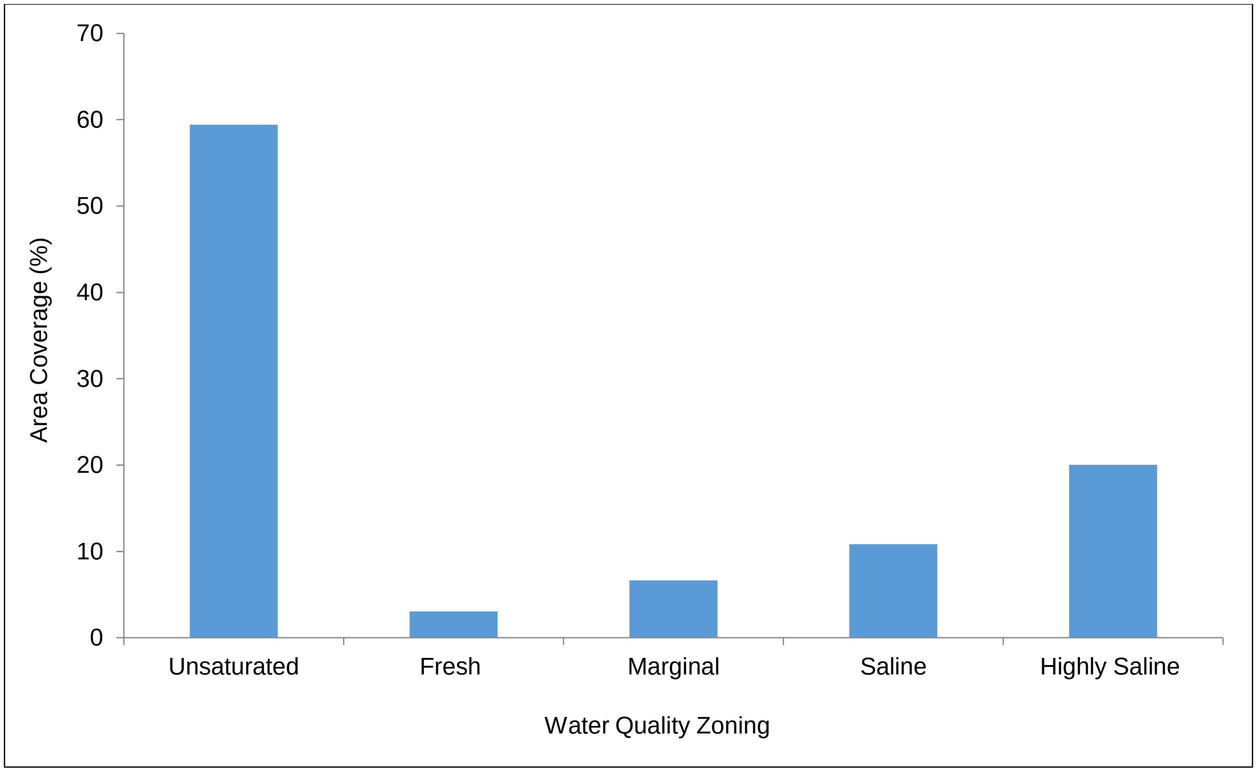

Figure 19: Area coverage at 25 m depth under different water quality zones

It is clear from the above figure that 59% area (11,690 km^2) is under unsaturated zone. Whereas 31% (6,142 km^2) of the area is classified as saline to highly saline, rendering it unsuitable for drinking purposes.

The groundwater quality at 50 m depth is given in Figure 20 and area coverage (%) under same depth is given in Figure 21. The groundwater quality at 26 - 50 m depth in southern areas like Diplo, Islamkot, Nagarparkar and Dahli tehsils falls into highly saline. The area under high salinity zone at this depth is 51% (10,105 km^2) area, whereas, 24% area is under unsaturated zone. The remaining 24% (4,755 km^2) area is under marginal and saline zones. It is mentioned here that the area under fresh groundwater zone is only 198 km^2 which is only 1% of the total area.

