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Integrated Hydrochemical Modelling and Statistical Analysis for Irrigation Water Quality Assessment: A Case Study of Hadejia Water Systems in Northern Nigeria

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Abstract- Understanding the hydrochemical characteristics of groundwater and surface water is vital for sustainable irrigation management in semi-arid environments. This study employed integrated hydrochemical modelling and statistical analysis to evaluate water quality and irrigation suitability in Northern Nigeria. Thirteen water samples: ten groundwater (G_1 to G_{10}) and three surface waters (R_1 to R_3) were analysed for major cations and anions (Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, NO_3^-), electrical conductivity (EC), total dissolved solids (TDS), and pH. Irrigation indices, including Sodium Adsorption Ratio (SAR), Percent Sodium (%Na), Kelley's Ratio (KR), and Magnesium Hazard (MH), were modelled to classify suitability using FAO and USSL standards. Multivariate techniques: Principal Component Analysis (PCA), Hierarchical Cluster Analysis (HCA), were applied to identify dominant processes and inter-parameter relationships. The results showed that EC ranged from 152.9 to 682 µS cm^{-1} (mean = 345.6 µS cm^{-1}), while TDS ranged from 97.9 to 436.5 mg L^{-1} (mean = 234.1 mg L^{-1}), classifying most samples as low-salinity (C_1) and medium-salinity (C_2) waters. SAR values (0.21- 2.54) confirmed low sodicity (S_1) across all samples, whereas Na% (14 - 48%) and KR (< 1) indicated excellent to good irrigation water. PCA revealed three principal components explaining 83% of total variance, dominated by mineral dissolution and ion-exchange processes. HCA separated samples into three clusters: Cluster I (groundwater with higher mineralisation) and Cluster II (river water with moderate ionic concentrations). Overall, water from the study area is suitable for irrigation with minimal management practices. Continuous monitoring is recommended to track potential salinisation as agricultural expansion intensifies.

Keywords: Key Irrigation1, Water quality, hydrochemistry, and water quality index. SAR, KR, MH, IWQI.

I. INTRODUCTION

Water is the cornerstone of agricultural productivity and food security worldwide, yet the quality and availability of freshwater are increasingly under threat. Rapid population growth, urban expansion, and the intensification of agricultural activities have placed immense pressure on surface and groundwater systems [1]. Globally, irrigation now accounts for more than two-thirds of total freshwater withdrawals, and in many regions, it is the primary driver of aquifer depletion and water quality degradation. The growing reliance on irrigation has been accompanied by the rising challenge of siltation, salinisation, and chemical contamination, which alter the hydrological and geochemical balance of water bodies [2, 3]. Furthermore, the combined effects of climate change manifesting as erratic rainfall, prolonged droughts, and elevated evapotranspiration exacerbate these problems by reducing recharge rates, concentrating dissolved ions, and accelerating soil and water salinity [4]. Such conditions not only threaten sustainable agricultural production but also pose severe ecological and socio-economic consequences in vulnerable environments [5].

Across developing regions, particularly in sub-Saharan Africa, the sustainability of irrigation water has become an increasingly urgent issue. Declining water quality and unpredictable hydrological regimes are undermining crop yields and threatening rural livelihoods [6]. Sediment deposition and nutrient loading in irrigation canals, coupled with inefficient drainage systems, have intensified the risks of waterlogging and soil degradation. The accelerated pace of climate-induced hydrological shifts such as changes in rainfall intensity, the contraction of river floodplains, and increased evapotranspiration has further strained water management efforts [7]. In many African countries, including Nigeria, these pressures are amplified by population growth, poor land-use planning, and limited monitoring of water quality parameters [8]. As a result, irrigation schemes that were once productive are now constrained by salinity hazards, alkalinity imbalances, and the accumulation of toxic ions, all of which limit soil permeability and crop performance [9].

In Nigeria, the challenge of maintaining irrigation water quality is particularly evident in the northern semi-arid regions, where climate variability and anthropogenic disturbances have significantly altered river systems. Reduced rainfall, excessive evaporation, and sediment inflows from poorly managed upstream catchments have led to declining water volumes and deteriorating quality [10]. The Hadejia River Basin which is one of the most important agricultural zones in northern Nigeria is a good example this situation. It supports thousands of farmers who depend on surface and groundwater for irrigation, yet recurrent siltation, high evapotranspiration, and contamination from agricultural and domestic sources have rendered large portions of the water unsuitable for sustained use. The hydrological modifications caused by upstream dam operations and climate fluctuations have also diminished the natural flood cycles essential for soil replenishment and ecosystem balance. Consequently, the need to assess and manage the quality of irrigation water in this region has never been more critical [11].

