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International Journal of Agriculture and Sustainable Development

Suitability Analysis of Groundwater for Irrigation in District Naseerabad, Baluchistan

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Citation | Soomro. S. A, Sami. K, Mehmood. F, Khan. Z. A, "Suitability Analysis of Groundwater for Irrigation in District Naseerabad Baluchistan", IJASD, Vol. 7 Issue. 3 pp 310-328, August 2025
DOI | https://doi.org/10.33411/ijasd/202573310328
Received | June 29, 2025 **Revised |** July 22, 2025 **Accepted |** July 27, 2025 **Published |** August 01, 2025.

In Baluchistan, the dependency on groundwater for agriculture is even more significant due to its arid and semi-arid climate. District Naseerabad of Baluchistan, Pakistan, is characterized by its unique geographical and climatic features. Baluchistan receives scant and erratic rainfall, averaging less than 200 millimeters annually, which is insufficient to sustain agricultural activities. In these regions, the scarcity of rainfall and high evapotranspiration rates limit the availability of surface water, making groundwater the primary and sometimes the sole source of water for irrigation. The present study was conducted in District Naseerabad, Baluchistan, during the year 2023-24. There are 4 tahsils and 32 union councils (UCs) in the district of Naseerabad. There are no tubewells installed in the union councils without the union councils of Chhatter, Karor, Phuleji, Shahpur, and Bundi. So the water samples were collected from these 5 union councils. The water samples were analyzed for EC, pH, Chloride, Calcium, Carbonate, Bicarbonate, Calcium, Magnesium, Nitrate, Sodium, Sulfate, and Potassium. TDS, SAR. SSP, PI, MAR, and KR indicators were determined for water suitability. The EC of water was under permissible limits in UC Bundi. The pH was within permissible limits in all UCs. TDS were within permissible limits in UC Chhatter and Bundi. Bicarbonate, Chloride, Sulfate, Calcium, Magnesium, Sodium, Potassium, and Nitrate were within permissible limits in all UCs. Assessing the suitability of groundwater for irrigation involves evaluating several key indices that provide insight into the potential long-term impacts of using groundwater on soil health and crop productivity. The variations in SSP could be attributed to differences in geological formations, human activities, and agricultural practices across the union councils. For suitability analysis, SAR and SSP were within permissible limits in UC Chhatter and Bundi. High PI values indicate that the water is likely to enhance soil permeability, while low PI values suggest a risk of reduced permeability due to sodium-induced soil dispersion. PIs were within permissible limits in UC Karor, Phuleji, Shahpur, and Bundi. MAR was over the permissible limits in UC Bundi. High KR values signify an elevated sodium hazard, which can lead to soil sodicity and degradation. KR were within permissible limits in UC Chhatter and Bundi. High MAR values indicate a disproportionate amount of magnesium, which can lead to soil compaction and reduced aeration, hampering root development and nutrient uptake.

Keywords: Suitability, Groundwater, Irrigation, Naseerabad, Baluchistan

Introduction:

Water plays a vital role in agricultural productivity, especially in arid and semi-arid regions where rainfall is unpredictable and inadequate. In Pakistan, this challenge is particularly evident in provinces such as Baluchistan, where agriculture largely relies on groundwater because of scarce surface water resources and the lack of dependable canal irrigation systems [1]. The District of Naseerabad, although part of the irrigated plains of Baluchistan, is increasingly reliant on groundwater for irrigation as surface supplies fluctuate due to climate variability and over-extraction upstream. However, the sustainability and suitability of this groundwater for irrigation purposes remain questionable. Groundwater quality plays a vital role in determining its usability for crop production. Parameters such as electrical conductivity (EC), sodium adsorption ratio (SAR), residual sodium carbonate (RSC), and total dissolved solids (TDS) significantly affect soil health and crop yields when used for irrigation [2]. Deterioration in groundwater quality due to over-extraction, inadequate recharge, and contamination can lead to salinization, sodicity, and decline of agricultural productivity [3]. In this context, evaluating the chemical characteristics of groundwater in District Naseerabad is essential to determine its irrigation suitability. Conducting such analysis is essential for promoting sustainable water resource management and enables farmers to make informed decisions regarding irrigation techniques and effective crop planning. [4], [5]; [6]; [7]; [8] emphasize the need for localized groundwater assessments to cope with regional hydro-geological diversity and to ensure water security for agriculture. This study aims to assess the suitability of groundwater in District Naseerabad for irrigation purposes by analyzing key physico-chemical parameters and comparing them with standard irrigation water quality guidelines. The results will support informed decision-making for sustainable agricultural development in the region.

Objectives and Novelty Statement of the Study:

The chemical properties and suitability of the groundwater in the area were analyzed for irrigation purposes. This study presents a comprehensive hydro-chemical evaluation of groundwater quality for irrigation in District Naseerabad, Baluchistan, focusing on the union councils with operational tube wells. In a region characterized by extreme aridity and limited surface water resources, this research uniquely assesses variability in water quality parameters and suitability indices such as SAR, SSP, PI, MAR, and KR across five union councils. The study highlights localized risks to soil health, including sodium and magnesium hazards, and provides critical, data-driven insight for sustainable groundwater management in a strategically important yet under-researched agricultural region of Pakistan.

Materials and Methods:

Study Area:

The present study was carried out in District Naseerabad, Baluchistan (Figure 1), which is located between 67° 44' 33" to 68° 26' 54" east longitudes and 28° 12' 13" to 29° 02' 58" north latitudes. The district comprises four tehsils, and each tehsil includes a total of 41 union councils. In district Naseerabad, the water table depth is from 300 feet to 400 feet. Groundwater samples were collected from those union councils where the tube wells were installed within the district of Naseerabad, Baluchistan.

Sample Collection:

The groundwater quality analysis was conducted for water samples collected from five union councils, providing a comprehensive representation of the area's groundwater resources. The samples were taken from specific locations where tube wells had been installed. Notably, tube wells are present only in the union councils of Chhatter, Karor, Phuleji, Shahpur, and Bundi, while no such installations exist in the remaining union councils. Three water samples from each tube well were collected. The water samples were labeled as R_1, R_2, and R_3 for each tube well. The coordinates of the locations of the tube wells are given in Table 1.

Analysis Procedures:

Groundwater samples were collected from selected tube wells in the study area following a standardized protocol to ensure consistency and reliability of the data. Each tube well was operated for one hour before sample collection. During this one-hour operation period, samples were collected at 20-minute intervals to account for any potential variations in water quality over time. Water samples were collected in pre-cleaned sampling bottles with a capacity of 500 ml. Immediately after collection, sampling bottle lids were securely closed to prevent open-air contamination and maintain the integrity of the samples.

Table 1. Coordinates of the locations of tube wells

Sr. No.	Location of tube wells	North coordinate	East coordinate
1	Union Council Chatter	28° 51 27”	68° 19 74”
2	Union Council Karor	31° 06 53”	71° 35 33”
3	Union council Phuleji	28° 58 38”	68° 20 31”
4	Union Council Shahpur	28° 43’ 10”	68° 24’ 53”
5	Union Council Bundi	28° 73’ 30”	69° 40’ 15”

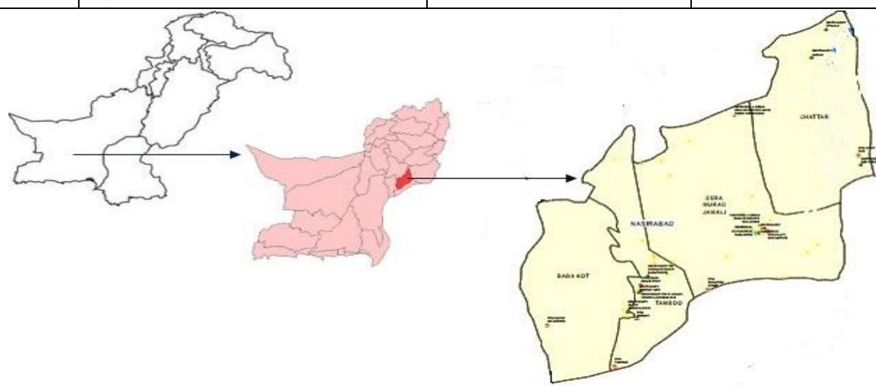
Figure 1. Area map of District Naseerabad, Baluchistan

Sample Preparation:

All sampling bottles were thoroughly cleaned and rinsed with distilled water to eliminate any potential contamination. Each sample bottle was labeled with crucial information, including the source of water collection, time of collection, date of collection, and sampling location. After collection, the samples were transported to the Department of Land and Water Management Laboratory, Faculty of Agricultural Engineering, Sindh Agriculture University, Tandojam, for detailed analysis.

