RESEARCH PAPER

GROUNDWATER QUALITY AND QUANTITY ANALYSIS FOR IRRIGATION PURPOSES IN OKARA, SAHIWAL AND KHANEWAL DISTRICTS OF PUNJAB, PAKISTAN

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ABSTRACT. Irrigated agriculture is the major determinant of economic growth potential as it accounts for 20% of the Gross Domestic Product (GDP) of the country. The current study focuses on the qualitative and quantitative assessment of groundwater in three districts i.e., Okara, Sahiwal and Khanewal of the Punjab province of Pakistan, which are considered highly fertile for agriculture production. The data were acquired from the Punjab Irrigation Department (PID) for 10 years (2010-2020) to assess the spatio-temporal patterns. The spatiotemporal mapping and variability of depth to the water table, electrical conductivity (EC), sodium absorption ratio (SAR), and residual sodium carbonate (RSC) were done as per the standards of the World Health Organization (WHO) and Punjab Irrigation Department using inverse distance weighting (IDW) statistical approach of GIS Techniques. The finding of the study revealed that overall water quality in the study area was reported as "fit" by following the WHO standards, whereas as per Punjab Irrigation Department standards, it was observed, as "Moderately fit". Moreover, in Sahiwal, Okara, and Khanewal districts, the average depth of the water table declined from 2010 to 2015 by 0.619, 1.286, and 0.164 metres and then increased from 2016 to 2020 by 1.698, 1.421 and 0.830 metres, respectively. Although currently the quality and quantity of groundwater were not in critical condition, with continued carelessness and the release of additional water from aquifers, these conditions could deteriorate in the near future. So, developing a suitable mechanism for supplying surface water to farmers, and adapting environmentally acceptable methods of recharging aquifers is much needed.

KEYWORDS: Groundwater, quality and quantity, Irrigation, Geospatial techniques, Pakistan

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INTRODUCTION

Water quality and quantity are both crucial for crop development, agricultural land productivity, and human utilization (Farooq et al. 2019; Butt et al. 2020; Leng et al. 2021). After a crisis arises of surface water resources over time (Shahzad et al. 2020) in Pakistan, approximately 73% of water is supplied to irrigated areas through groundwater (Qureshi 2020). Groundwater is regarded as the most trustworthy alternative source for irrigation, domestic consumption, and industrial uses, particularly in dry and semi-arid countries (Awais et al. 2017). Groundwater was once thought to be safe for use in agriculture, but at that time, both its quality and quantity were vulnerable to being depleted, especially in Pakistan. But occasionally, even after rain and natural disasters like floods, the amount of water grew, but the quality of the water continued to deteriorate and be disrupted (Basharat et al. 2015). Due to population development, industrialization, and inadequate drainage systems, unrestricted and irregular groundwater consumption is depleting the aquifers, which has significant implications for the water table and saltwater intrusion (Ruzikulova et al. 2021; Riaz et al. 2016).

Studies from the past have revealed the ongoing depletion of groundwater in several areas of the Indus Basin, as well as the imbalances between abstraction and recharge (Usman et al. 2015). In Pakistan, excessive groundwater use affects agricultural production and the secondary salinization of deep groundwater (Usman et al. 2012). The physiochemical characteristics of soil and crop productivity are impacted by groundwater quality (Simsek and Gunduz 2007; Kareem et al. 2016). Both natural and artificial activities affect the quality of the water, and the discharge of wastewater into fields has become a significant issue. Poor-quality water can damage the soil's structure and reduce its ability to hold both air and water by displacing calcium and magnesium ions from the soil. As a result, crops suffered from improper growth and damage. The type of water and level of soluble salts decide whether it is suitable for irrigation. For a better knowledge of groundwater quality, scientists have used a variety of chemical indices, such as the Electric Conductivity, Sodium Absorption Ratio, and Residual Sodium Carbonate (Ramesh and Elango 2012; Zara et al. 2015).

Multiple factors are responsible for the degradation of water quality and quantity in the Okara, Sahiwal, and Khanewal districts such as agricultural pollution in which excessive application of fertilizers and pesticides, has resulted in water pollution as these chemicals are carried by runoff into rivers and streams, thereby contaminating water sources. Industries present in these districts also release untreated wastewater into water bodies. Furthermore, the process of rapid urbanization has strained the water supply due to heightened water demand, resulting in overexploitation of groundwater and subsequent aquifer depletion. The influence of climate change is significant as well, with shifting weather patterns causing irregular rainfall and negatively impacting water availability (Basharat and Ata-ur-Rehman 2013). If the annual domestic water demand of a person is taken as 33.5 m^3 then according to the population of Okara, Sahiwal, and Khanewal in the year 2015 that was 2,915,324, 2,414,994, and 730,928, respectively, the corresponding domestic water demand in 2015 for Okara, Sahiwal, and Khanewal was found to be 101.51 MCM, 80.6 MCM, and 24.45 MCM (Khanam et al., 2023). If the population growth rate is considered as 2.03% per year the water demand is increased from 101.507 MCM in 2015 to 167.9 MCM in 2040, 80.66 MCM in 2015 to 133.418 in 2040, and 25.449 MCM to 54.808 in 2015 to 89.810 in 2040 in Okara, Sahiwal, and Khanewal districts (Khanam et al., 2023).

Water demand for agriculture in Okara, Sahiwal, and Khanewal according to the agricultural land cover area was 530.3362, 1713 MCM and 445.308 MCM respectively in 2015 (Shahid et al. 2023). The assessment of water quality, and quantity and its appropriateness for irrigation purposes is a vital aspect of water management. For this purpose, GIS is a suitable technology. Its inverse distance weighted (IDW) interpolation, ordinary kriging, overlay analysis, and Geostatistical (Awais 2017) techniques are widely used for detecting the suitability of groundwater for irrigation purposes. Since mapping based on IDW is a recent breakthrough for verifying water quality and quantity for irrigation, economic growth must understand trends in water level and quality, as well as the accompanying patterns of change across time and geography. To assess the spatiotemporal fluctuations of groundwater level, mineralization, and soil salinity in irrigated areas of Uzbekistan's Syrdarya Province, maps were made using IDW techniques in GIS (Kulmatov et al. 2022). To understand the spatiotemporal distribution of fluctuations in groundwater quality and level, many studies have used Geostatistical and IDW approaches.

For irrigation reasons, it is currently necessary to offer a visual depiction of groundwater quality and quantity that can assess the scope of the issue and help us conserve water for the future (Elci and Polat 2011). There isn't much information available or published in Pakistan that focuses on the quantity and quality of groundwater for irrigation. In the districts of Okara, Sahiwal, and Khanewal, there has not been any research on the spatiotemporal fluctuations of groundwater using IDW and geo statistics. The main objectives of this study are 1. Mapping of individual groundwater irrigation parameters to assess the spatial distribution across the study region. 2. Quantification and spatial distribution of Groundwater quantity using geospatial techniques 3. Assessment of spatio-temporal variability of groundwater quantity and quality over '6-10 years' time span.

MATERIALS AND METHOD

Study Area

Khanewal, Sahiwal, and Okara districts were selected as study areas for this research (Figure 1). These districts are located in the southeast of Punjab, Pakistan. The Sahiwal, Khanewal, and Okara districts, with corresponding latitudinal extents of 30°.66'82"N, 30°.28'64"N, and 30°.81'38"N, and longitudinal extents of 73°.11'14" E, 71°.93'20"E, and 73°.45'34"E, covering 3224.2 sq. km, 4367.5 sq. km, and 4413.0 sq. km of area, respectively. Most of the Okara, Sahiwal and Khanewal districts fall in the command areas of the Lower Bari Doab Canal (LBDC) irrigation system which is the second-largest irrigation system in Punjab. The climate in these areas is semiarid. The coldest months are December through February when temperature usually drops to 2°C. Whereas, the hottest months are May, June and July, when temperature often reaches up to 50°C. The average rainfall in this region is about 2000 mm importantly, the 2010 mighty flood in the study area led to an increase in groundwater levels in aquifers.

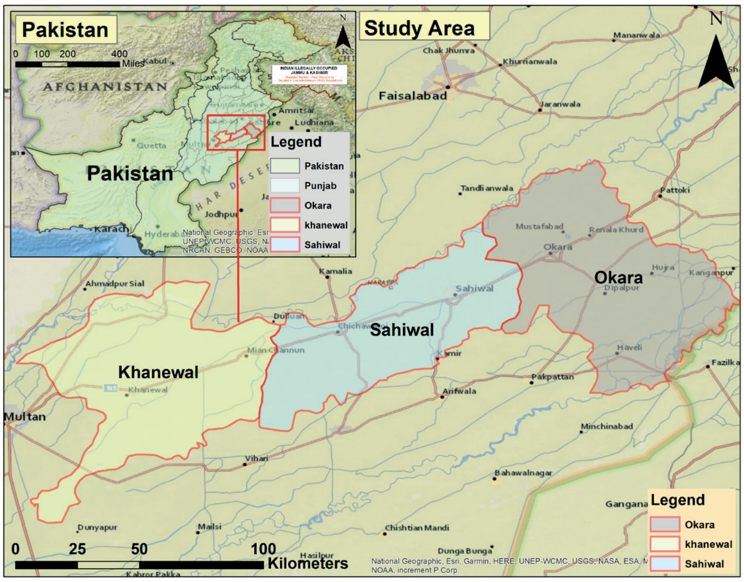

Fig. 1. Location of the study area (Okara, Sahiwal and Khanewal districts)

Data and its Sources

Three quality measures, including EC, SAR, and RSC, (Figure 2) are typically used to represent the water quality of groundwater for irrigation purposes in this study (Arshad and Shakoor 2017). Water quality of groundwater data for the years 2015 and 2020 and water quantity of groundwater data for the years 2010, 2015, 2016, and 2020 were collected from the Punjab Irrigation Department (PID). Water quality and water quantity data of groundwater were further classified as per WHO and Pakistan Council of Research in Water Resources (PCRWR) standards.