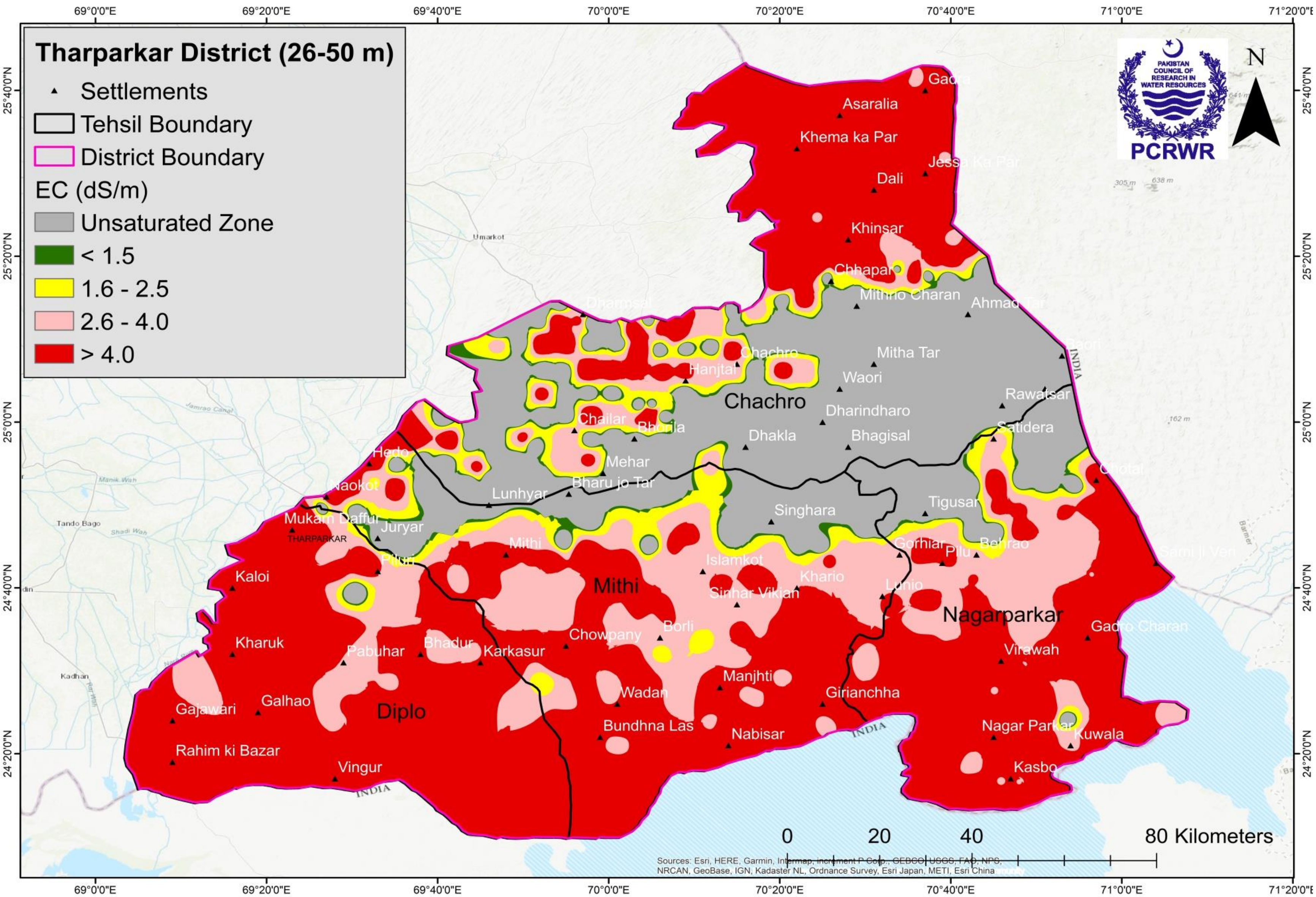

Figure 20: Spatial variations in EC at 50 m depth in Tharparkar

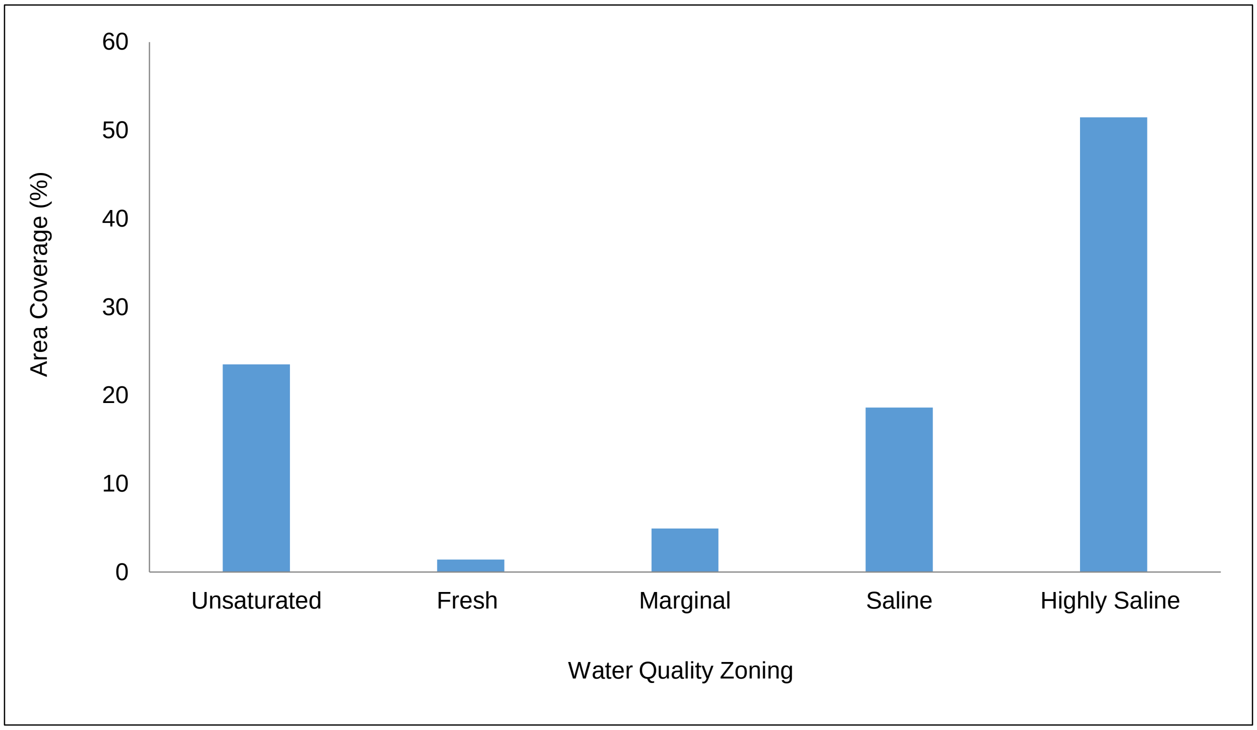

Figure 21: Area coverage at 50 m depth under different water quality zones

The groundwater quality at 75 m depth is given in Figure 22 and area coverage (%) under same depth is given in Figure 23. The groundwater quality at 51 - 75 m depth is further deteriorated and highly saline at 76% (15,058 km^2) area in Mithi, Chachro, Diplo and Nagarparkar, and remaining 24% (4,755 km^2) area is under marginal to saline and un-saturated zones.