Chemical Analysis of Groundwater:

Electrical Conductivity (EC):

EC was measured using a digital EC meter, calibrated with standard KCl solutions. The electrode was immersed in the water sample, and the reading was recorded after stabilization. The results were expressed in dS/m.

pH:

pH was determined using a digital pH meter, calibrated with buffer solutions of pH 4.0, 7.0, and 10.0. The electrode was rinsed with distilled water between samples, immersed in the sample, and the pH value was recorded after stabilization.

Chloride:

Chloride concentration was determined using the Argentometric Titration (Mohr's Method). A known volume of sample was titrated against standardized silver nitrate solution using potassium chromate as an indicator. The chloride concentration was calculated based on the volume of silver nitrate consumed and expressed in mg/L.

Calcium:

Calcium was measured using EDTA titration. A known volume of sample was titrated against standardized EDTA solution using murexide as an indicator. The calcium concentration was calculated based on the volume of EDTA consumed and expressed in mg/L.

Carbonate and Bicarbonate:

Carbonate and bicarbonate were determined through acid-base titration. A known volume of sample was titrated against standardized HCl using phenolphthalein and methyl orange as indicators for carbonate and bicarbonate, respectively. Carbonate and bicarbonate concentrations were calculated based on the volumes of acid consumed.

Magnesium:

Magnesium concentration was calculated as the difference between total hardness and calcium hardness, both determined by EDTA titration.

Nitrate:

Nitrate was analyzed using UV spectrophotometry. Nitrate concentration was determined by measuring the absorbance of the sample at 220 nm and 275 nm using a UV-Vis spectrophotometer.

Sodium:

Sodium was determined using flame photometry. The flame photometer was calibrated using standard sodium solutions. The sample was aspirated into the flame, and the emission intensity was measured at 589 nm.

2.5.9 Sulfate

Sulfate concentration was measured using the turbidimetric method. Barium chloride was added to the sample, and the resulting turbidity was measured at 420 nm using a spectrophotometer.

Potassium:

Potassium was determined using flame photometry. The flame photometer was calibrated using standard potassium solutions. The sample was aspirated into the flame, and the emission intensity was measured at 766 nm.

Total Dissolved Solids (TDS):

TDS was measured using a calibrated TDS meter. The probe was immersed in the water sample, and the reading was recorded after stabilization.

Suitability Assessment of Groundwater Using Chemical Indicators:

The suitability of groundwater was assessed using a range of chemical indicators.

Sodium adsorption ratio (SAR):

The SAR is a crucial indicator of the sodium hazard in irrigation water. High SAR values indicate a greater risk of sodium accumulation in the soil, which can lead to reduced soil permeability and structural degradation. It was calculated using the following formula [1]:

$$SAR = \frac{Na^{+}}{\sqrt{\left(\frac{C_a^{2+} + Mg^{2+}}{2}\right)}}$$

Where:
SAR = Sodium adsorption ratio
Na = Sodium
Ca = Calcium
Mg = Magnesium

Soluble Sodium Percentage (SSP):

The SSP indicates the sodium content in water relative to other cations. High SSP values suggest a higher risk of sodium accumulation in the soil, which can adversely affect soil structure and plant growth. It was calculated using the following equation [1]

$$SSP = \left(\frac{Na^{+} + K^{+}}{Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}}\right) \times 100$$

Where:
SSP = Soluble sodium percentage
Na = Sodium

K = Potassium
Ca = Calcium
Mg = Magnesium

Permeability Index (PI):

The PI assesses the long-term effects of irrigation water on soil permeability. The PI values are classified as Class I: PI > 75% (Suitable for irrigation), Class II: 25% < PI < 75% (Marginally suitable for irrigation), and Class III: PI < 25% (Unsuitable for irrigation). It was calculated using the following equation [1]:

$$PI = \frac{Na^{+} + \sqrt{HCO_3^{-}}}{(Ca^{2+} + Mg^{2+} + Na^{+})} \times 100$$

Where:
PI = Permeability index
Na = Sodium
HCO = Bicarbonate
Ca = Calcium
Mg = Magnesium
Na = Sodium

Magnesium Absorption Ratio (MAR):

The Magnesium Ratio evaluates the effect of magnesium in irrigation water on soil properties. High magnesium content relative to calcium can lead to magnesium toxicity in plants and adversely affect soil structure. It was calculated using the following equation [1]:

$$MAR = \frac{Mg^{2+}}{Mg^{2+} + Ca^{2+}} \times 100$$

Where:
MAR = Magnesium absorption ratio
Mg = Magnesium
Ca = Calcium

Kelly's ratio (KR):

Kelly's Ratio is another indicator used to assess the suitability of water for irrigation. Kelly's Ratio provides an additional perspective on the sodium hazard, complementing the information provided by SAR and SSP. It was calculated using the following equation [1]:

$$KR = \frac{Na^{+}}{Mg^{2+} + Ca^{2+}} \times 100$$

Where:
KR = Kelly's ratio
Na = Sodium
Mg = Magnesium
Ca = Calcium

Statistical Analysis:

The statistical analysis was done using statistical software (Statistics 8.1) to assess the significance among different parameters. Mean comparisons were carried out between the groups of treatments using the LSD test at 5% probability level ($p < 0.05$ and 0.001).

Results:

Chemical Analysis of Groundwater:

Electrical Conductivity:

The results of the EC of the water samples taken from the union councils are shown in Figure 2. Detailed analysis shows that the highest EC was recorded in R1 (Karor), with an average value of 5.53 dS/m (±0.2709), significantly exceeding the FAO recommended limit of 3 dS/m. Other wells in Karor (R2 and R3) also showed high EC values of 4.87 dS/m and

4.14 dS/m, respectively. In contrast, the lowest EC was observed in R_3 (Bundi) at 1.27 dS/m (±0.0520), which is below the FAO limit. Wells in Bundi consistently exhibited the lowest EC values among all sampled sites, with R_1 and R_2 showing values of 1.85 dS/m and 1.50 dS/m, respectively. Chhatter and Phuleji exhibited moderate EC values, with R_1, R_2, and R3 recording 4.52 dS/m, 4.25 dS/m, and 3.74 dS/m, respectively, and Phuleji R_1, R_2, and R_3 recording 5.09 dS/m, 4.02 dS/m, and 3.46 dS/m, respectively. Shahpur showed lower EC values, ranging from 2.84 dS/m to 1.96 dS/m. An analysis of Electrical Conductivity (EC) levels in wells across Naseerabad indicates considerable variation. Elevated EC values were observed in Karor and Phuleji, likely due to the presence of saline geological formations and agricultural runoff. In contrast, lower EC levels in Bundi suggest minimal agricultural activity and the presence of effective natural filtration systems.

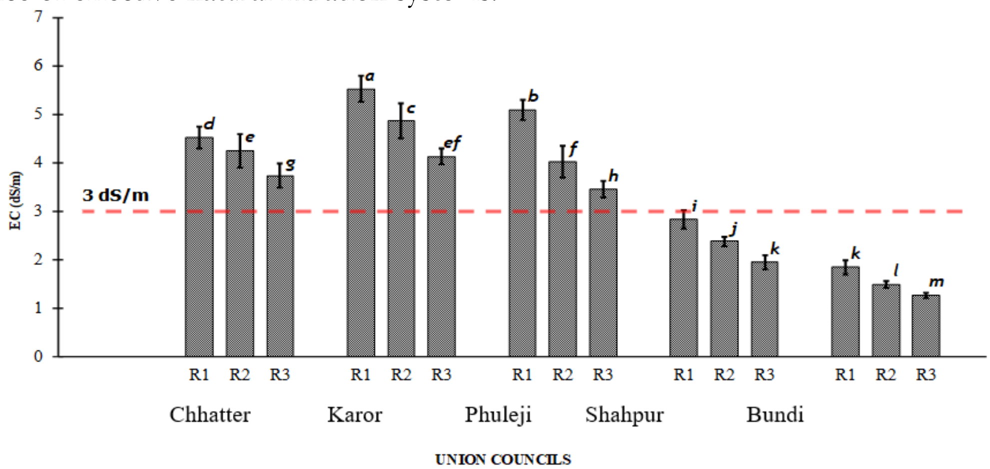

Figure 2. EC in groundwater across various UCs of the district Naseerabad

Potential of Hydrogen:

The results of the pH of groundwater are shown in Figure 3. The pH values across the wells exhibit a notable range, with the highest value recorded in R2 (Phuleji) at 8.71 (±0.4979), indicating a moderately alkaline condition. This was followed closely by R_2 (Bundi) and R_2 (Shahpur) with pH values of 8.54 (±0.3488) and 8.47 (±0.5531), respectively. Conversely, the lowest pH was observed in R_1 (Chhatter) at 6.70 (±0.4376), which falls within the slightly acidic to neutral range. Detailed analysis shows that while most wells-maintained pH values within the FAO recommended range of 6.5 to 8.5, exceeded this limit. Wells in Karor demonstrated a broad pH range with R_2 reaching 8.40 (±0.6859) and R_1 at 7.50 (±0.3062). Similarly, Shahpur and Phuleji also displayed significant variability, with Shahpur's R_1 and R_2 showing pH values of 7.30 (±0.4172) and 8.47, respectively. Elevated pH levels in areas like Karor and Phuleji are linked to carbonate-rich geological formations and agricultural runoff, while neutral pH levels in Chhatter indicate lesser impacts from these factors.