Data Processing

Geospatial and geostatistical techniques were used for spatial analysis (Nasar-u-Minallah et al. 2023) and mapping of water quality and quantity of groundwater for selected districts of Punjab Pakistan. The groundwater data was initially processed and refined to rectify the existing errors (Kareem et al. 2016; Farooq et al. 2019). A geostatistical analysis using IDW (Fatima et al., 2023) was performed which is shown in Figure 3. The spatial water quality mapping for EC, SAR, and RSC was prepared and classified into three categories as presented in the results sections. To employ discrete raster maps with a single integer value for overlay analysis, the categorized maps were reclassified (Sahar et al. 2013) using the raster overlay approach. The highest value was assigned to the class that was least favourable or unsuitable, and the lowest value was assigned to the class that was most favourable for irrigation purposes. Similarly, reclassification was carried out for water quantification. To compute the area, beneath each class, raster surfaces were created using "Raster to Polygon" (Nasar-u-Minallah et al. 2021).

Data Analysis

Toxicity, alkalinity, salinity, and sodicity are the four major problems associated with poor groundwater quality. The water quality parameters used herein are EC, SAR, and RSC, and the water quality standards of the World Health Organization and Punjab Irrigation Department are adopted to classify the irrigation water quality. The spatial and temporal changes in the groundwater levels are intended for the sustainable development of water resources (Butt et al. 2020). Geospatial techniques have been an important approach for groundwater management studies in recent years. Spatial analysis tools in the geographical information system (GIS) were used to study the spatiotemporal variation of groundwater over 10 years for water quantity, whereas changes in water quality were assessed from 2014 to 2020.

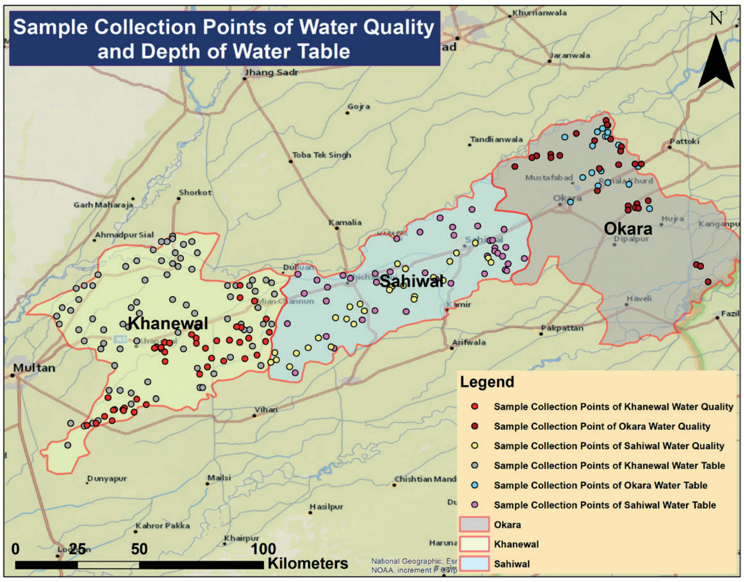

Fig. 2. Locations of the sample collection points of selected districts

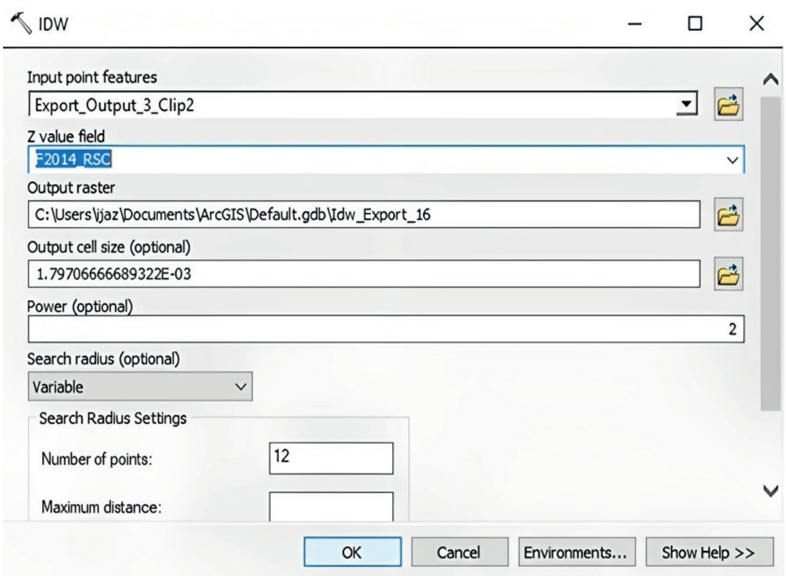

Fig. 3. "IDW" tool for interpolation of the points

With the help of the inverse distance weighted approach, the data were spatially interpolated (Fatima et al. 2023). The inverse distance weighted interpolation technique was used because the collected data was limited to a larger extent and this method is recommended and suggested for such types of data sets and studies (Kumar et al. 2018). Among all interpolation methods, including kriging, natural neighbour, spline, and trend, inverse distance weighted is the most straightforward as it has the advantage of being relatively simple to define and, hence, simple to grasp the outcomes. Figure 4 illustrates the whole methodology of performed research comprehensively.

Accuracy Assessment

Out of the total field samples for water quality and water quantity data of groundwater, 20% of samples were considered for validation and not incorporated in the analysis. These validation points were overplayed with the water quality and water quantity maps for accuracy assessment.

RESULTS AND DISCUSSION

Spatial Distribution of Groundwater Quality Parameters

The WHO groundwater quality standards for EC and SAR parameters demonstrate that the water quality in Khanewal is suitable for irrigation because the majority of the region falls under the low category and just a tiny section of the territory falls under the moderate category. In the Khanewal district, the RSC criteria for water quality exceed the severe (unfit) level, rendering the water unfit for agriculture. All three parameters (RSC, EC, and SAR) are within a tolerable range, indicating satisfactory water quality in Sahiwal. Sahiwal district relies heavily on irrigation. The Okara district's water quality falls into the low category for SAR, EC, and RSC parameters, meaning it is also suitable for growing crops and poses no risks to irrigated land. The results of different indicators are detailed below.

Electrical Conductivity (EC): Electrical conductivity is an incredibly significant parameter for determining the quality of groundwater. The evaluation or quantification of groundwater's EC content is crucial. According to WHO standards, a level of EC (dc/m) less than 1.5 is recommended for irrigation purposes. If the EC level is between 1.5 and 3, some crops can tolerate it, but not others. More than 3 is considered a severe level of EC, making it inappropriate for any type of agricultural or irrigation use. The EC concentration according to the WHO standards in Sahiwal district has not undergone any appreciable alteration throughout time. The overall area at low elevation is the same for both 2014 and 2020 i.e. 2834 sq. km, while the overall area at moderate elevation is also the same for both years i.e. 391 sq. km (Figure 5a, b). In Okara district, the area classified in the low class has decreased from 4384 sq. km to 4376 sq. km over a period i.e. 2014-2020 and the area classified as an intermediate class increased from 29 37 sq. km in this period. Okara's spatial distribution mapping reveals that the majority of the region contains high-quality water that is appropriate for agriculture (Figure 5c, d), whereas, In Khanewal, the region with suitable water quality expanded from 4034 sq. km to 4048 sq. km from 2014-2020 as a result of the water's EC level being maintained and improving over time, while the moderate zone shrank from 334 sq. km in 2014 to 319 sq. km in 2020 (Figure 5e, f).

Sodium Absorption Ratio (SAR): The sodium adsorption ratio illustrates the risk of sodium. The SAR estimation is used to determine whether water is acceptable for an irrigation system as this parameter measures how much sodium is taken up by the soil. SAR results are graded as suitable (10), moderately suitable (10–18), and not suitable (>18) by WHO standards. According to the WHO standards, the low-level zone in Sahiwal increased from 3210 sq. km of the area in 2014 to 3221 sq. km of the area in 2020. The moderate quality zone in Sahiwal was reduced from 14 sq. km of the area in 2014 to 4 sq. km of the area in 2020 (Figure 6a, b). SAR is stable in groundwater for irrigation purposes in the district of Okara (Figure 6c, d). The moderate quality zone in Khanewal increased from 1 sq. km of area in 2014 to 8 sq. km of area in 2020. The area under the low category of Khanewal is the same in the years 2014 and 2020. There is no change to be detected between 2014 and 2020 (Figure 6e, f).