Khuhawar *et al.,* (2019) also concluded that 58% populations of tehsils mainly Mithi, Chachro and Diplo are consuming groundwater with EC greater than 4.68 dS/m. This value is much higher than the permissible limit of WHO for human consumption. These findings are in close agreement with present PCRWR study highlighting further deterioration of groundwater quality.

This study also indicates that EC analyzed through laboratory is more than 4.0 dS/m at shallow depths in 69% of above-mentioned areas. Further, Khuhawar *et al.,* (2019) concluded that 15% of the population in the areas consuming drinking water that is relatively less harmful having EC between 2.34 and 4.68 dS/m. About 27% of the population is using groundwater with EC less than 2.34 dS/m, which can be used under hard environment.

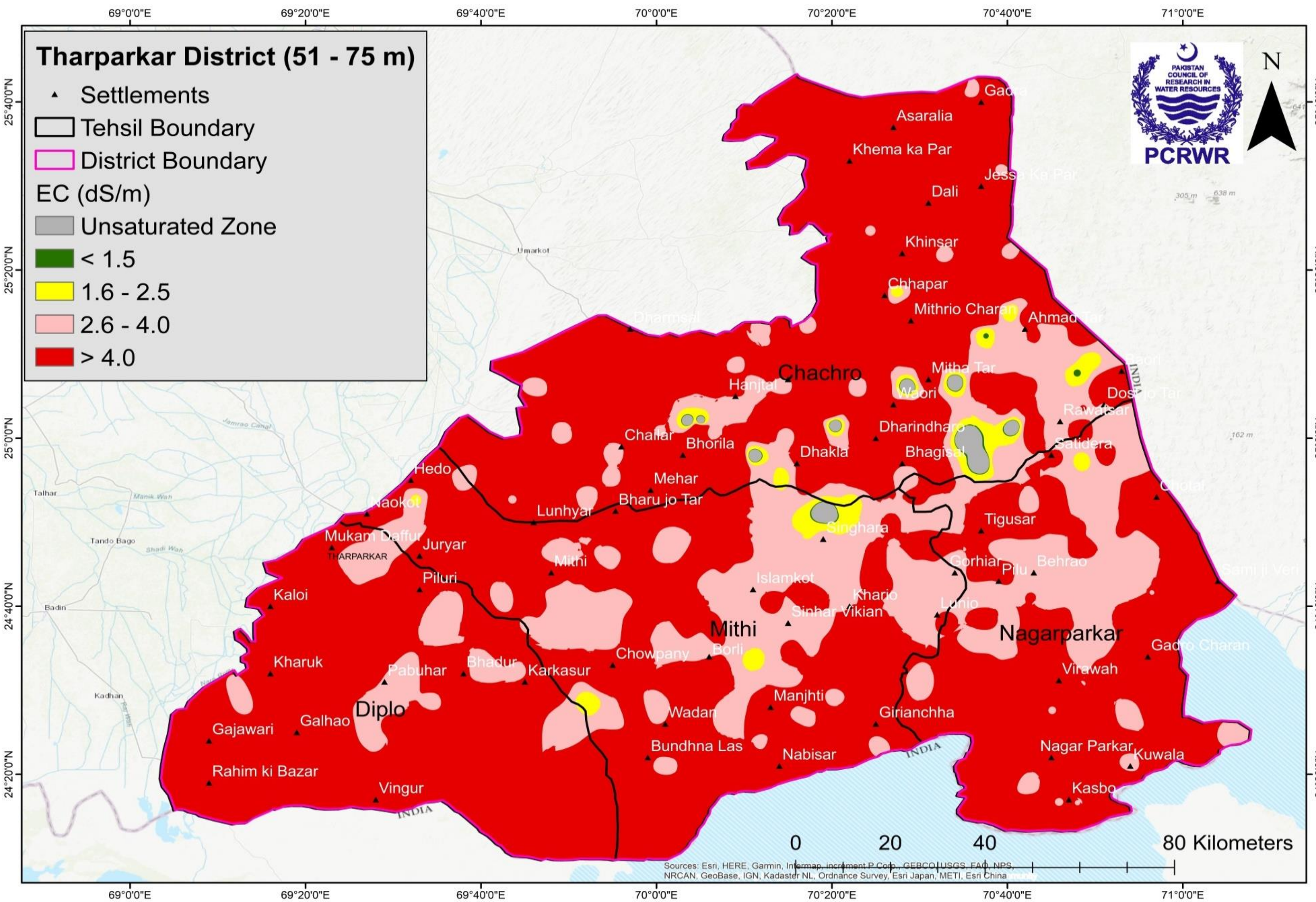

Figure 22: Spatial variations in EC at 75 m depth in Tharparkar

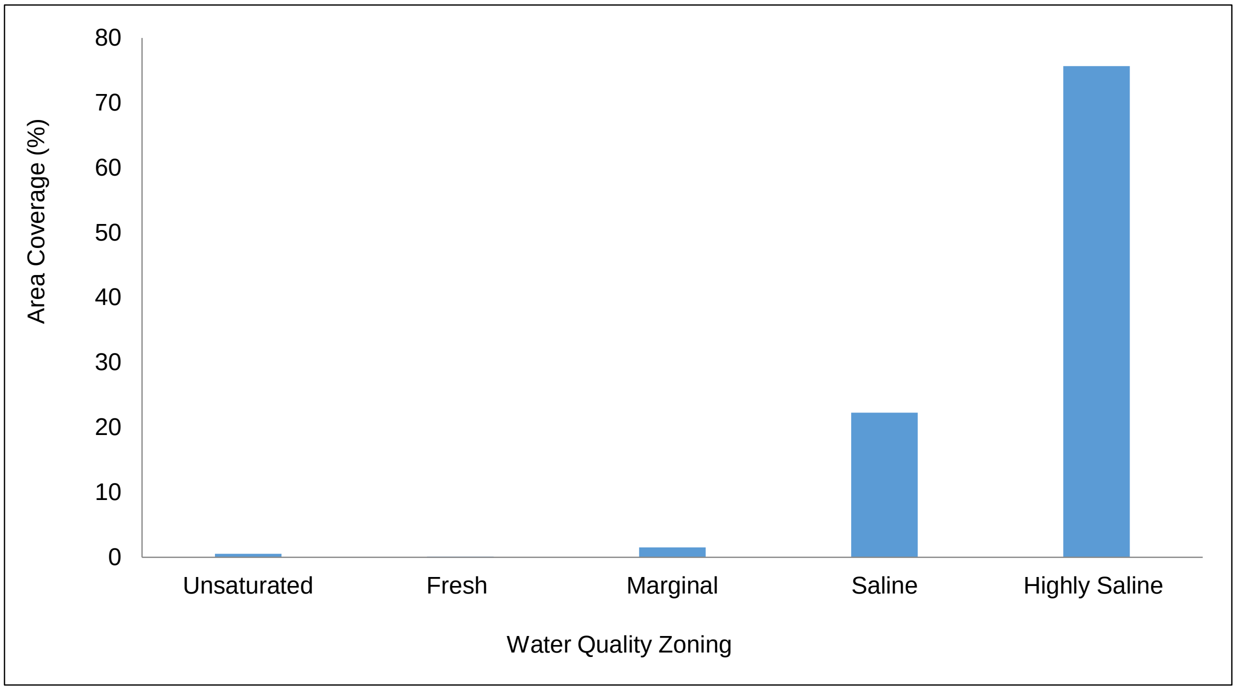

Figure 23: Area coverage at 75 m depth under different water quality zones

Natesh *et al.,* (2020) conducted a study on impact assessment of groundwater quality in Islamkot. They concluded that the consumption of polluted groundwater posed high risk for the public health. It was also concluded from the health impact assessment survey, that the occurrence of various waterborne and water-related diseases was common among the residents of the study area. Consequently, the use of poor quality groundwater should instantaneously be stopped and new techniques should be adopted. Rainwater harvesting, irrigation network expansion, installation of reverse osmosis, de-Arsenic & Fluorination plants and freshwater supply schemes should be introduced. Water quality monitoring and health impact assessment should be conducted constantly.

The PCRWR study shows that the groundwater quality at 76 - 100 m depth is highly saline in 82% (16,247 km^2) area of Mithi, Chachro, Diplo and Nagarparkar. Whereas, remaining 18% (3,566 km^2) area is under saline zones (Figure 24). The groundwater quality downwards upto 300 m depth is shown in Figures 25 - 28.