Total Dissolved Solids:

The results of the TDS of groundwater are shown in Figure 4. The TDS values exhibit a broad range across the wells, with the highest concentration recorded in R_1, R_2, and R_3 (Karor), indicating a severe deviation from the FAO recommended limit of 2000 mg/L. This high TDS concentration suggests significant contamination. Similarly, other wells in Phuleji, such as R_1, R_2, and R_3, also show elevated TDS levels of 3114 mg/L (±127.1416) and 2647 mg/L (±108.0703), respectively. These values are higher than the permissible limits. Conversely, the lowest TDS levels were observed in R_1 (Chhatter) at 513 mg/L (±41.8863), which is below the secondary FAO limit of 500 mg/L, indicating better water quality. Other wells in Chhatter, such as R_2 and R_3, also show low TDS values of 614 mg/L (±50.1329) and 713 mg/L (±29.1081), respectively. These results suggest minimal anthropogenic impact and effective natural filtration processes. Wells in Bundi show moderate TDS levels, with R_1, R_2, and R_3 having TDS values of 1106 mg/L (±90.3045), 1316 mg/L (±64.4774), and 1514 mg/L (±86.5072), respectively, indicating a moderate level of contamination. As seen in this figure, the TDS values in the UCs of Chhatter, Karor, Phuleji, Shahpur, and Bundi display a significant range from low to extremely high concentrations.

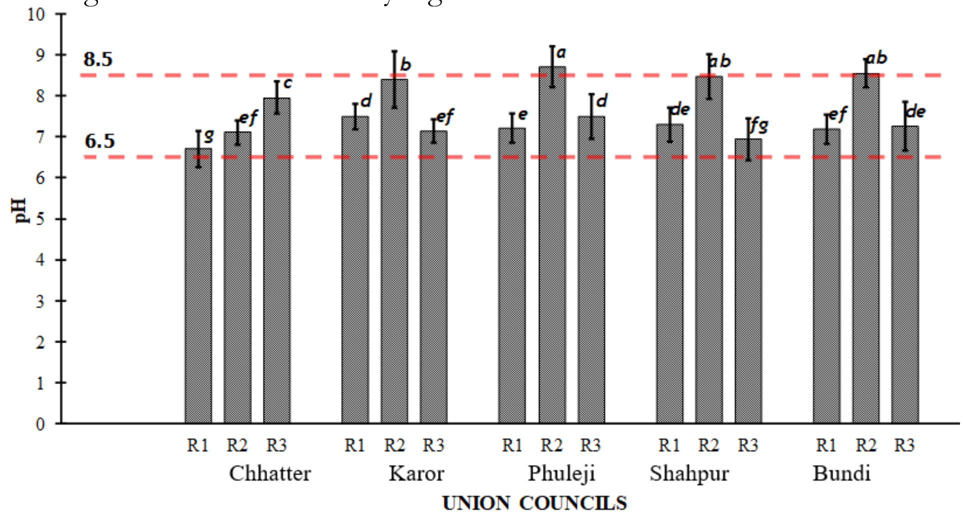

Figure 3. pH in groundwater across various UCs of district Naseerabad

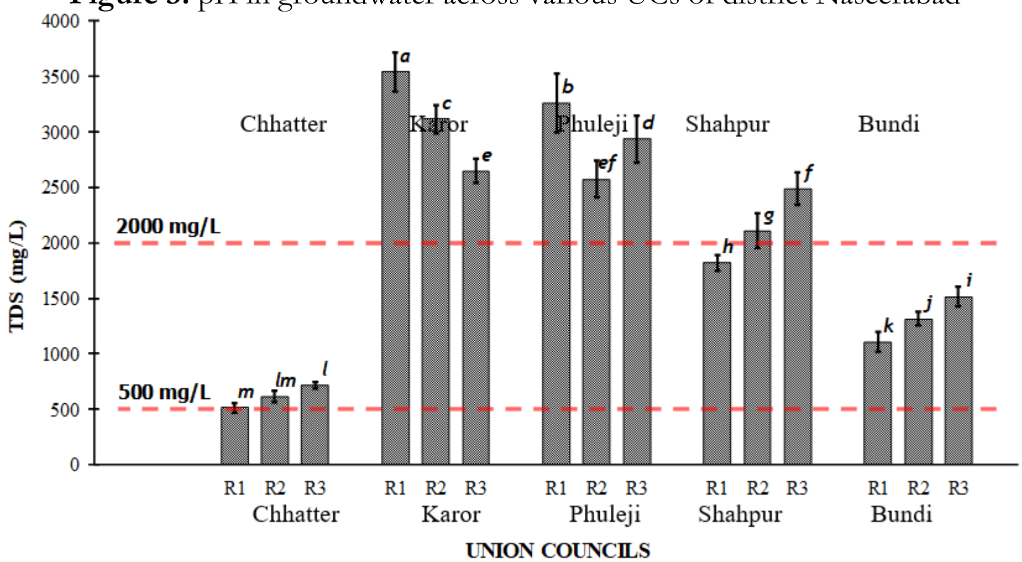

Figure 4. TDS in groundwater across various UCs of district Naseerabad

Bicarbonate:

The results of the bicarbonate of groundwater are shown in Figure 5. The highest bicarbonate levels were observed in R1 (Karor) at 15.24 mg/L (±0.6221), followed by R_1 (Phuleji) with 14.09 mg/L (±0.5754), and R_2 (Karor) at 13.41 mg/L (±1.0949). In contrast, the lowest bicarbonate levels were recorded in R_3 (Chhatter) at 1.22 mg/L (±0.0597), and other wells in Chhatter, such as R_1 and R_2, also exhibited low HCO_3 concentrations of 1.47 mg/L (±0.0601) and 1.38 mg/L (±0.1017), respectively. In Shahpur, the wells demonstrated moderate bicarbonate levels, with R_1 at 8.03 mg/L (±0.6557), R_2 at 6.75 mg/L (±0.3305), and R_3 at 5.53 mg/L (±0.4065). UC Bundi also displayed lower bicarbonate concentrations, with values ranging from 2.09 mg/L (±0.1705) in R_3 to 3.03 mg/L (±0.1734) in R_1.

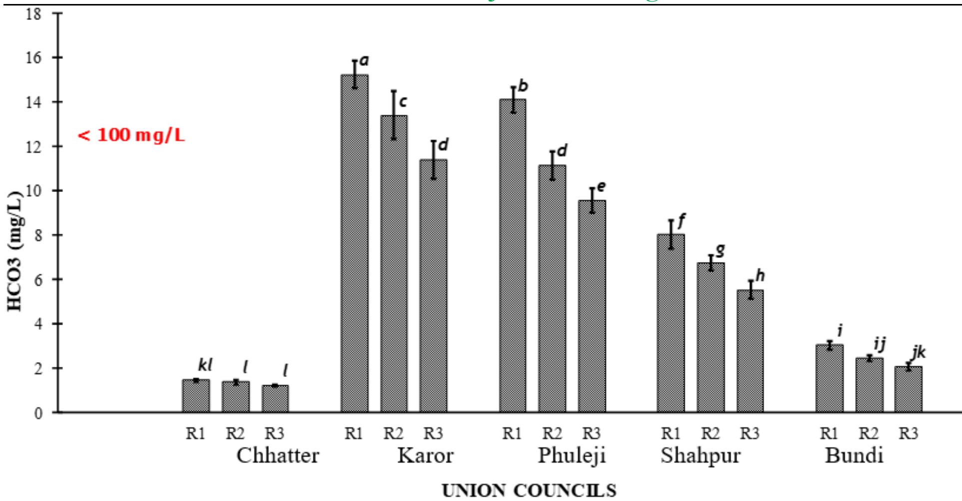

Figure 5. Bicarbonates in groundwater across various UCs of district Naseerabad

Chloride:

The results of the Chloride of the groundwater are shown in Figure 6. Detailed comparison of Cl concentrations across the union councils highlights significant differences. The highest chloride levels were recorded in R_1 (Karor) at 19.85 mg/L (±1.2966), followed by R_1 (Phuleji) with 18.31 mg/L (±1.4950), and R_2 (Karor) at 17.47 mg/L (±1.2836). The elevated concentrations in Karor and Phuleji suggest significant chloride inputs from anthropogenic sources such as agricultural activities and possible saline intrusion due to over-extraction of groundwater. In contrast, the lowest chloride levels were found in R_3 (Chhatter) at 1.50 mg/L (±0.0978), with other wells in Chhatter, such as R_1 and R_2, also exhibiting low chloride concentrations of 1.81 mg/L (±0.0739) and 1.70 mg/L (±0.0695), respectively, indicating minimal chloride contamination. Union Council Shahpur displayed moderate chloride levels, with R_1 at 10.32 mg/L (±0.4213), R_2 at 8.67 mg/L (±0.7078), and R_3 at 7.11 mg/L (±0.3482). Union Council Bundi also showed low concentrations, ranging from 2.17 mg/L (±0.1418) in R_3 to 3.15 mg/L (±0.1802) in R_1, suggesting limited contamination sources. Elevated chloride levels in Karor and Phuleji are attributed to agricultural runoff and saline intrusion, while lower levels in Chhatter and Bundi indicate minimal anthropogenic impact.

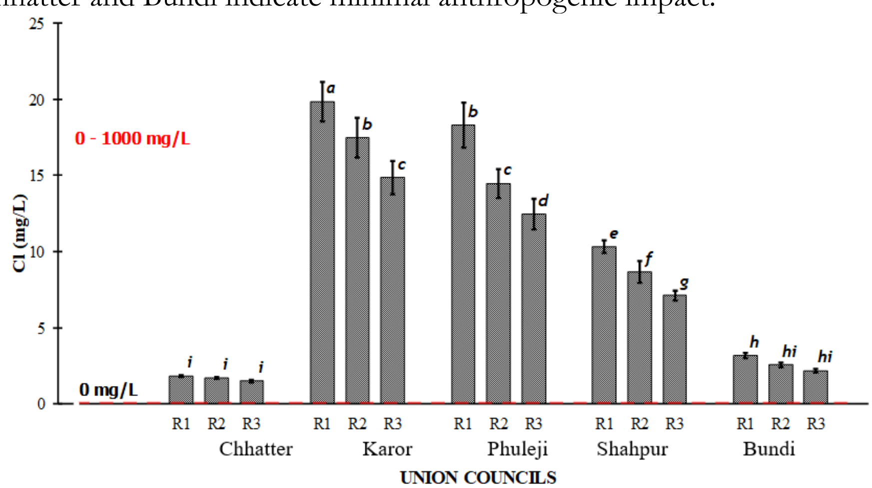

Figure 6. Chlorides in groundwater across various UCs of district Naseerabad

Sulfate:

The results of Sulphate in the groundwater are shown in Figure 7. In a detailed comparison, the highest sulfate concentrations were observed in R_3 (Karor) at 28.318 mg/L (±2.3122), followed closely by R_3 (Phuleji) at 28.177 mg/L (±1.1503) and R_2 (Karor) at 24.624 mg/L (±1.6085). These high values suggest significant sulfate inputs, due to agricultural runoff or industrial activities. Conversely, the lowest sulfate levels were detected in R_1 (Chhatter) at 2.238 mg/L (±0.0914), with other wells in Chhatter, such as R_2 and R_3, also showing low concentrations of 2.372 mg/L (±0.1356) and 2.657 mg/L (±0.2169), respectively. These low values indicate minimal anthropogenic influence in Chhatter. Union Council Shahpur exhibited moderate sulfate levels, with R1 at 11.476 mg/L (±0.8433), R_2 at 13.312 mg/L (±0.5435), and R_3 at 15.708 mg/L (±0.7695). This suggests a balanced impact of natural geological factors and moderate agricultural activities. Similarly, Union Council Bundi demonstrated low sulfate concentrations, ranging from 5.330 mg/L (±0.3046) in R1 to 7.294 mg/L (±0.5360) in R_3, indicating limited contamination sources and natural sulfate presence.

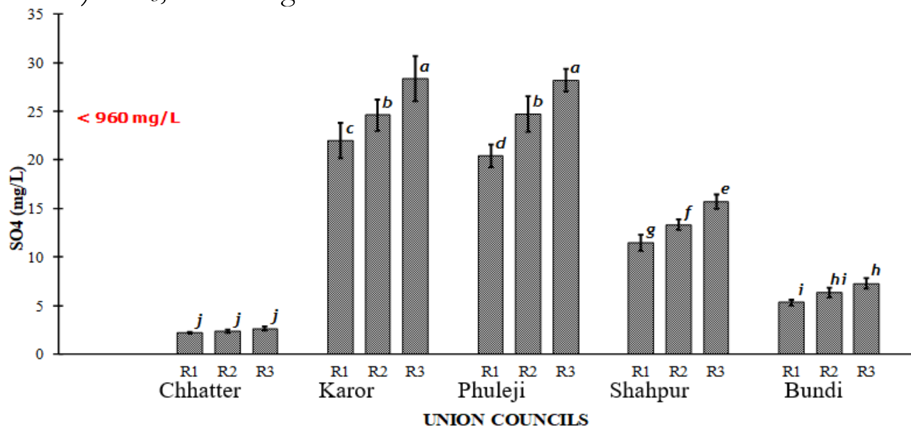

Figure 7. Sulfate in groundwater across various UCs of district Naseerabad

Calcium:

The results of Calcium in groundwater are shown in Figure 8. In a detailed comparison, the highest calcium concentrations were found in R_3 (Karor) at 11.44 mg/L (±0.4670), closely followed by R3 (Phuleji) at 11.40 mg/L (±0.5585) and R2 (Karor) at 9.95 mg/L (±0.4873). Conversely, the lowest calcium concentrations were observed in R_1 (Chhatter) at 0.87 mg/L (±0.0428), R_2 at 0.93 mg/L (±0.0680), and R_3 at 1.04 mg/L (±0.0677). Union Council Shahpur exhibited moderate calcium levels, with R_1 at 4.64 mg/L (±0.3410), R_2 at 5.38 mg/L (±0.3076), and R_3 at 6.35 mg/L (±0.5186). Similarly, Union Council Bundi demonstrated lower calcium concentrations, ranging from 2.89 mg/L (±0.2357) in R_1 to 3.95 mg/L (±0.3225) in R_3.

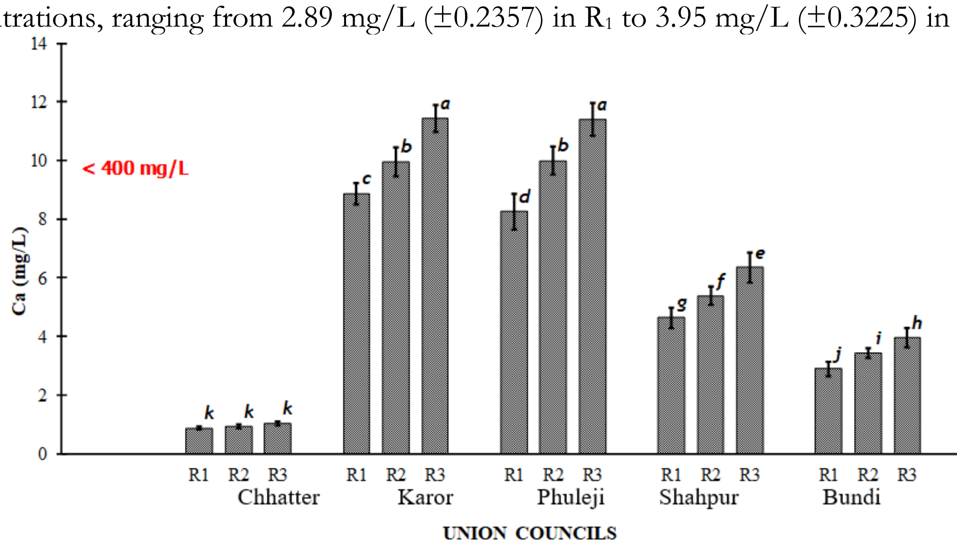

Figure 8. Calcium in groundwater across various UCs of district Naseerabad

Magnesium:

The results of Magnesium in groundwater are shown in Figure 9. In detailed comparison, the highest magnesium concentrations were observed in R_3 (Karor) at 6.57 mg/L (±0.3755) and R_3 (Phuleji) at 6.47 mg/L (±0.3170). R_3 (Bundi) also exhibited high magnesium levels at 6.69 mg/L (±0.3278), which could be attributed to the dissolution of magnesium-bearing minerals in the aquifers of this region. Conversely, the lowest concentrations were recorded in R_1 (Chhatter) at 0.41 mg/L (±0.0268), R_2 at 0.44 mg/L (±0.0285), and R_3 at 0.49 mg/L (±0.0359). Union council Shahpur showed moderate magnesium levels, with R_1 at 2.63 mg/L (±0.2150), R_2 at 3.05 mg/L (±0.2244), and R_3 at 3.60 mg/L (±0.1766). Similarly, UC Bundi demonstrated variability with high Mg concentrations, notably in R_2 at 5.82 mg/L (±0.4751) and R_1 at 4.89 mg/L (±0.3993). Magnesium levels, highest in Karor, Phuleji, and Bundi, are well below the FAO standard of 150 mg/L.