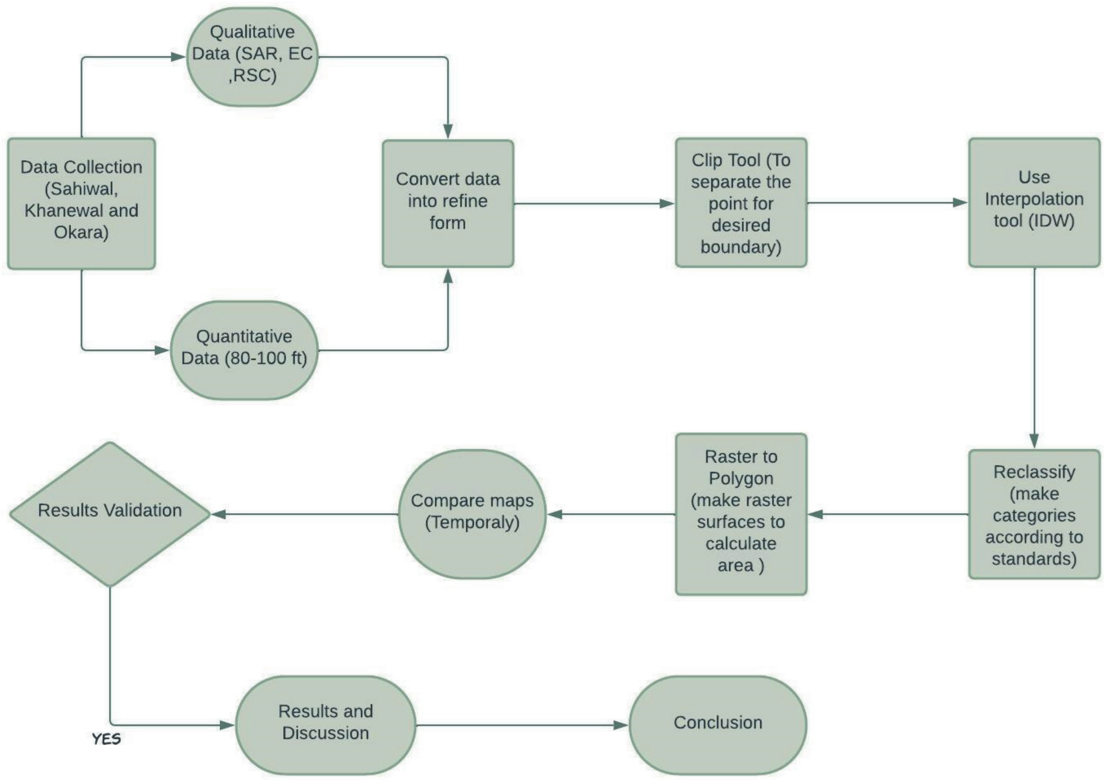

Fig. 4. The flowchart of the Research Methodology

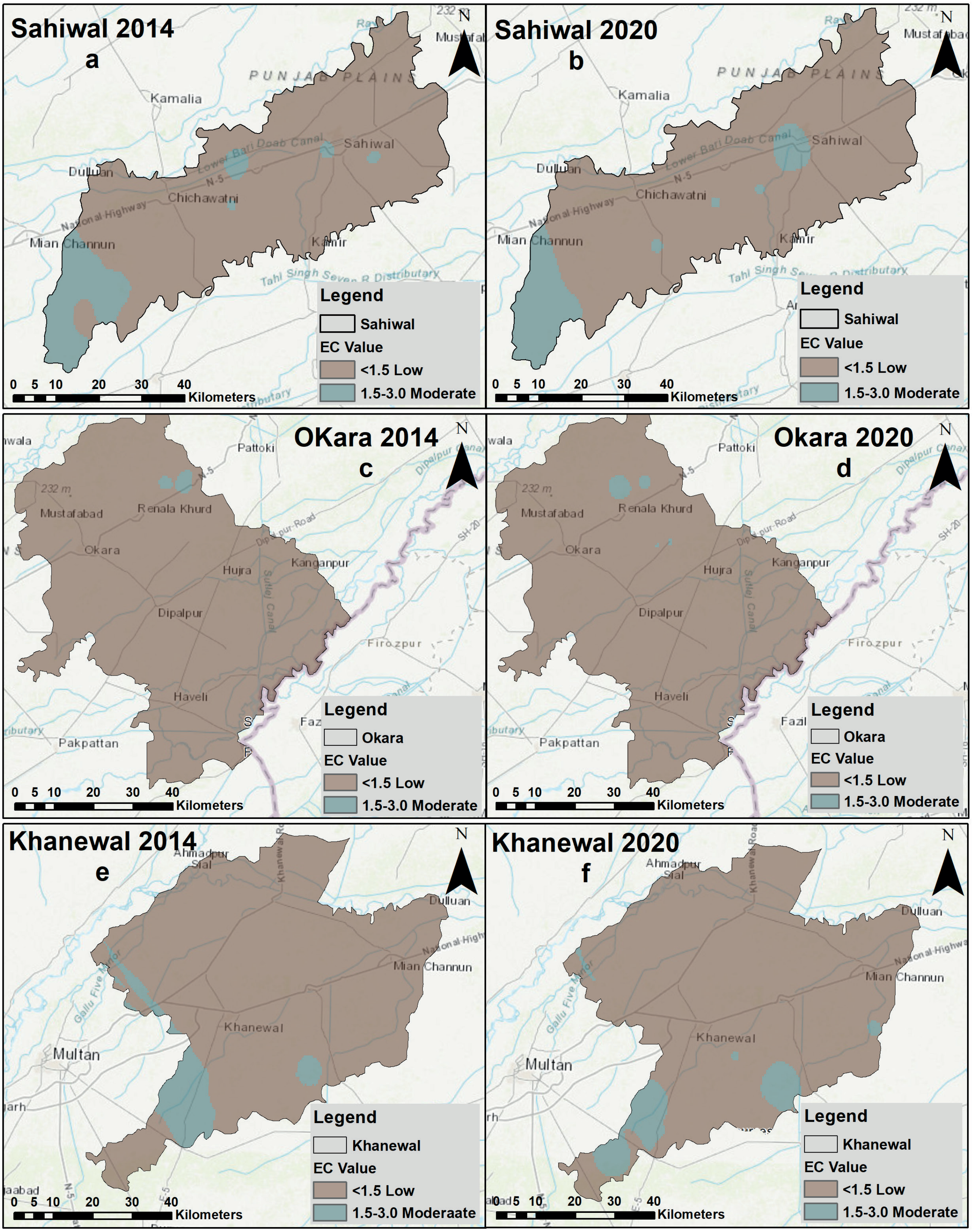

Fig. 5. The Concentration of EC (WHO Standards) in Groundwater of Sahiwal (a, b), Okara (c, d), and Khanewal (e, f) districts.

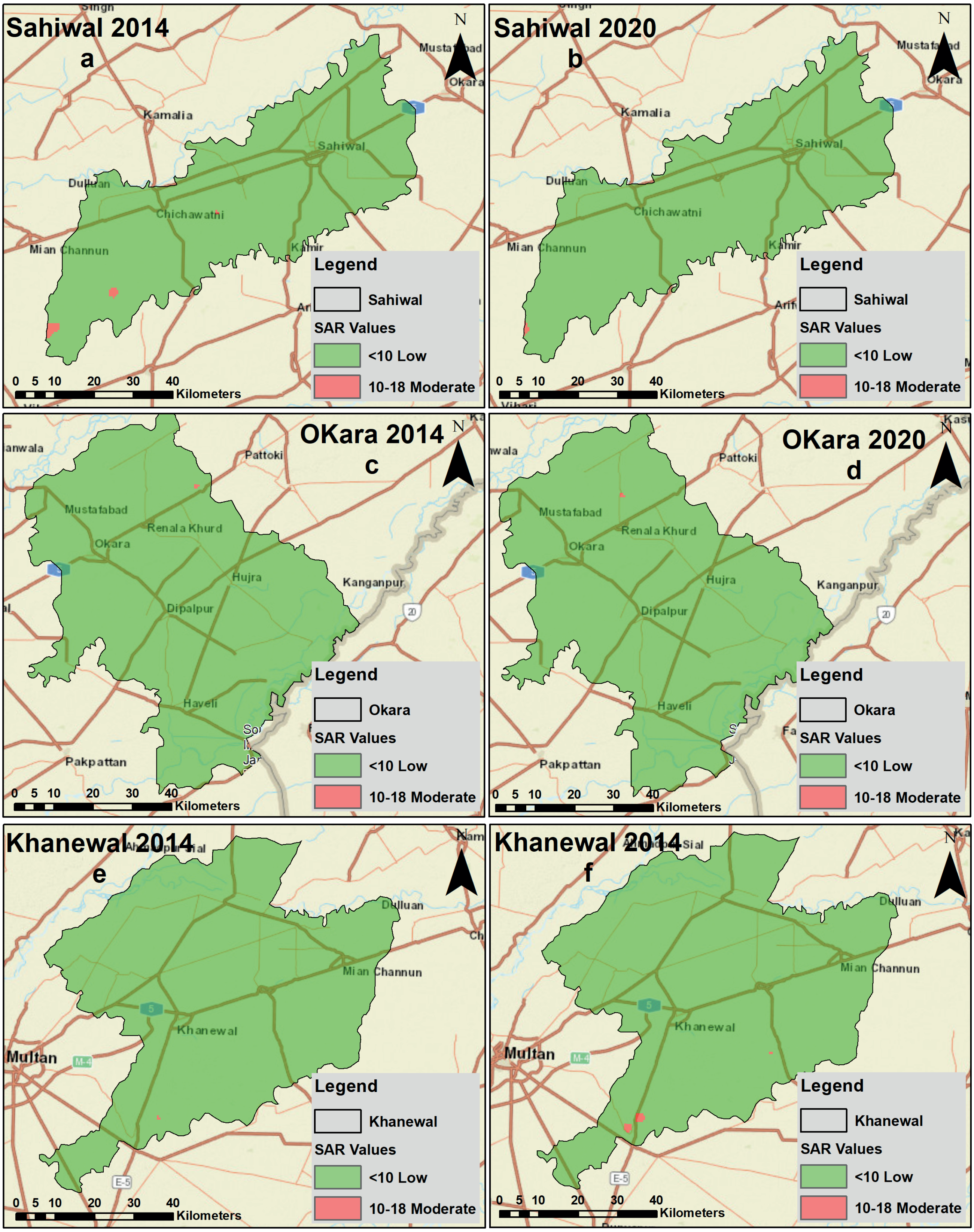

Fig. 6. The Concentration of SAR (WHO standard) in Groundwater of Sahiwal (a, b), Okara (c, d), and Khanewal (e, f) districts