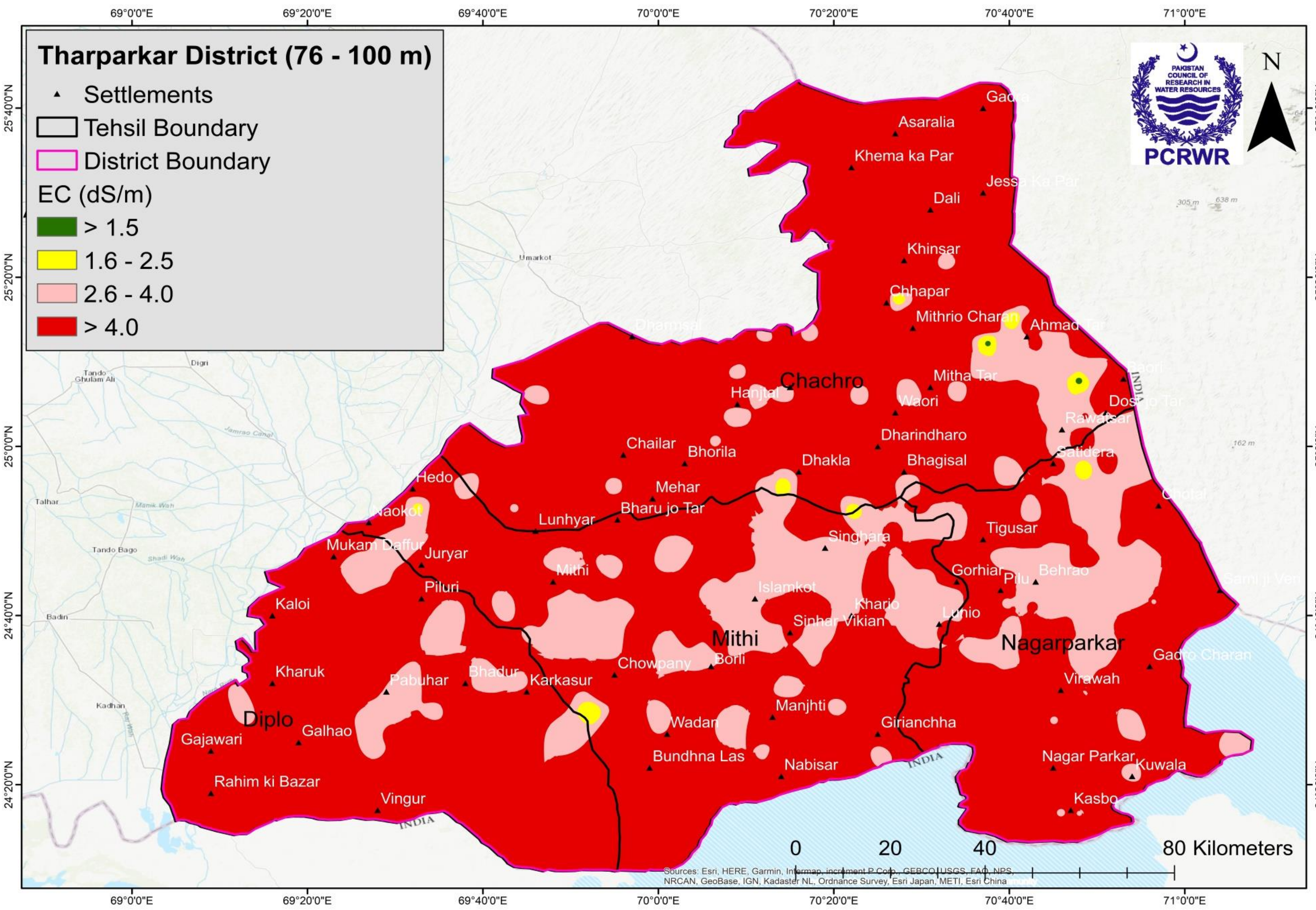

Figure 24: Spatial variations in EC at 100 m depth in Tharparkar

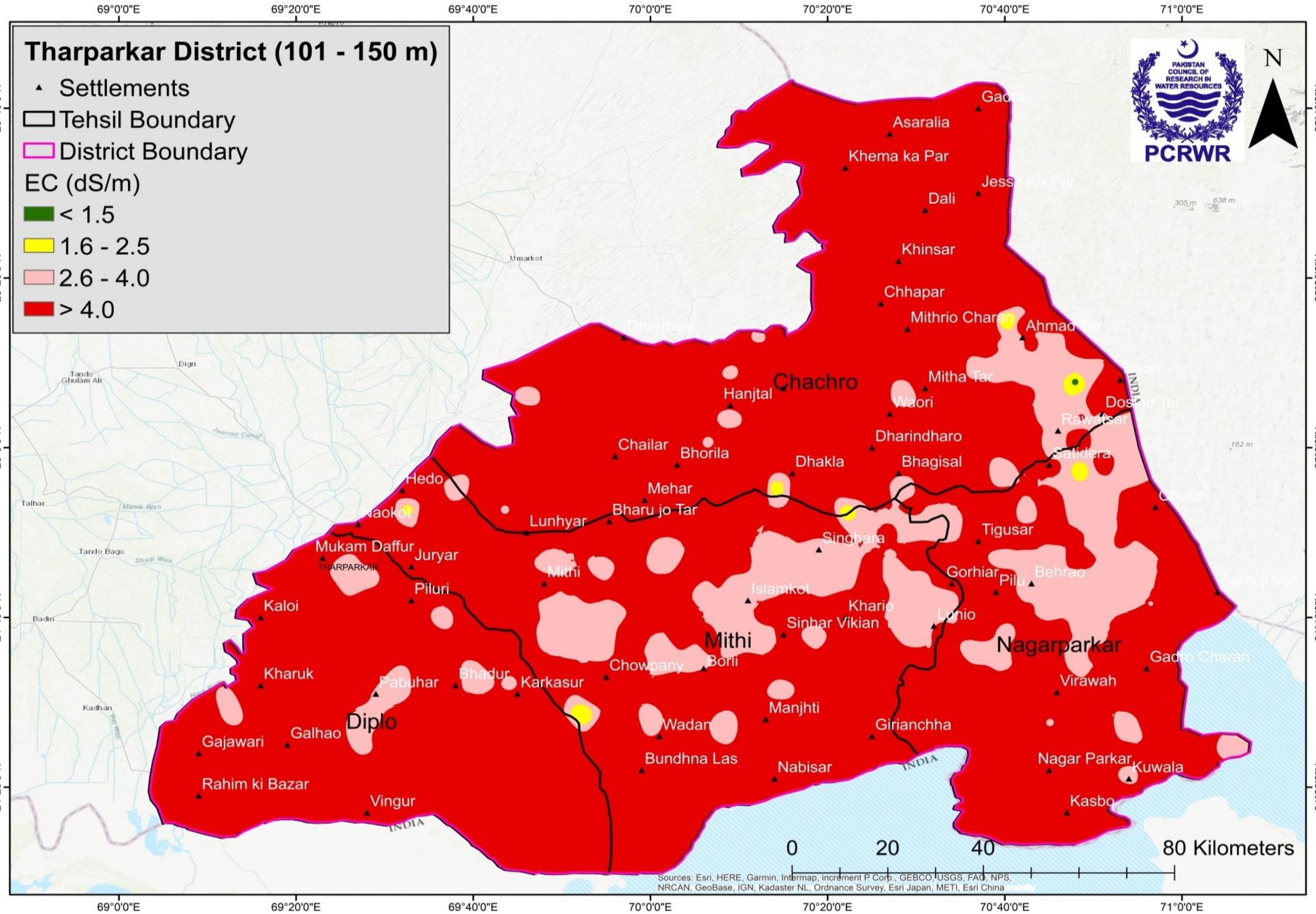

Figure 25: Spatial variations in EC at 150 m depth in Tharparkar

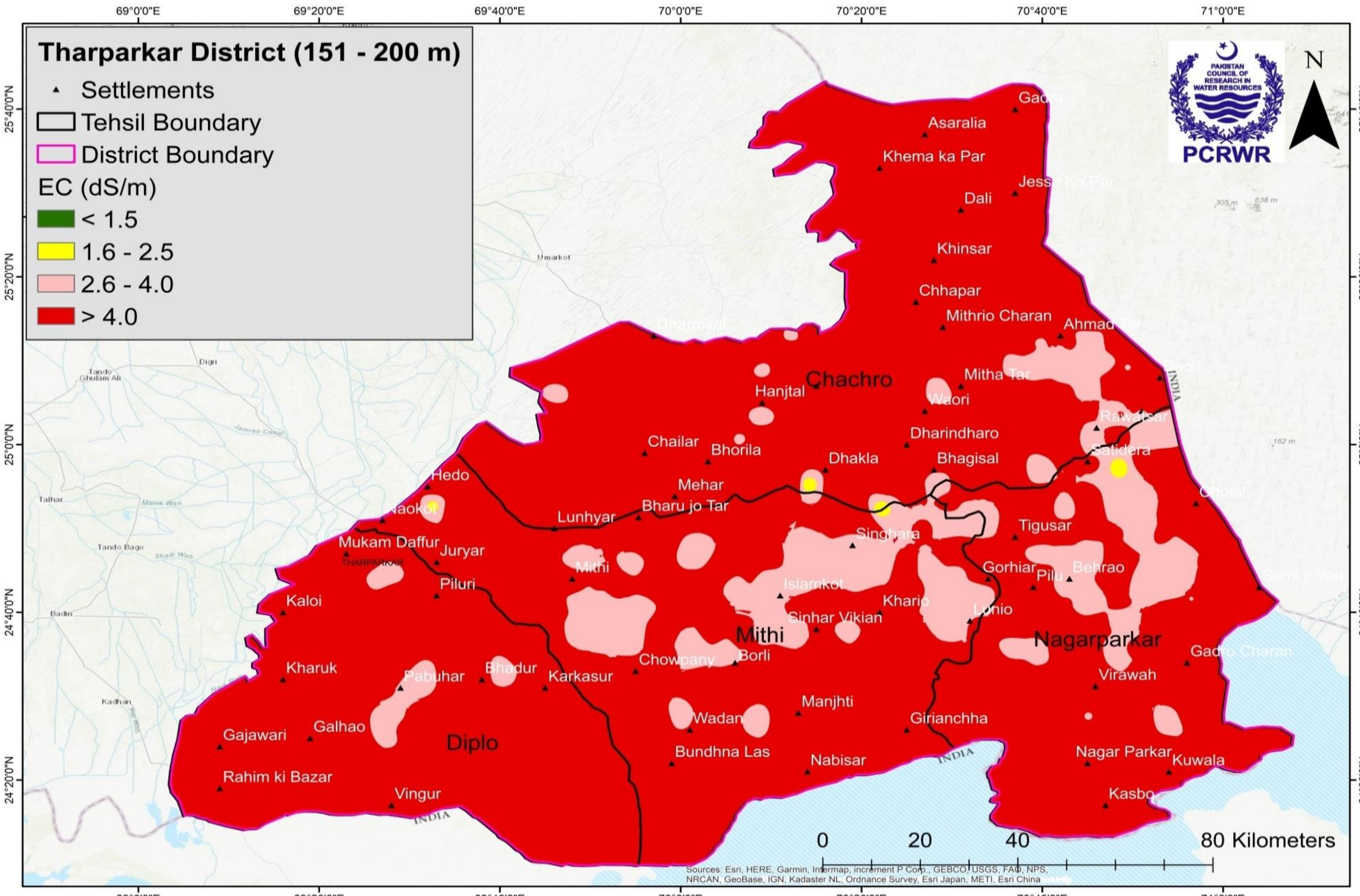

Figure 26: Spatial variations in EC at 200 m depth in Tharparkar

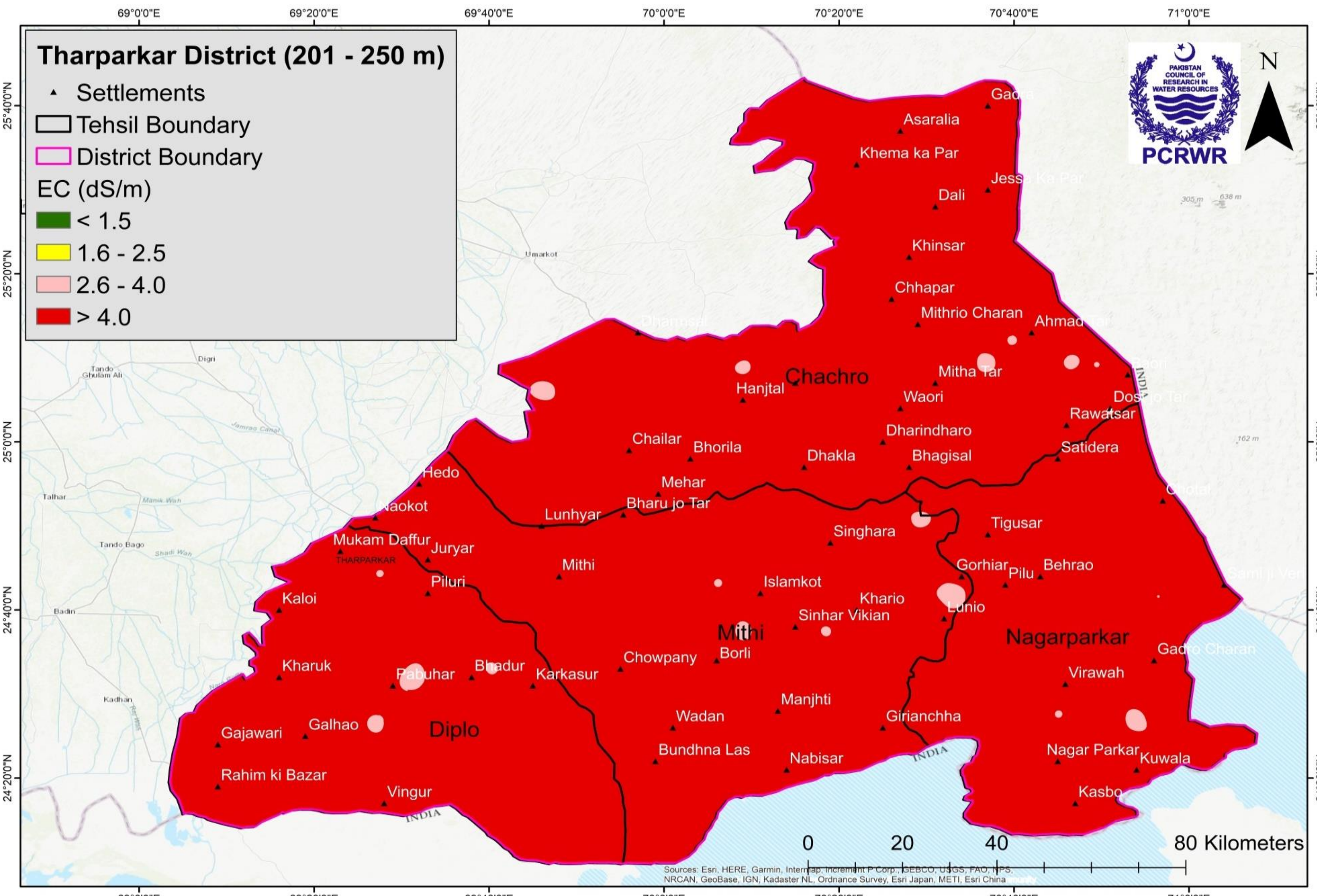

Figure 27: Spatial variations in EC at 250 m depth in Tharparkar

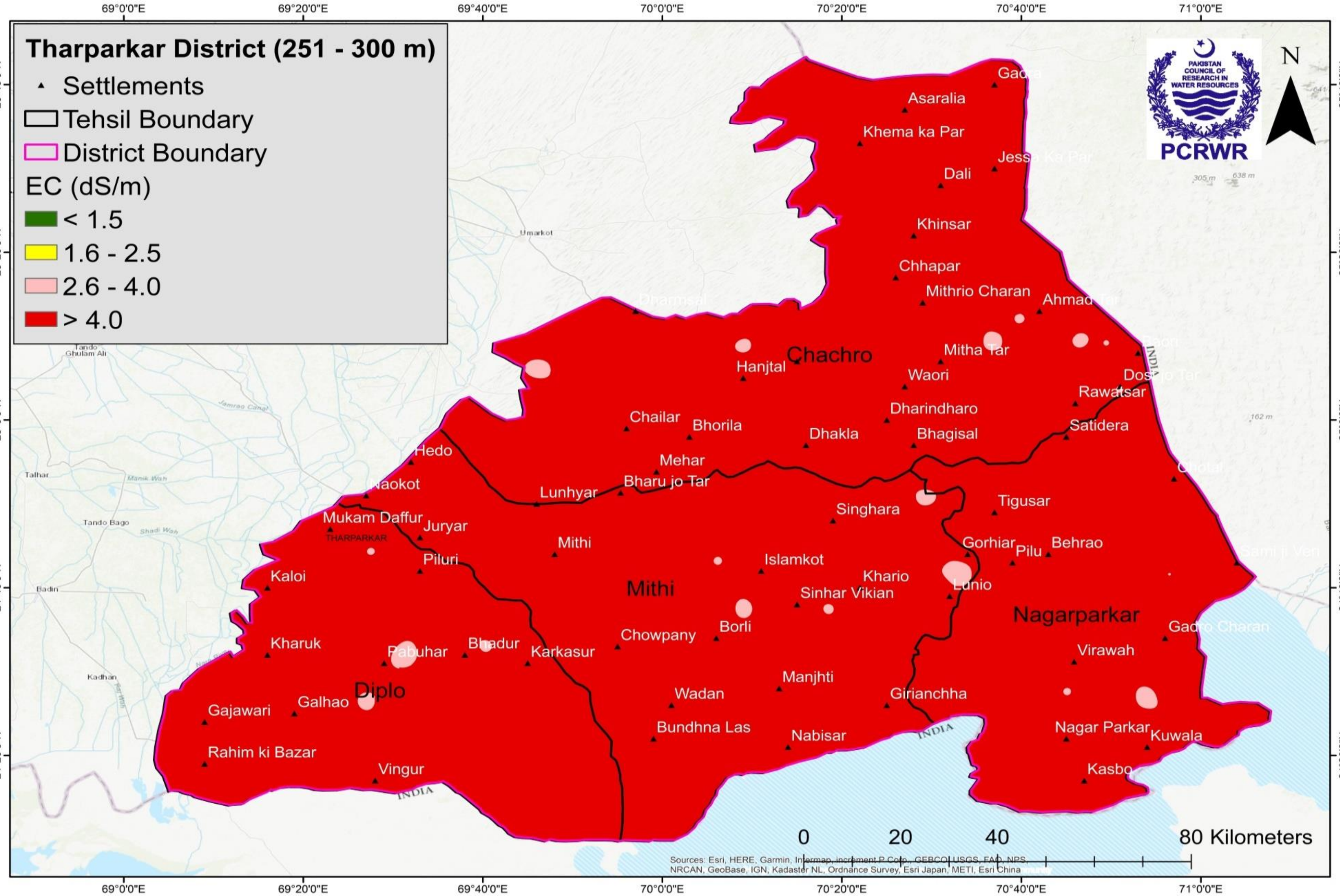

Figure 28: Spatial variations in EC at 300 m depth in Tharparkar

At depths ranging from 101-150 m and 151-200 m, the groundwater quality deteriorates, with 85% and 88%, respectively, being highly saline. Hence, at deeper depths the groundwater quality poses a significant challenge due to its high salinity levels (EC > 4.0 dS/m). The elevated salinity levels in the deep groundwater make it unsuitable for direct human consumption. Moreover, the scarcity of freshwater exacerbates the problem, forcing communities to use the available saline groundwater despite its adverse effects. The groundwater quality from 201 - 300 m depth is highly saline for 99% (19,615 