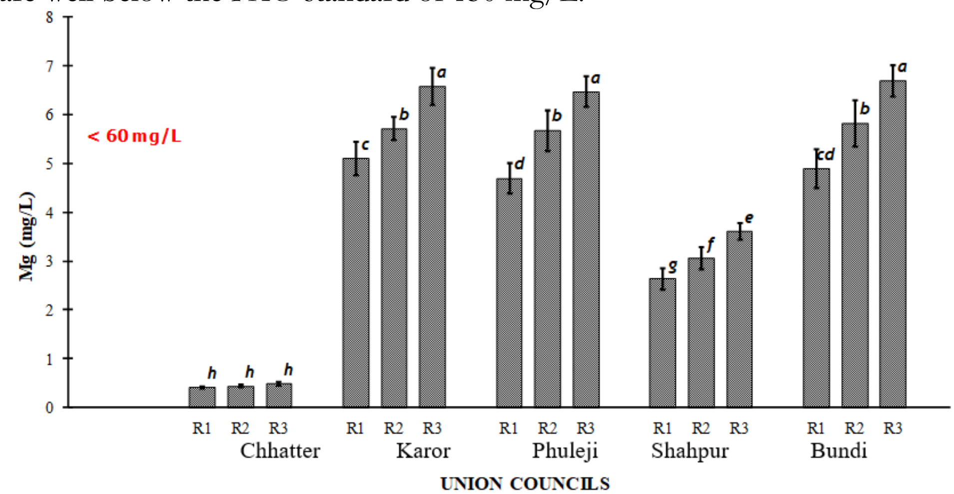

Figure 9. Magnesium in groundwater across various UCs of district Naseerabad

Sodium:

The results of Sodium in groundwater are shown in Figure 10. A detailed analysis indicates that the highest sodium concentrations were found in R_3 (Karor) at 39.47 mg/L (±1.9338) and R_3 (Phuleji) at 38.38 mg/L (±3.1339). In contrast, the lowest sodium concentrations were recorded in R1 (Chhatter) at 1.09 mg/L (±0.0532), R_2 at 1.15 mg/L (±0.0658), and R_3 at 1.29 mg/L (±0.1053). Union Council Shahpur displayed moderate sodium levels, with R_1 at 14.78 mg/L (±0.8449), R_2 at 17.15 mg/L (±0.7000), and R_3 at 20.23 mg/L (±0.8260). Similarly, Union Council Bundi showed varying sodium concentrations, notably in R_1 at 6.78 mg/L (±0.5538), R_2 at 8.07 mg/L (±0.3954), and R_3 at 9.28 mg/L (±0.6063). The highest sodium levels are found in Karor and Phuleji, but all concentrations are below the FAO standard limit of 200 mg/L, suggesting safe sodium levels for human consumption.

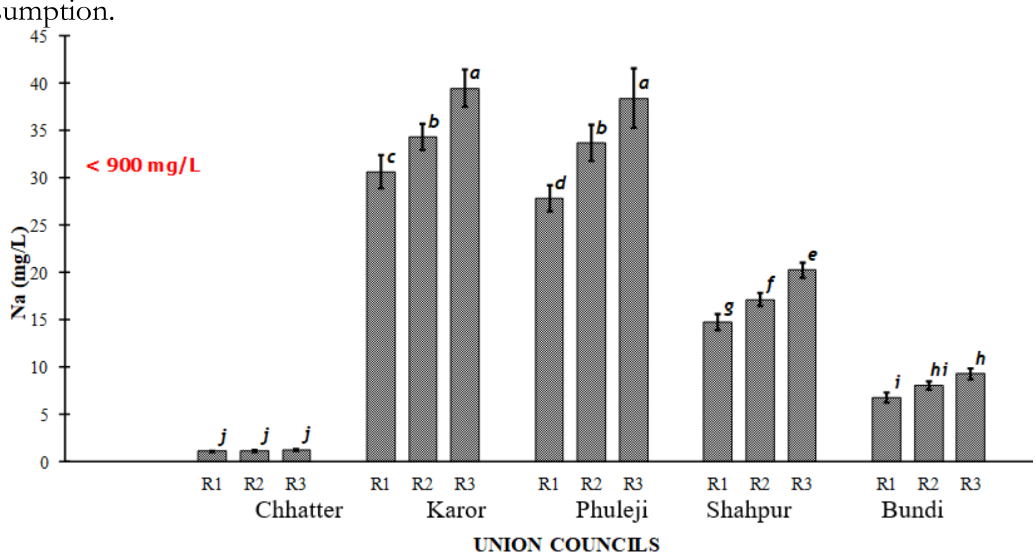

Figure 10. Sodium in groundwater across various UCs of district Naseerabad

Potassium:

The results of Potassium in the groundwater are shown in Figure 11. Comparing the wells, the highest potassium concentrations were observed in R_3 (Phuleji) at 0.56 mg/L (±0.0228) and R_2 at 0.49 mg/L (±0.0360), indicating substantial potassium sources in these areas, due to the weathering of potassium-bearing minerals or agricultural runoff. In contrast, the lowest concentrations were found in R_1 (Chhatter) at 0.06 mg/L (±0.0026), R_2 at 0.07 mg/L (±0.0038), and R_3 at 0.07 mg/L (±0.0049), suggesting minimal geological or anthropogenic potassium inputs. Union Council Shahpur exhibited moderate potassium levels, with R_1 at 0.15 mg/L (±0.0110), R_2 at 0.17 mg/L (±0.0099), and R_3 at 0.20 mg/L (±0.0083), reflecting a balance between natural mineral dissolution and potential contamination. Similarly, Union Council Bundi showed varied concentrations, notably in R_1 at 0.25 mg/L (±0.0122), R_2 at 0.30 mg/L (±0.0243), and R_3 at 0.34 mg/L (±0.0279), indicating moderate potassium inputs.

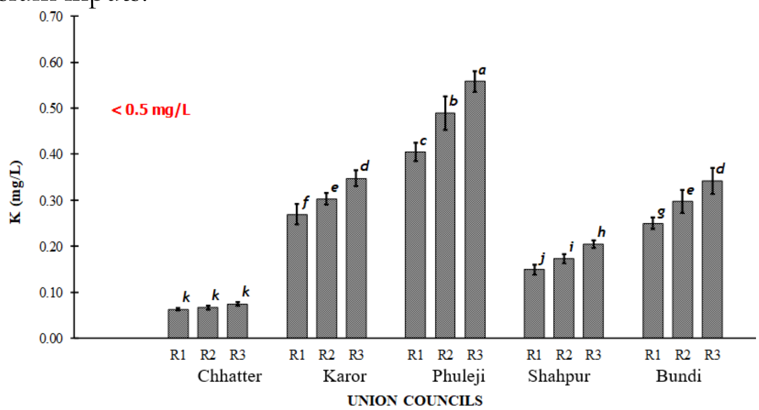

Figure 11. Potassium in groundwater across various UCs of district Naseerabad

Nitrate:

The results of Nitrate in the groundwater are shown in Figure 12. Detailed analysis of nitrate concentrations shows that the highest levels were detected in R_1 (Karor) at 0.03 mg/L (±0.0012), followed by R_2 and R_3, both at 0.02 mg/L with slightly different standard deviations (±0.0013 and 0.0012, respectively). This suggests a potential source of nitrate contamination in this union council, due to agricultural activities or improper waste management practices. In contrast, the lowest nitrate concentrations were consistently observed in R_1, R_2, and R_3 (Bundi), all registering 0.00 mg/L (±0.0000), indicating minimal to no nitrate pollution in this area, due to less intensive land use or effective natural filtration. Union Council Phuleji exhibited uniform low nitrate concentrations across its wells, with R_1, R_2, and R_3 each recording 0.01 mg/L but with minimal variation (±0.0005, 0.0004, and 0.0005, respectively). Similarly, Union Council Shahpur had low nitrate levels, with R_1, R_2, and R_3 recording 0.01 mg/L with slight variations in standard deviation (±0.0009, ±0.0004, and ±0.0004, respectively. These findings suggest a lower influence of anthropogenic sources in these regions.