AS per PID, classification is as follows; good (0–6), moderate (6–8), or poor (>10) for irrigation purposes. According to the PID standards, the spatio-temporal distribution of the SAR describes that good water quality area with no hazard to irrigation declined in Sahiwal, Khanewal, and Okara from 977 sq. km, 2996 sq. km, 4140 Sq. Km in 2014 to 424 sq. km, 1464 sq. km, and 1344 sq. km in 2020, respectively. While the moderate water quality area increased from 2233, 1371, and 272 Sq. Km on 2014 to 2797, 2895, 3068 Sq. Km in 2020 (Figure 7). The unsuitable water quality area under the severe category also moved toward declination from 14 sq. km in 2014 to 4 sq. km in 2020 in Sahiwal, which shows the level of SAR (mg/L) has been improved within the study period (Figure 7a, b). The area under the severe category has been the same for district Okara between 2014 and 2020 (Figure 7c, d). In the Khanewal district, the unsuitable water quality area under study has been increased from 1 sq. km in 2014 to 8 sq. km in 2020. This variation shows water quality moving toward an unsuitable level over time (Figure 7e, f).

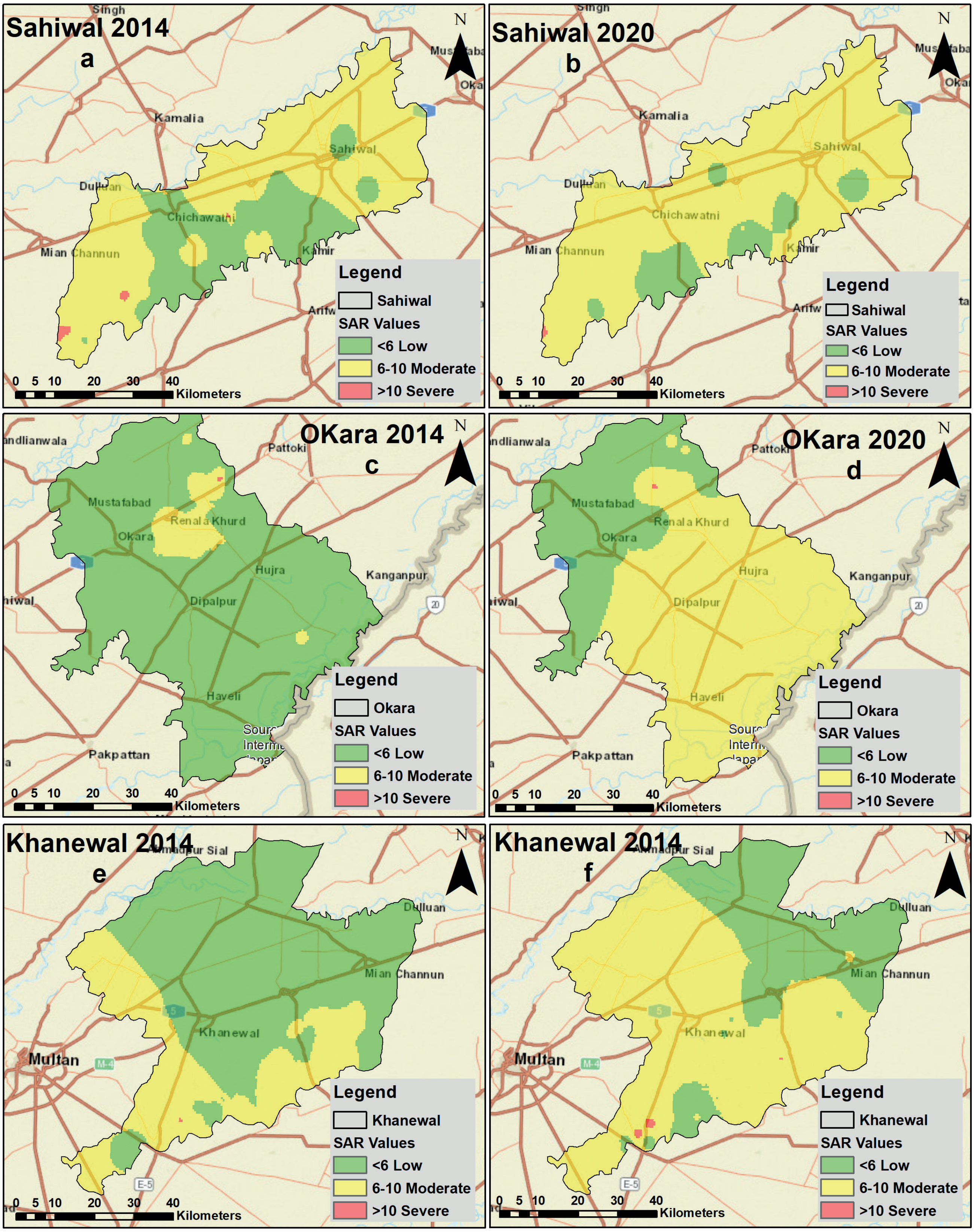

Fig. 7. The Concentration of SAR (PID Standard) in Groundwater of Sahiwal (a, b), Okara (c, d), and Khanewal (e, f) districts

Residual Sodium Carbonate (RSC): RSC variable is used to measure the water's bicarbonate content. The natural material degrades when the pH of the water is raised due to a high bicarbonate concentration. Calcium and magnesium are prone to falling into the water with high RSC estimates, which can raise the sodium content of debris. As per WHO, RSC is classified as; good (2.5), marginal (2.5–5.0), and not good (>5.0). In Sahiwal, the area under the low category increased from 3085 sq. km in 2014 to 3176 sq. km in 2020, and under the moderate category, reduced from 140 sq. km in 2014 to 48 sq. km in 2020 (Figure 8a, b). In 2020, some parts of Khanewal (4 sq. km) fall under the severe category, while the lower category has an extent of 3934 sq. km, as compared to 2014, which has an extent of 3654 sq. km. So the area under moderate level is reduced from 713 sq. km to 430 sq. km (Figure 8e, f).

According to Punjab Irrigation Department (PID) standards RSC (meq/L) is categorized as; good (0–1.25), moderate (1.25-2.5), and poor (>2.5). The visual representation shows that water quality improves within the study period. A remarkable change can be detected in Sahiwal district, which had a moderate zone of 1132 sq.