km^2) area. The reason for highly saline groundwater in Tharparkar may be due to region's arid climate, geological characteristics, limited recharge, inadequate water management, and potential impacts of climate change.

Highly saline water can still be utilized for saline agriculture and saline aquaculture purposes. Saline agriculture involves various types of vegetation, including grasses, shrubs, salt tolerant fruit trees and crops that can tolerate and thrive in high salt concentrations (Qureshi and Perry, 2021). By growing these salt-tolerant plants, farmers can make productive use of the saline groundwater and turn it into a resource rather than a limitation. Similarly, highly saline water can also be used successfully for saline aquaculture in this region (Gul *et al.,* 2023). Therefore, the use of saline groundwater under the prevailing conditions can be an alternate source of livelihood.

4. Conclusions and Recommendations

Based on the findings of the study, the major conclusions along with recommendations are summarized as under:

i) Tharparkar predominately comprises sandy soil texture. Sandy soil has high infiltration rate, high porosity and low water holding capacity. The groundwater is deep in tehsil Chachro and shallow in Diplo and Nagarparkar. The reason for shallow depth in Nagarpakar is due to seepages from existing dams and areas closer to the sea and Rann of Kutch area.

ii) The concentration of Arsenic is significantly found in Chachro tehsil, and some parts of Mithi and Diplo. The Fluoride concentration is found in all four tehsils. This may be due to Fluoride bearing mineral in sediments and rocks.

iii) The usable groundwater quality (EC $\leq$ 2.5 dS/m) is found at 25 m depth in southern areas of Diplo, Islamkot and Nagarparkar tehsils which may be used for drinking and irrigation purposes. The groundwater salinity is high at greater depths i.e. more than 100 m.

iv) To address the issue of highly saline groundwater, a comprehensive approach is necessary, involving regular monitoring of groundwater quality, awareness campaigns to educate residents, investments in desalination technologies and efforts to conserve the water through rainwater harvesting and recharging the groundwater aquifers.

v) The shallow hand pumps may be installed in the vicinity of southern areas of Diplo, Islamkot and Nagarparkar tehsils to facilitate the local communities for their domestic, agriculture and livestock needs.

vi) The highly saline groundwater can be used by adopting saline agriculture and saline aquaculture. By utilizing salt-tolerant plants and aquatic species, these practices offer sustainable ways to utilize the available resources and improve the livelihoods of the local communities. Therefore, promotion of saline agriculture and aquaculture in these areas may be taken up on priority basis.

vii) Thar is vast land with abundance of natural resources, flora and fauna, significant biodiversity and a rich cultural heritage. However, due to frequent droughts and lack of proper utilization of the local resources, the area has the highest poverty rate in the province. Therefore, to harness the indigenous resources and promote the socio-economic development of the area, there is a need to establish a Thar Development Authority on the analogy of the Cholistan Development Authority.

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