Carbonate:

The study investigated carbonate levels in wells across different union councils in Naseerabad. The carbonate concentration in all analyzed well water samples was "Nil", indicating an absence of carbonate ions (CO_3), which is a crucial water quality parameter that influences pH, alkalinity, and corrosiveness. The absence of carbonate ions across all union councils suggests a consistent geological and hydrogeological regime in the study area. However, further investigation into factors influencing carbonate levels, such as aquifer lithology, groundwater flow patterns, and recharge mechanisms, would provide valuable insights into the hydrogeochemical processes governing the observed carbonate distribution. The carbonate concentration in all analyzed well water samples was "Nil."

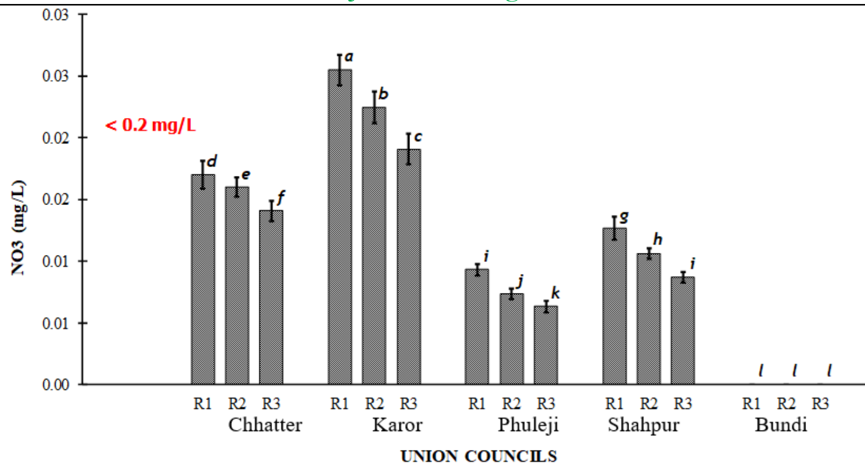

Figure 12. Nitrate in groundwater across various UCs of district Naseerabad

Correlation Among Various Water Quality Parameters:

A detailed correlation analysis was conducted to investigate the relationships between various water quality parameters, as shown in Figure 13. The analysis revealed that the EC exhibited a strong positive correlation with Cl (r = 0.60), SO_4 (r = 0.60), and Na (r = 0.41), indicating that high levels of these ions contribute significantly to the overall salinity and conductivity of the water samples. However, EC has a moderate negative correlation with NO3 (r = -0.16), suggesting that nitrate concentrations have a lesser influence on conductivity. pH shows a weak positive correlation with TDS (r = 0.19), HCO_3 (r = 0.21), and SO_4 (r = 0.18), implying that the presence of these ions can slightly increase the alkalinity of the water. However, pH has a moderate negative correlation with NO_3 (r = -0.24), indicating that higher nitrate levels may lead to a more acidic water environment. TDS exhibited a strong positive correlation with HCO_3 (r = 0.93), Cl (r = 0.94), and SO_4 (r = 0.89), suggesting that these ions are major contributors to the total dissolved solids in the water samples. TDS also has a moderate positive correlation with Ca (r = 0.62), Mg (r = 0.91), and Na (r = 0.67), indicating that these cations also contribute to the overall dissolved solids content. HCO3 shows a strong positive correlation with Cl (r = 0.99), SO_4 (r = 0.88), and Ca (r = 0.88), implying that the presence of these ions is strongly associated with bicarbonate levels in the water samples. Additionally, HCO_3 has a moderate positive correlation with Mg (r = 0.51) and Na (r = 0.58), suggesting that these cations may also influence bicarbonate concentrations. Cl exhibits a strong positive correlation with SO_4 (r = 0.87), Ca (r = 0.87), and Na (r = 0.48), indicating that these ions are strongly associated with chloride levels in the water samples. However, Cl has a moderate negative correlation with NO_3 (r = -0.89), suggesting that higher nitrate concentrations may be related to lower chloride levels. SO4 shows a strong positive correlation with Ca (r = 0.99) and Na (r = 0.67), implying that the presence of these cations is intricately linked to sulfate levels in the water samples. Additionally, SO_4 has a moderate positive correlation with Mg (r = 0.98) and a weak positive correlation with NO3 (r = 0.76), suggesting that these ions may also influence sulfate concentrations. Ca exhibits a strong positive correlation with Mg (r = 0.72) and Na (r = 0.98), indicating that the presence of these cations is strongly associated with calcium levels in the water samples. However, Ca has a moderate negative correlation with K (r = -0.80), suggesting an inverse relationship between calcium and potassium concentrations. Mg shows a strong positive correlation with Na (r = 0.68) and a moderate negative correlation with NO_3 (r = -0.84), implying that higher magnesium levels are associated with higher sodium concentrations and lower nitrate levels in the water samples. Na exhibits a moderate positive correlation with K (r = 0.75) and a weak positive correlation with NO_3 (r = 0.28), suggesting that higher sodium levels may be related to higher concentrations of potassium and nitrate in the water samples. Potassium (K) exhibited a weak negative correlation with nitrate (NO_3) (r = -0.31), suggesting that increased potassium concentrations may be linked to a slight decrease in nitrate levels within the water samples.

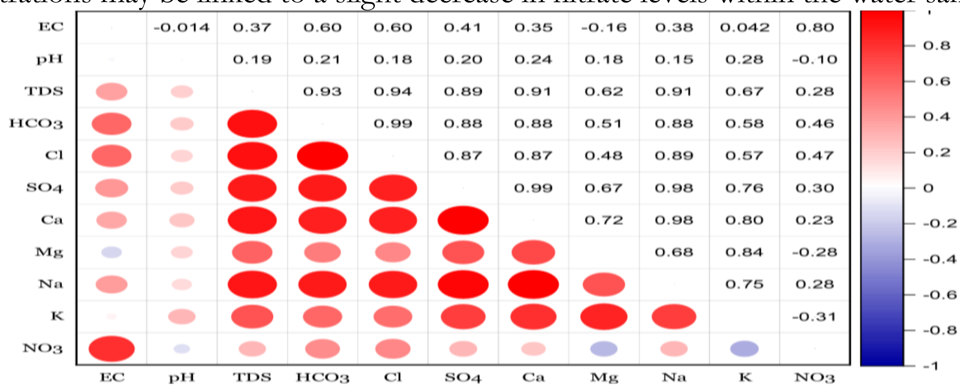

Figure 13. Correlation analysis among the investigated water quality parameters

Suitability Analysis of Groundwater Using Different Indicators:

Sodium Adsorption Ratio:

The results of the SAR of the groundwater are shown in Figure 14. The highest SAR value was observed in UC Karor at 13.16, significantly within the FAO's upper limit of 15. Conversely, UC Chhatter reported the lowest SAR values, well within the FAO's recommended range. The highest SAR was found in the union council Karor and Phuleji, while the moderate SAR was in the union council Shahpur and Bundi. The Sodium Adsorption Ratio (SAR) is a key parameter for evaluating groundwater suitability for irrigation, as it affects soil structure and permeability.