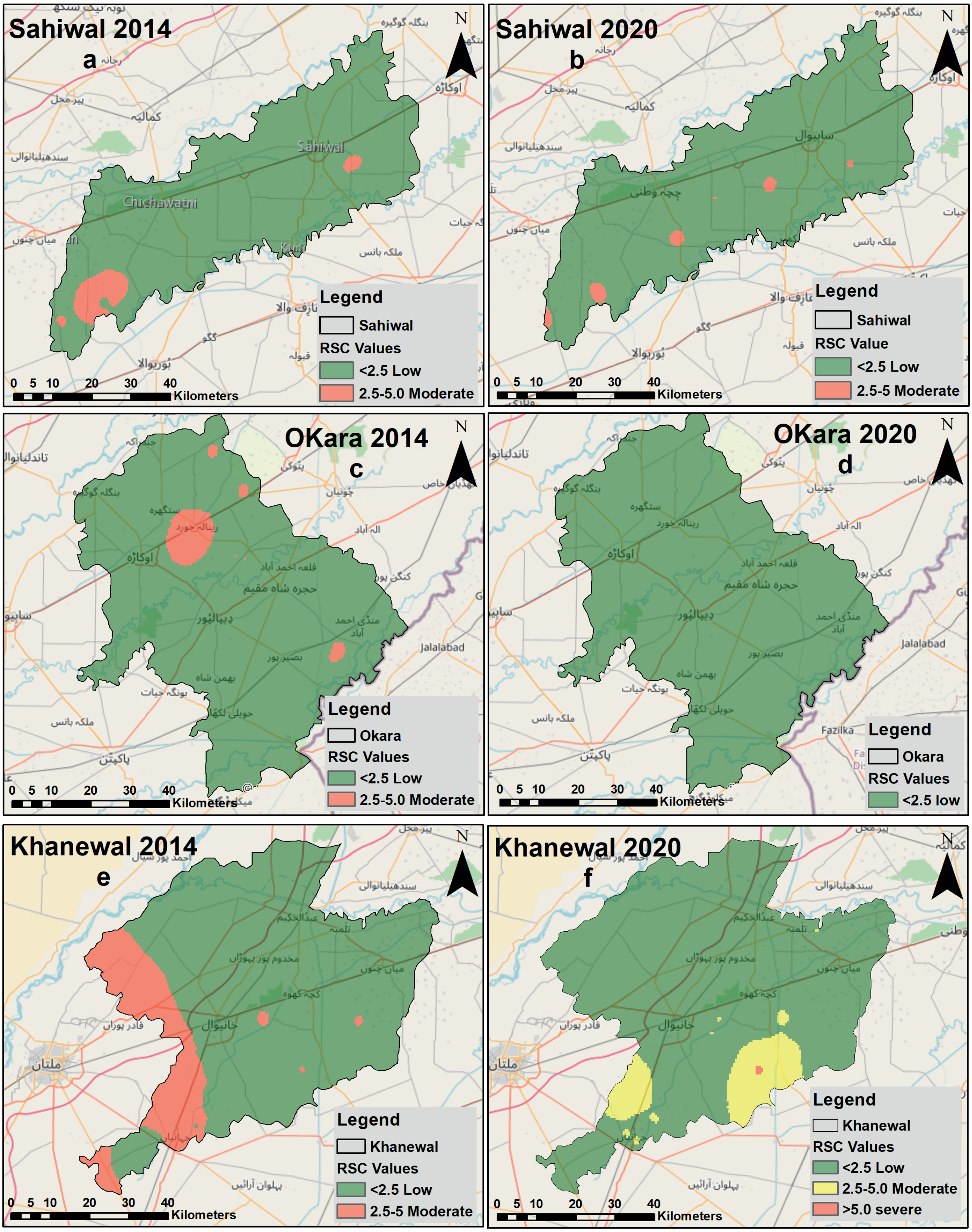

Fig. 8. The Concentration of RSC (WHO standard) in Groundwater of Sahiwal (a, b), Okara (c, d), and Khanewal (e, f) districts

km area in 2014 to 2353 sq. km area in 2020, while a severe zone decreased over time from 140 sq. km in 2014 to 40 sq. km in 2020. The low-quality zone area changed from 1953 sq. km in 2014 to 823 sq. km in 2020 (Figure 9a, b). According to the district Okara map (Figure 9c, d), water quality with the RSC parameter also improved over time. In 2014, 4247 sq. km of the area was under the low category and 166 sq. km area under the moderate level but in 2020 all areas the low category. The variation of SAR over Okara district (Figure 9c, d) elaborates that the best water quality zone for irrigation purposes falls (646 to 292 sq. km) and the moderate zone rises (3,605 to 4121 sq. km). The visual representation of Sodium Residual Carbonate in Khanewal revealed that the best water quality zone increased from 978 sq. km in 2014 to 1934 sq. km in 2020, the moderate water quality zone was reduced from 2676 sq. km to 2142 sq. km, and the highly vulnerable water quality zone dropped from 713 sq. km in 2014 to 291 sq. km in 2020 (Figure 9e, f).

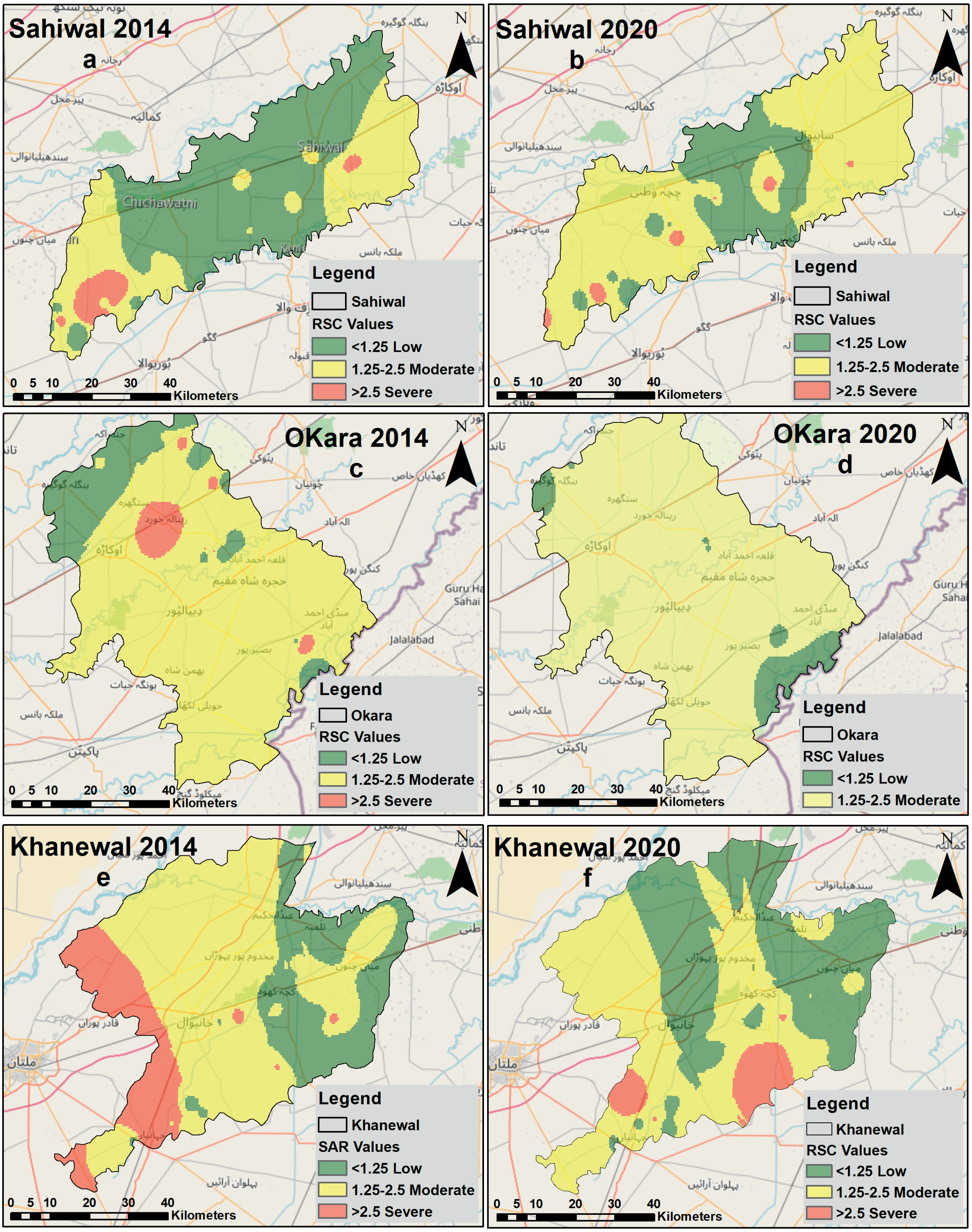

Fig. 9. The Concentration of RSC (PID standard) in groundwater of Sahiwal (a, b), Okara (c, d), and Khanewal (e, f) districts

Monitoring of Water Quantity

District Okara: Water table mapping illustrates how the water table has declined from 2010 to 2020 (Figure 10) in the Okara district. The southeast region of the study area has witnessed a significant decline in the water table as a larger portion has shifted to 6.1-7.6 meters (20-25 feet) class in 2020 where water was available below 6.1 meters (20 feet) in 2010. Similarly Northeast region has also experienced a declining trend as the water table drops up to 9.1 meters (30 feet) in the year 2020. There are four classes for a better understanding of the water table. In Okara, the area covered in the 1st, 2nd, 3rd, and 4th classes of 2010 was 1384 sq. km, 2030 sq. km, 815 sq. km, and 184 sq. km. In 2015, the area was 3099 sq. km, 611 sq. km, 639 sq. km, and 63 sq. km, while in 2016, the area was 1416 sq. km, 1384 sq. km, 1610 sq. km, and 3 sq. km, which changed to 457 sq. km, 2290 sq. km, and 1720 sq. km in 2020 (Figure 10).

District Sahiwal: Sahiwal district experienced a mixed trend in terms of the water table in 2015, some regions' water depth improved, but in 2020 a significant decline

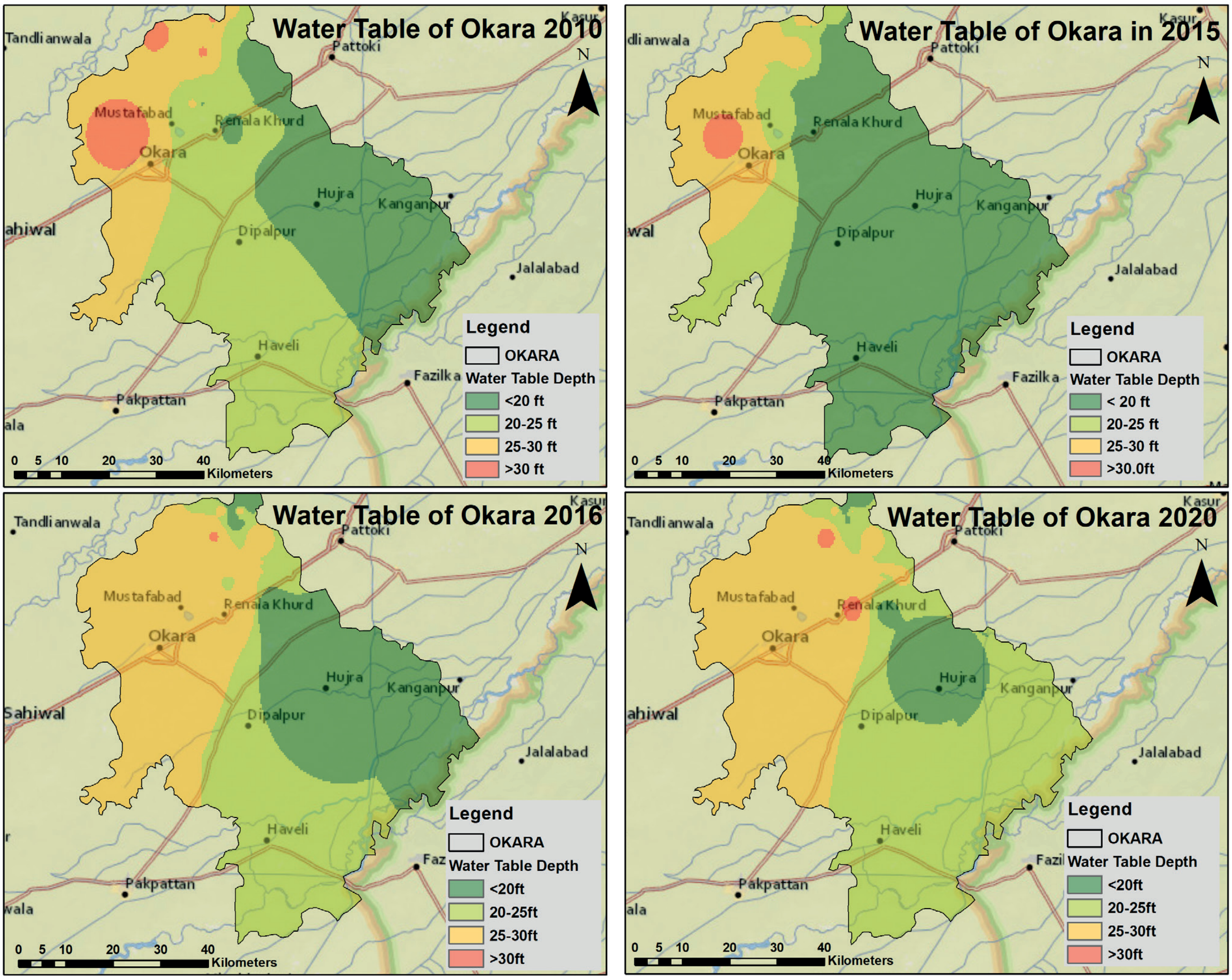

Fig. 10. Water Table Depth of Okara district from 2010-2015 & 2016-2020

in the water table was observed specifically in the north-west and south-west of the district (Figure 11). According to the classification of Sahiwal (Figure 11) and the area covered under it, in the first category, 122 sq. km of the area was covered in 2010, 181 sq. km in 2015, 709 sq. km in 2016, and 175 sq. km in 2020. 1441 sq. km of the area were covered in 2010, 1629 sq. km in 2015, 1401 sq. km in 2016, and 756 sq. km in 2020 under the second category. In the third category, 1189 sq. km of the area was covered in 2010, which was reduced to 639 sq. km in 2015, then increased to 951 sq. km in 2016 and 1679 sq. km in 2020. The fourth category shows that 473 sq. km of the area was covered in 2010, which was reduced to 144 sq. km in 2015, and 163 sq. km of area in 2010, which suddenly increased to 614 sq. km in 2020. This variation shows that the water table declined from 2016 to 2020 during drought conditions.

District Khanewal: Almost the same pattern has been observed for Khanewal district, where south-east and south-west regions undergone in decline from 2010 to 2020 (Figure 12). Five classes of different depths covering different areas are shown on the map of Khanewal (Figure 12). In the first class, 381 sq. km of the area was covered in 2010, which increased to 451 sq. km in 2015. 217 sq. km of the area was covered in 2016, which declined to 144 sq. km in 2020. In the second class, 560 sq. km of the area was covered in 2010, compared to 633 sq. km in 2015. 887 sq. km of the area were covered in 2016, compared to 794 sq. km in 2020. In the third class, 585 sq. km of the area was covered, which was reduced to 533 sq. km in 2015. 963 sq. km were covered in 2016, which decreased to 877 sq. km in 2020. In the fourth class, 1505 sq. km of the area was covered in 2010, which was reduced to 1497 sq. km in 2015. 1480 sq. km of the area was covered in 2010, which declined to 912 sq. km in 2020. In the fifth class, 1334 sq. km of the area was covered in 2010 as compared to 1254 sq. km in 2015. 821 sq. km of the area was covered as compared to 1670 sq. km in 2020.

Figure 13 illustrates the overall water table trend in three districts. Almost the same pattern exists in all districts over a one-decade period (2010-2020). As is well known, Pakistan had floods during 2015-2016, which led to the improvement of the water table this duration. Between 2010 and 2015, the water table's depth dropped, indicating an improvement in the water level during that time. This is mostly because the 2014 flood significantly replenished the aquifer in the Khanewal and Sahiwal regions (Ashraf, 2023). In contrast, the years 2016 to 2020 saw relatively little rainfall, which allowed for enough groundwater extraction to meet the needs of agriculture during this time.

VALIDATION OF RESULTS

Reclassified maps for both water quantity and quality for each year were validated with the field validation points. It was observed that classification ranges of both water quality and quantity are aligned and found consistent with the validation points as illustrated in Figures 14 and 15 respectively. The Punjab Irrigation Department has also verified the findings of this study.

DISCUSSION

The study's primary goal was to precisely map the quantity and quality of groundwater available for irrigation. Following the specific requirements, the quality of groundwater influences its usefulness for various