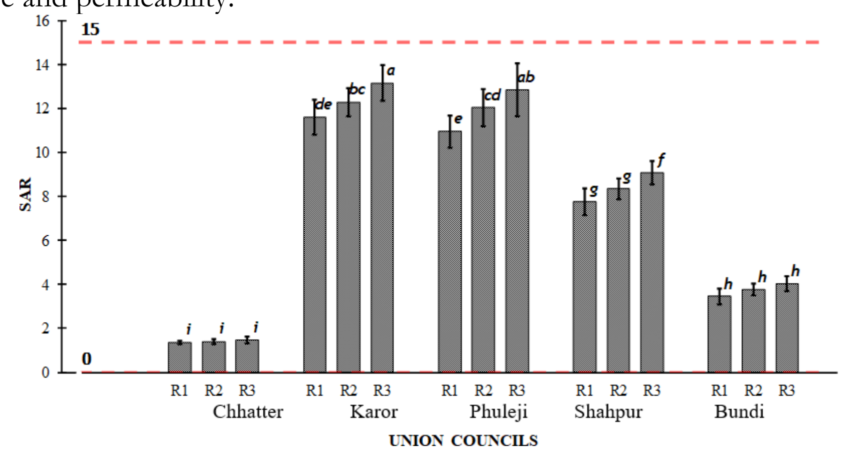

Figure 14. SAR in groundwater across various UCs of the district Naseerabad

Soluble Sodium Percentage:

The results of the SSP of the groundwater are shown in Figure 15. The tube wells in UC Karor, UC Phuleji, and UC Shahpur have SSP values exceeding the FAO recommended standard limit of 60%. In contrast, tube wells in the union council of Chhatter and Bundi have SSP values below this limit. As can be seen in Figure 15, the highest SSP value (68.83) was observed in UC Karor, while the lowest (47.18) was in UC Chhatter. The study of water quality in Naseerabad, Baluchistan, revealed significant variation in the soluble sodium percentage (SSP) across different wells. The SSP is a key parameter for assessing groundwater suitability for irrigation, with high values indicating excessive sodium content that can lead to soil salinization and sodicity.

Permeability Index:

The results of the PI of the groundwater are shown in Figure 16. The highest PI was observed in R_1 (Chhatter) with a value of 97.01, which falls into Class I (>75%), considered excellent according to FAO's standards limits. Conversely, the lowest PI was recorded in R_3

(Bundi) with a value of 53.80, falling into Class III (<25%), deemed unsuitable for irrigation. As shown in Figure 16, the PI values vary across the tube wells, indicating the heterogeneity of water quality in the region.

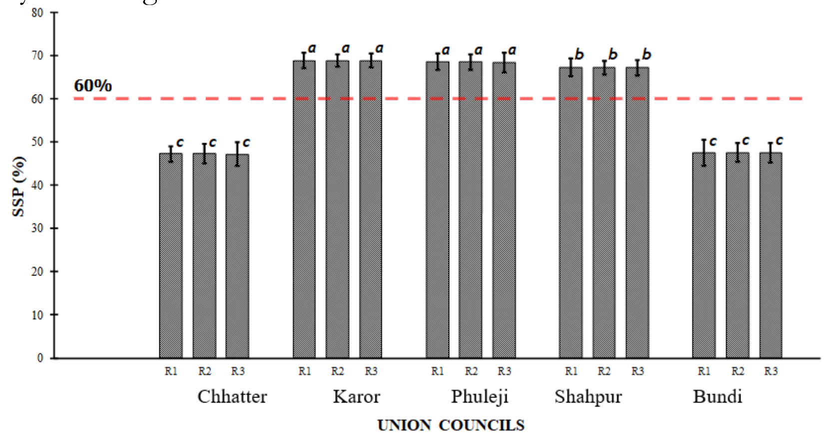

Figure 15. SSP in groundwater across various UCs of district Naseerabad

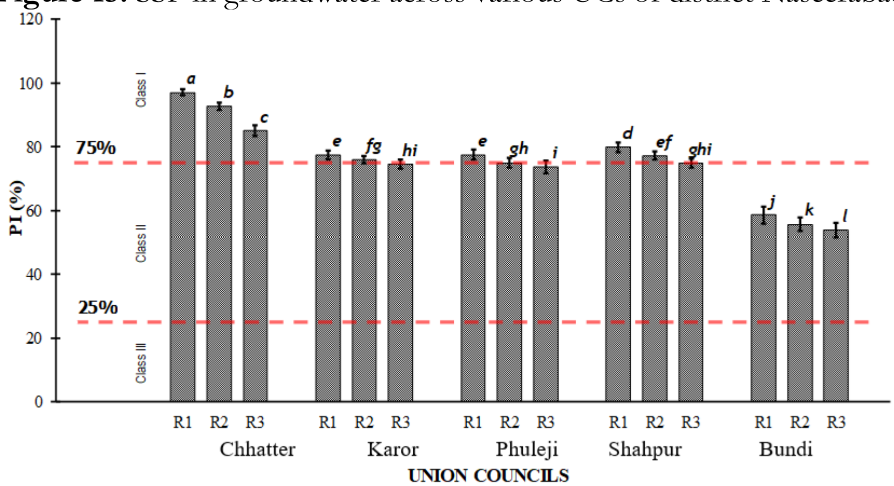

Figure 16. PI in groundwater across various UCs of district Naseerabad

Magnesium Absorption Ratio:

Figure 17 shows the MAR of the groundwater samples. The MAR values ranged from 32.03 in UC Chhatter to 62.89 in UC Bundi, with the latter exceeding the FAO recommended standard limit of 50%. This suggests potential problems with soil alkalinity in UC Bundi, which can negatively impact crop yield. These differences were statistically significant ($p < 0.001$) and may be attributed to geological differences and human activities.

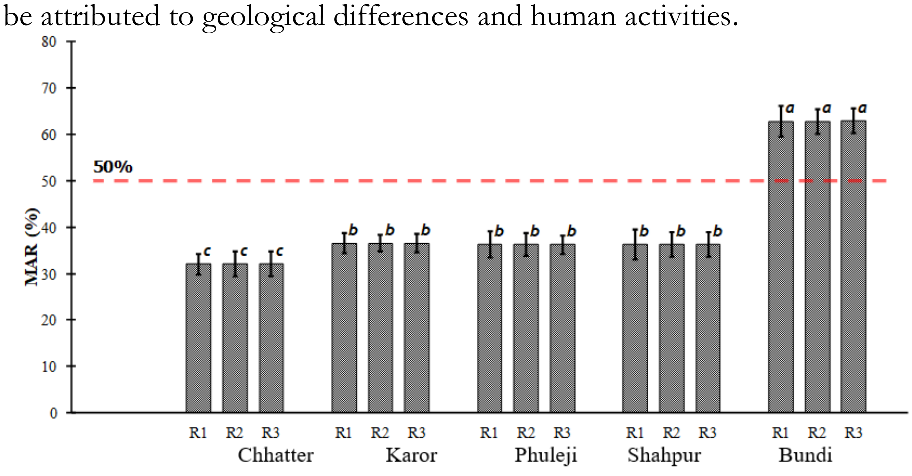

Figure 17. MAR in groundwater across various UCs of the district of Naseerabad

Kelly Ratio:

The results of the KR of the groundwater are shown in Figure 18. The KR values, indicative of sodium levels relative to calcium and magnesium, ranged from 0.85 in UC Chhatter to 2.20 in UC Karor and UC Phuleji. As per the recommended standards of FAO, the KR values less than 1 are suitable for irrigation; thus, the groundwater from UC Chhatter and UC Bundi are suitable, while the groundwater from UC Karor, Phuleji, and Shahpur is unsuitable due to the excessive KR ratio.

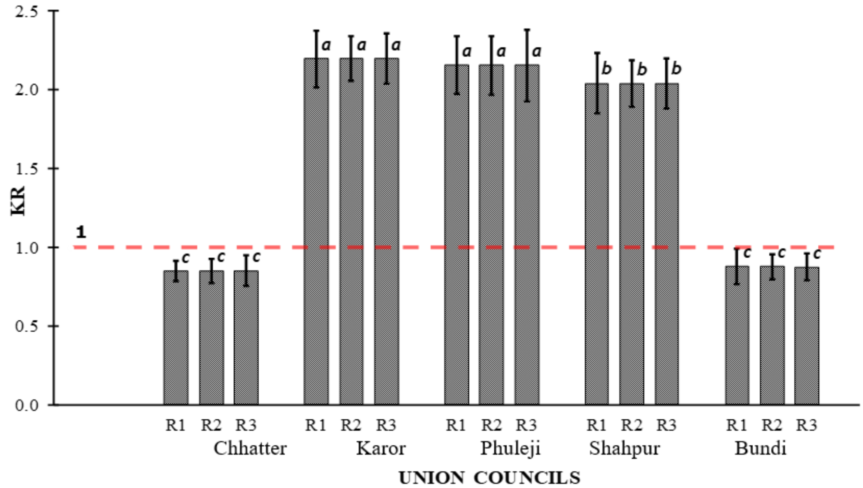

Figure 18. KR in groundwater across various UCs of the district of Naseerabad

Correlation Among Various Suitability Parameters:

The correlation analysis of various suitability parameters for water quality in different wells within the union councils of district Naseerabad, Baluchistan, reveals significant interrelationships among the parameters studied. As shown in Figure 19, the SAR exhibits strong positive correlations with SSP and KR, with r-values of 0.94 and 0.95, respectively. This indicates that higher SAR values are associated with increased SSP and KR, which are crucial for understanding water salinity issues. Additionally, SAR shows a moderately negative correlation with MAR (r = -0.29), suggesting that increased SAR is associated with decreased MAR, impacting soil structure and crop productivity. SAR's negligible correlation with PI (r = -0.080) implies limited direct influence on soil permeability. SSP, similarly, has strong positive correlations with SAR and KR (r = 0.94 and 0.99) and a moderate negative correlation with MAR (r = -0.46), indicating an inverse relationship with magnesium's role in soil chemistry. The negligible correlation between SSP and PI (r = 0.12) suggests a minimal impact on soil permeability. KR's strong positive correlations with SAR and SSP (r = 0.95 and 0.99) highlight its relevance in water suitability for irrigation. Its minimal correlation with PI (r = 0.11) and negative correlation with MAR (r = -0.45) further define the balance between sodium and magnesium ions. MAR's negative correlations with SAR, SSP, and KR (r = -0.29, -0.46, and -0.45) underscore the reduction of magnesium with increased sodium-related parameters. Its substantial negative correlation with PI (r = -0.86) indicates that lower MAR significantly reduces soil permeability, affecting drainage properties. PI shows weak correlations with SAR, SSP, and KR (r = -0.080, 0.12, and 0.11), but a strong negative correlation with MAR (r = -0.86), emphasizing magnesium's crucial role in maintaining soil permeability.

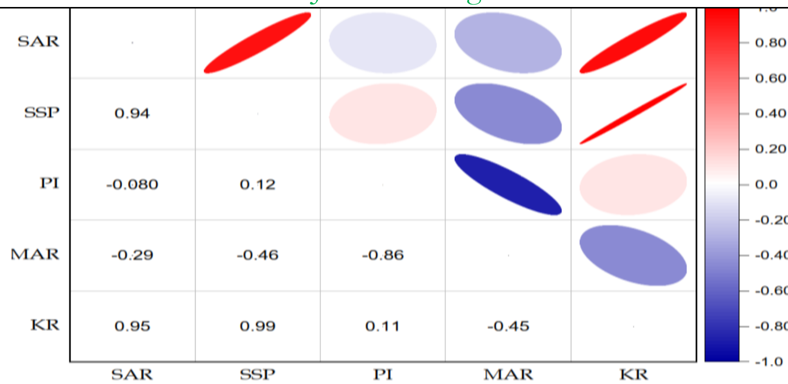

Figure 19. Correlation analysis among the investigated suitability parameters

Discussions:

Chemical analysis of groundwater:

Only Bundi wells meet recommended standards. EC, a key indicator of salinity, is critical for assessing water suitability for irrigation. High EC impairs soil health, reduces crop productivity, and poses health risks when consumed, necessitating mitigation strategies to address contamination sources and ensure sustainable water use [9]. A balanced pH (6.5–8.5) is critical for soil health, nutrient availability, and crop growth. Extremes in pH can cause nutrient imbalances, toxicities, and reduced plant productivity, highlighting the need for monitoring and managing groundwater quality for sustainable use [10]. High TDS levels can lead to soil salinity, reduced fertility, poor soil structure, and lower crop yields, potentially resulting in saline or sodic soils that are difficult to manage and less productive [11]. Elevated HCO_3 levels in Karor and Phuleji are linked to carbonate mineral dissolution and agricultural runoff. Bicarbonate, an indicator of alkalinity, impacts water quality for irrigation. High levels can raise soil pH, hinder nutrient absorption, and reduce calcium and magnesium availability, negatively affecting crop health and productivity [12]. Elevated chloride levels in Karor and Phuleji are attributed to agricultural runoff and saline intrusion, while lower levels in Chhatter and Bundi indicate minimal anthropogenic impact. High chloride levels in groundwater can harm salt-sensitive crops, causing leaf burn, reduced growth, and lower yields. Accumulated chloride in soil further damages roots and impairs nutrient uptake, emphasizing the need for managing chloride contamination [13].

Higher sulfate levels in Karor and Phuleji are linked to agricultural runoff and potential industrial pollution, while lower levels in Chhatter and Bundi reflect minimal anthropogenic impact. While sulfates are essential in small amounts for plant growth, high concentrations can cause soil acidification, nutrient imbalances, foliar burns, and reduced crop yields, making sulfate levels an important consideration for water quality management [14]. Calcium concentrations, highest in Karor and Phuleji, are within safe limits for irrigation, all falling below the 100 mg/L threshold. Similarly, magnesium levels, highest in Karor, Phuleji, and Bundi, are well below the FAO standard of 150 mg/L. Both calcium and magnesium are essential for plant growth and soil structure, but excessive levels can lead to soil crusting and water infiltration issues. In drinking water, high levels contribute to hardness, which can cause scaling but also provide beneficial dietary minerals. Balancing these levels is crucial for agricultural water quality [15]. The highest sodium levels are found in Karor and Phuleji, but all concentrations are below the FAO standard limit of 200 mg/L, suggesting safe sodium levels for human consumption. High sodium concentrations in groundwater can harm soil structure, reduce permeability, and affect plant growth. The Sodium Adsorption Ratio (SAR) is used to assess irrigation risks, with high SAR values indicating potential soil dispersion, poor aeration, and waterlogging, which can negatively impact crop growth [16]. Potassium levels vary across union councils due to geological differences and agricultural practices. All potassium concentrations are below the FAO standard limit of 50 mg/L, indicating safe levels for human consumption. Potassium is vital for plant nutrition, promoting root development and disease resistance, and enhancing crop growth. However, excessive potassium can disrupt nutrient uptake, causing imbalances that may affect plant health [17]. Nitrate levels are well below the FAO standard limit of 50 mg/L, indicating safe groundwater for human consumption. While high nitrate levels, often due to fertilizer leaching, can cause nutrient imbalances in crops and contribute to water eutrophication, the current nitrate concentrations in Naseerabad do not pose significant soil health risks [18]. Carbonates can also react with calcium and magnesium to form insoluble compounds, reducing the availability of these essential nutrients in the soil [19].

Suitability Analysis of Groundwater Using Different Indicators:

In Naseerabad, SAR values showed considerable variation across union councils, with higher SAR values in some areas indicating potential risks for soil degradation and reduced water infiltration [18]. High SAR values, often linked to geological formations or agricultural practices, can lead to soil dispersion, decreased permeability, and lower crop yields. The study highlights the importance of monitoring SAR to predict sodium-related risks and ensure sustainable irrigation practices. High sodium concentrations can negatively impact soil health, reduce nutrient viability, and harm crop growth, necessitating appropriate water treatment solutions for sustainable use [20]. The study of water quality in Naseerabad, Baluchistan, revealed significant variation in the soluble sodium percentage (SSP) across different wells. Monitoring SSP is essential for identifying water sources that could negatively impact crop growth and soil quality, highlighting the need for appropriate water management strategies to mitigate sodium-related issues [21]. The PI is essential for evaluating water quality in terms of its impact on soil permeability for irrigation. The Permeability Index assesses the risk of soil dispersion and reduced permeability due to sodium content, helping to maintain suitable conditions for crop growth and soil health [22]. ANOVA and LSD analyses of the Magnesium Ratio (MAR) in Naseerabad's wells revealed significant variations, with the highest MAR in UC Bundi and the lowest in UC Chhatter. The Magnesium Absorption Ratio (MAR) assesses the balance of magnesium in irrigation water, with high MAR values indicating excessive magnesium, which can harm soil structure and plant health by causing compaction and reducing root development [23]. The ANOVA and LSD analysis of the Kelly Ratio (KR) in Naseerabad wells revealed significant variations in water quality across different union councils, with minimal variation within the same union council, indicating consistent water quality. Monitoring KR is vital to ensure sustainable agricultural practices by identifying water sources that may affect soil health and implementing appropriate management strategies [24][25].

Conclusions:

According to FAO standards, the groundwater quality in District Naseerabad varied across union councils. EC, SAR, SSP, and KR were within permissible limits in UCs Chhatter and Bundi. pH, bicarbonate, chloride, sulfate, calcium, magnesium, sodium, potassium, and nitrate levels were acceptable in all UCs. PI values met the FAO criteria in Karor, Phuleji, Shahpur, and Bundi. However, MAR exceeded permissible limits in UC Bundi, indicating a potential magnesium hazard.

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