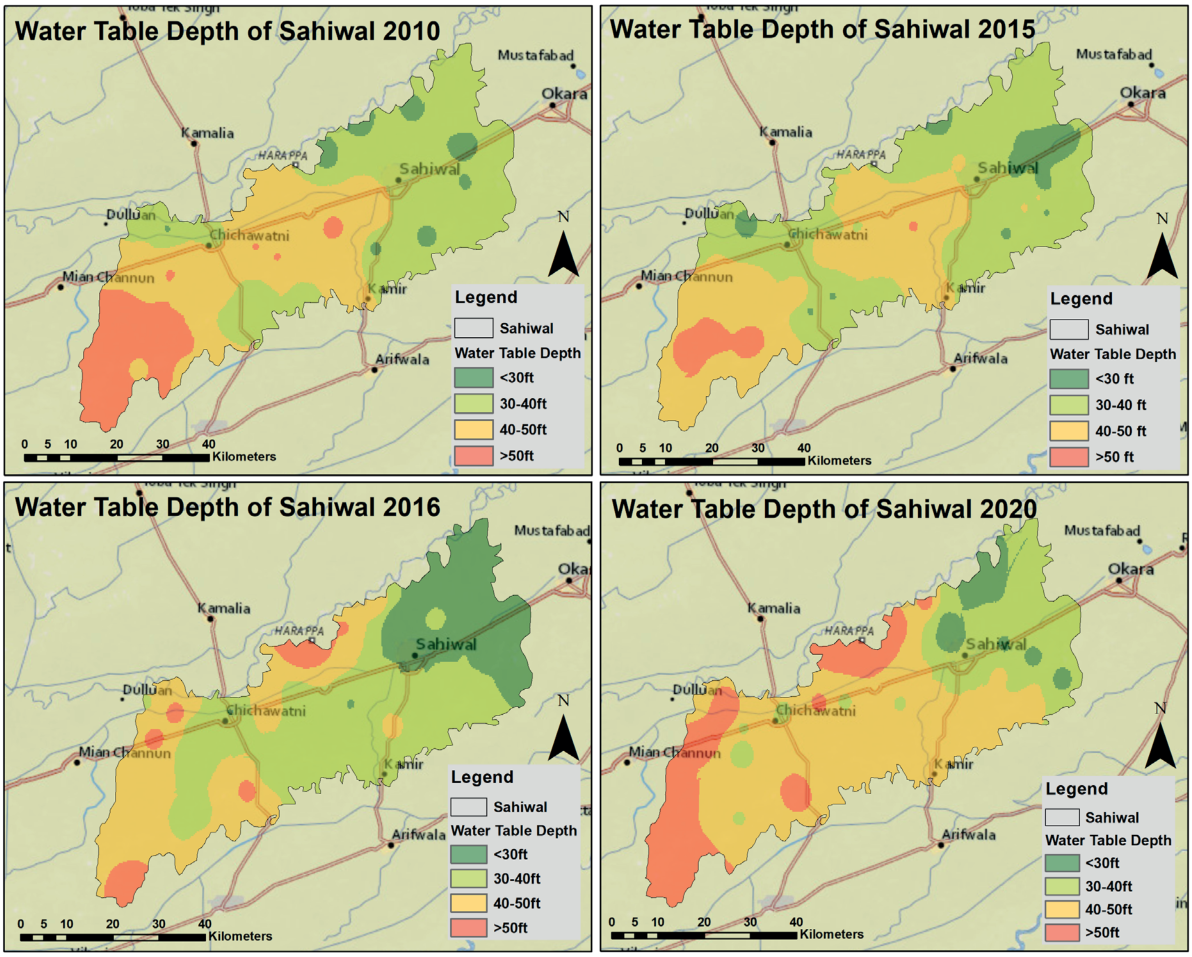

Fig. 11. Water Table Depth of Sahiwal District from 2010-2015 & 2016-2020

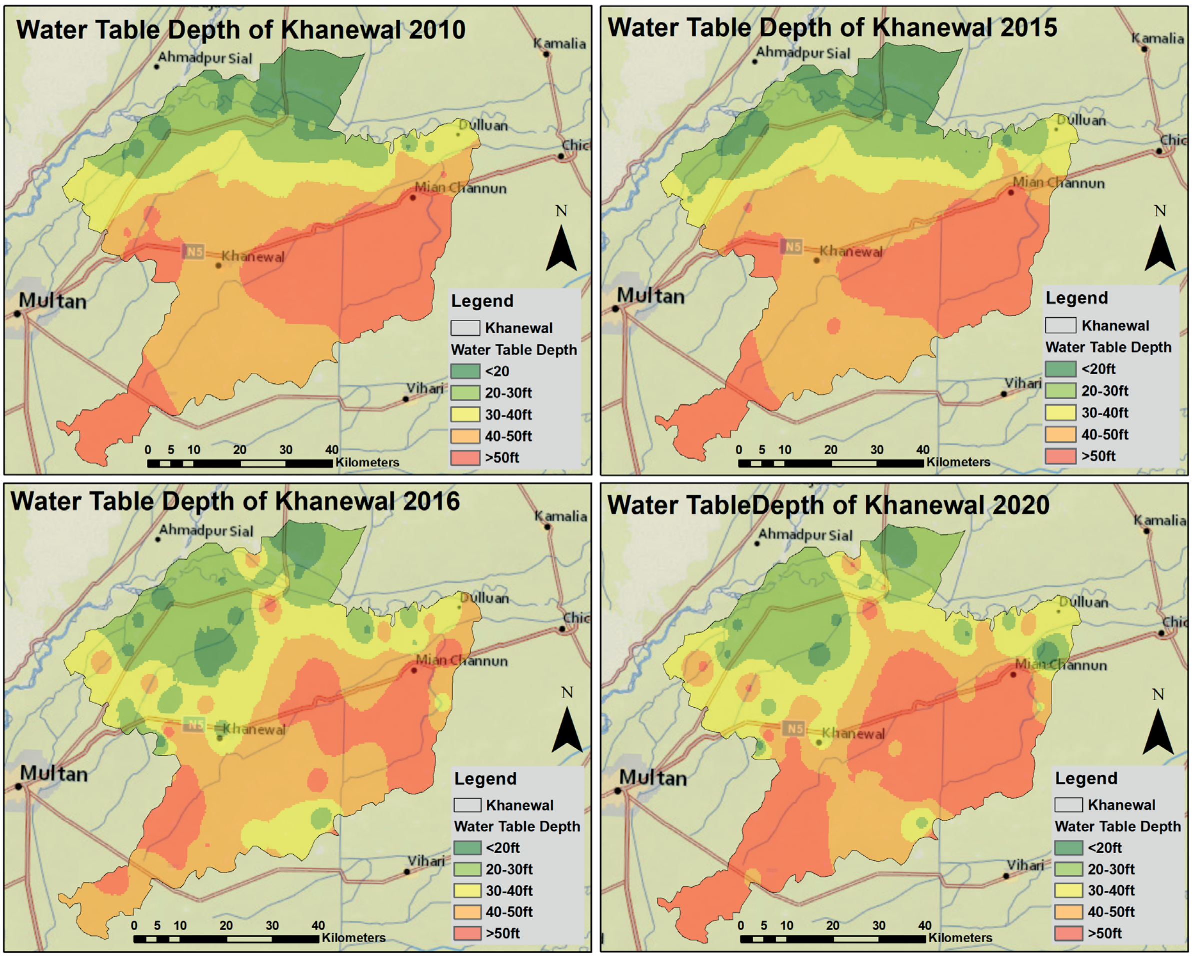

Fig. 12. Water Table Depth of Khanewal District from 2010-2015 & 2016-2020

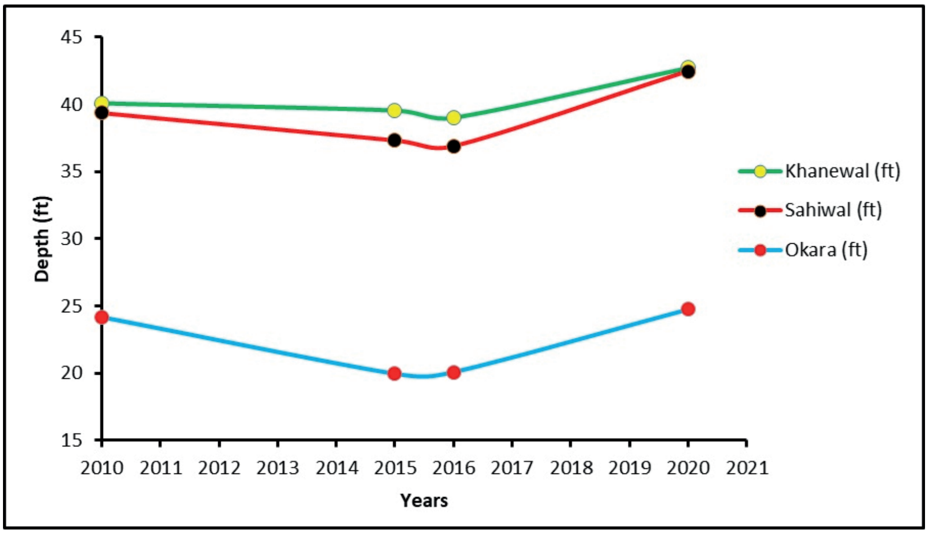

Fig. 13. Variations in water table depth of Okara, Sahiwal, & Khanewal districts

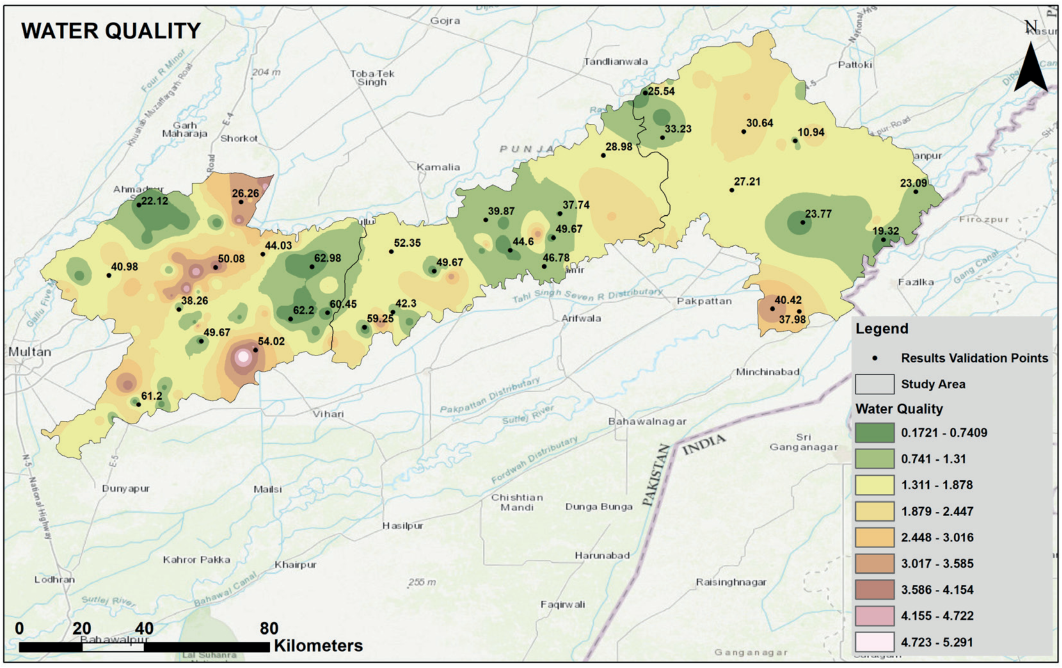

Fig. 14. Sample sites of water quality for the validation of results

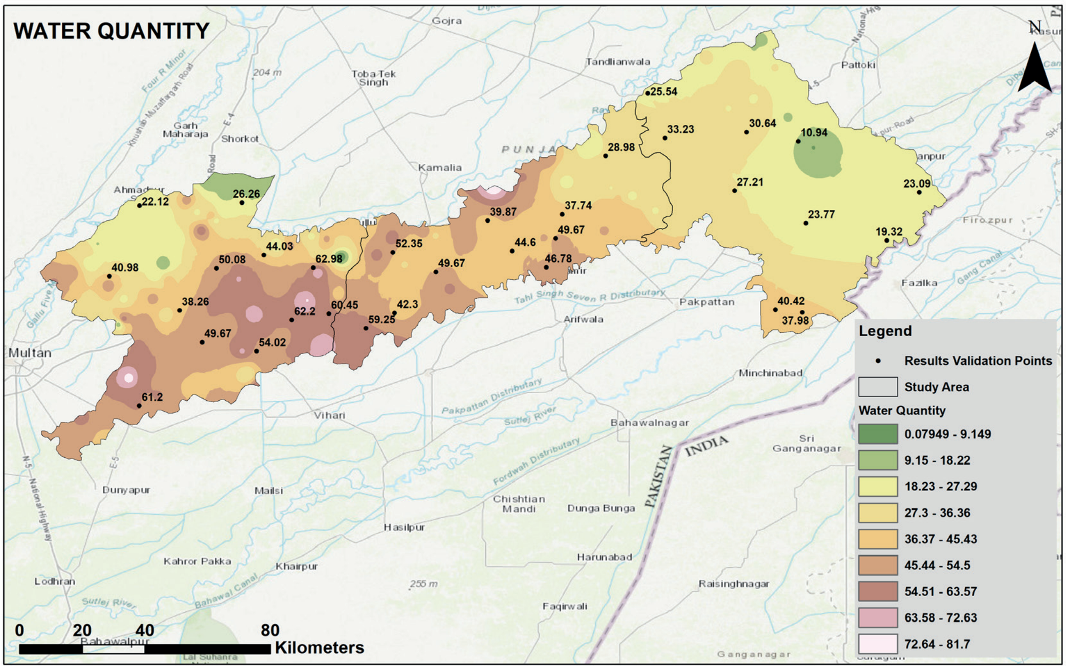

Fig. 15. Sample sites of water quantity for the validation of results

applications. For the objectives of this study, three quality measures—EC, SAR, and RSC—are commonly utilized to depict the water quality of groundwater for irrigation. When identifying irrigation water types, Electrical Conductivity is crucial. The ability of water to transport current is referred to as the concept of conductivity (Riaz et al. 2018). Plants cannot survive in highly salinized water, which also poses a risk to human health (Borecka et al. 2016). Typically, EC is used to measure water salinity. A "physiological" drought may occur when there are high salt concentrations in the soil. Osmotic pressure in soil solution is caused by high salt concentration in irrigation water (Thorne and Peterson 1954). In addition to directly affecting plant growth, salts also have an impact on soil structure, permeability, aeration, texture, and hardness (Trivedy and Geol 1984). In other words, even when it appears that the field has enough moisture, the plants begin to wilt because the roots can no longer absorb the water (Isbell 2016).

The variation in EC is primarily attributed to geochemical processes like ion exchange, reverse exchange, evaporation, silicate weathering, rock water interaction, and sulphate reduction and oxidation processes (Ramesh 2008) as well as anthropogenic activities like application of prevailing agrochemicals in the area (Ramesh & Elango 2012). The study's findings demonstrate that the EC concentration in the Sahiwal district has not significantly changed over time when compared to WHO criteria. Okara's geographical distribution mapping demonstrates that the majority of the area has high-quality water that is suitable for agriculture. Due to the water's EC level being maintained and rising over time in Khanewal, the area with suitable water quality grew from 2014 to 2020. Any region's higher groundwater EC concentration may be the result of excessive groundwater abstraction. Fragmented rocks and shale dissolve in the water as a result of excessive groundwater extraction, raising the salt level (Mabrouk et al. 2019). Additionally, strong evaporation causes salts to accumulate in dry and semi-arid regions, resulting in high-salinity groundwater that prevents plant roots from absorbing enough water to meet their metabolic needs (Chen and Feng 2013; Chen et al., 2019; Xu et al. 2019).

SAR measures the alkali/sodium threat to crops, making it a crucial criterion for establishing the appropriateness of groundwater for irrigation (Ramesh & Elango 2012). When SAR values increase, overall ground stability can drop by as much as 30%. The SAR in groundwater assesses how sodium hazards interact with calcium and magnesium concentrations (Li et al., 2020). The current study's findings demonstrate that between 2014 and 2020, the area in Sahiwal classified as a low-level zone increased following WHO standards. Sahiwal's moderate quality zone had been reduced by 10 km between 2014 and 2020. Groundwater used for irrigation in the Okara district contains constant levels of SAR during the study period between 2014 and 2020. In Khanewal, between 2014 and 2020, the moderate quality zone expanded by 7 km. There has been no change between 2014 and 2020 in the area that falls within Khanewal's low category by WHO standards. The Spatio-temporal distribution of the SAR demonstrates the good water quality class reported decline between 2014 and 2020 under PID criteria. On the other hand, Okara, Sahiwal, and Khanewal saw an increase in moderate water class observations over this period. The area in Sahiwal with poor water quality under the severe category also moved in the direction of declination, indicating that the SAR (mg/L) level has increased. Unsuitable water quality area under areas rose by 7 km in the Khanewal district between 2014 and 2020. From 2014 to 2020, the district Okara area that falls under the severe category remained the same. Seasonal variations have been observed to have an impact on groundwater SAR, which can decrease soil permeability and obstruct crops' ability to absorb water (Tahmaseb et al. 2018).

The sodicity risk is typically identified by a higher RSC value in irrigation water (Awais et al., 2017). In soil particles, sodium tends to absorb if the RSC value of the water is high (Eaton 1950). RSC has been calculated to assess the risky impact of $CO3^{2-}$ and HCO_{3-} on the quality of water for agricultural purposes (Eaton 1950). The graphic representation of the current study demonstrates the improvement in water quality during the investigation. Sahiwal district has undergone a notable transformation, with a moderate zone expanding by 1221 km between 2014 and 2020 and a severe zone decreasing by 100 km within that same period. Between 2014 and 2020, the low-quality zone's perimeter changed by 1130 km. Water quality with the RSC metric also increased over time, as seen by the district Okara map. The best water quality zone increased by 956 sq. km from 2014 to 2020, the moderate water quality zone shrunk by 543 sq. km, and the highly vulnerable water quality zone shrunk by 422 sq. km from 2014 to 2020, according to Khanewal's visual representation of Sodium Residual Carbonate. In terms of residual sodium carbonate, Richards 1954 was the only study to look at the potentially harmful effects of carbonate and bicarbonate on soil and crop health. Continuous usage of water with an excessive RSC can limit the flow of air and water through the soil and harm the soil structure, which lowers crop production (Latha and Rao 2012). As a result, based on their predicted RSC values, the majority of the groundwater samples that are currently available in the region are appropriate for irrigation.

According to the findings, the overall water quality in the study area was deemed "fit" by WHO standards but only "Moderately fit" by Punjab Irrigation Department standards. In contrast, the Sahiwal, Okara, and Khanewal districts saw an average reduction in water table depth from 2010 to 2015 of 0.61, 1.28, and 0.16 metres, respectively, and an increase from 2016 to 2020 of 1.69, 1.42 and 0.83 metres. In 2010, 2015, 2016, and 2020, the water table of the study area exhibited an inverse relationship. The visual representation demonstrates that during the first interval, from 2010 to 2015, the water level decreased while during the second, from 2016 to 2020, the depth of the water table rose. The sustainable circumstances for underground water were changed by floods in Pakistan between 2010 and 2015, which raised the level of subsurface water. This is mainly because of flood conditions in 2014 which recharged the aquifer in Khanewal and Sahiwal regions to a significant level (Ashraf et al., 2023). Whereas, the period from 2016 to 2020 remained dry comparably as fewer rainfalls have been reported which results in sufficient groundwater extraction to fulfil the agriculture needs in this period. Due to significant rains that lowered groundwater levels, Pakistan experienced a drought season from 2016 to 2020. Surface water is also impacted by this drought (Sahar et al., 2023). There isn't enough surface water left over from the drought to adequately irrigate crops. As a result, farmers use subsurface water, which also contributes to lowering the water table.

The outcome is consistent with prior research (Demeke and Andualem, 2018; Melese and Belay 2022). Okara experienced the highest depletion rate, 0.94 m/year, during the dry years of 1998 to 2002. The Okara Division's highest depletion rate during the drought also demonstrates the significantly greater contribution of rains to meeting crop water needs and groundwater recharging. For Sahiwal and Khanewal, the average rate of groundwater depletion from 1987 to 2008 was 0.36 m/year. However, there is no discernible depletion of the groundwater in either Balloki or Okara, where levels are constant (Bashrat 2012). According to Basharat and Tariq (2012), the irrigation system in the Indus Basin has experienced differential variations in rainfall, which have in turn led to changes in the demand for irrigation water. Although the quantity and quality of groundwater in the chosen district (research area) are not currently in a critical state, future deterioration is likely with continued carelessness and the release of additional water from aquifers. Therefore, it is essential to create a proper system for supplying surface water to farmers, implement water conservation measures, and use environmentally friendly methods of replenishing aquifers.

CONCLUSION

The area under good quality in Sahiwal and Okara in 2014 was 60% and 15%, respectively, but in 2020 that area had decreased to 26% and 7%. In contrast, between 2014 and 2020, water quality in the Khanewal district increased by 22% to 44%. Overall water quality has been found "good" in the study area by comparing the WHO standard with a moderate range according to the Punjab Irrigation Department standards. According to the findings, the current decline in groundwater quality in Okara, Sahiwal, and Khanewal is not a very serious issue, but over-draining an aquifer (especially in salty areas) might drastically lower groundwater quality in the coming future. The depth of the water table decreased from 2010 to 2015, which means the water level improved between these years. This is mainly because of flood in 2014 recharged the aquifer in the Khanewal and Sahiwal regions to a significant level. In comparison, the period from 2016 to 2020 remained dry as fewer rainfalls were reported which resulted in sufficient groundwater extraction to fulfil the agriculture needs in this period. A significant increase in the depth of the water table has been observed in the Khanewal and Sahiwal districts from 2016 to 2020. Contrary to expectations, Okara district showed almost consistent results in water quantity over this period. In the Sahiwal and Okara districts, respectively, 52% and 22% area covered more than 12.192 metres and 7.62 metres depth to the water table in 2014 which increased to 71% and 40% after 10 years. Therefore, in the Khanewal district, 35% of the area is less than 12.192 metres (2010), and that number rises to 41% by 2020. The depletion of groundwater increases over time. The primary problem in the current situation of rising water needs is the sustainability of groundwater irrigation. In handling this problem in future, there is a need to promote the use of artificial recharge techniques such as infiltration ponds, recharge wells, and percolation tanks to refill groundwater, as well as encourage the implementation of water-saving technology, including efficient irrigation systems and rainwater harvesting.

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