This study, therefore, focuses on evaluating the irrigation water quality of the Hadejia Basin using multiple hydrochemical indices, including the Sodium Adsorption Ratio (SAR), Soluble Sodium Percentage (SSP), Sodium Percentage (Na%), Kelly's Ratio (KR), Magnesium Hazard (MH) and the Irrigation Water Quality Index (IWQI). These indices collectively provide insight into the suitability of groundwater and surface water for agricultural use, the degree of salinity and sodicity hazards, and the overall chemical composition influencing soil water interactions [12]. Through comprehensive monitoring and statistical interpretation of these indices, this research aims to enhance understanding of the hydrochemical processes governing irrigation water quality in the basin, provide a scientific basis for improved management strategies, and contribute to sustainable agricultural practices under changing climatic and environmental conditions.

Previous studies on irrigation water quality in the Hadejia Basin have provided important baselines for understanding groundwater behaviour in semi-arid environments. Notably, Tukur et al. (2018, 2019) examined shallow groundwater and reported that most samples were suitable for moderately salt-tolerant crops. Their analysis based on EC, SAR, %Na, PI, KR, and MH highlighted seasonal variation but remained largely descriptive, with limited statistical depth. The present study advances this foundation through a broader analytical framework. In addition to traditional indices, it applies correlation analysis, PCA and HCA to identify dominant geochemical controls and spatial associations influencing irrigation water quality. Overall, this work aimed at strengthening the understanding of irrigation water dynamics in the Hadejia Basin and provides a more data-driven basis for sustainable water management in semi-arid regions.

II. MATERIALS AND METHODS

Study Area

The Hadejia Basin lies within the semi-arid zone of north-eastern Nigeria, extending between latitudes 12°15′ and 12°45′ N and longitudes 9°30′ and 10°30′ E. It forms part of the larger Hadejia-Nguru wetland complex and drains a catchment that supports extensive irrigated agriculture. The area experiences a tropical continental climate characterised by two distinct seasons: a long dry season (October to May) and a short-wet season (June to September). Mean annual rainfall ranges between 500 mm and 700 mm, while average temperatures vary from 26 °C during the wet season to above 40 °C in the dry months. The dominant soils are sandy loams and clayey alluvium, which are moderately to poorly drained and prone to salinity when subjected to prolonged irrigation. Groundwater is the primary source of domestic and agricultural water, abstracted mainly from shallow hand-dug wells and boreholes tapping the Chad Formation aquifer system [13].

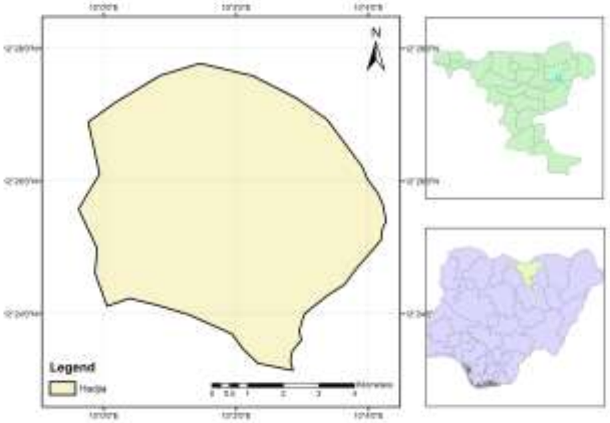

Figure 1: Map of the Study area (Hadejia Local Government Area of Jigawa State, Nigeria)

Sampling and Analytical Procedures

A total of 13 samples (10 from groundwater and 3 from surface water) were collected from selected boreholes and the river, respectively, across the basin during the dry season, when irrigation activity is at its peak and evaporative concentration is highest. Each sample was collected in pre-cleaned polyethylene bottles, filtered through 0.45µm membrane filters, and preserved at 4°C and was immediately taken to the laboratory for analysis. The American Public Health Association (APHA, 2017) methods were followed for the determination of physicochemical parameters.

Electrical conductivity (EC), total dissolved solids (TDS), and pH were measured in situ using portable digital meters. Major cations Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^+), and Potassium (K^+) were analysed using atomic absorption spectrophotometry (AAS), while anions, such as Chloride (Cl^-) and Nitrate (NO_3^-), were determined by spectrophotometric methods. All ionic concentrations were expressed in milligrams per litre (Mg/L), which were later converted to milliequivalents per litre (Meq/L) for hydrochemical evaluation [11].

Irrigation Water Quality Assessment

To evaluate the suitability of groundwater for irrigation purposes, several well-established indices were employed. These indices collectively assess the potential hazards associated with salinity, sodicity, alkalinity, and ion toxicity, which influence soil permeability and crop productivity.

Sodium Adsorption Ratio (SAR)

The Sodium Adsorption Ratio measure the interaction between Na+, Ca2+, and Mg2+ and its effects on soil permeability. A low SAR usually suggests limited sodicity risk, but this can be misleading when Ca2+ and Mg2+ are naturally scarce. Thus, SAR is most reliable when interpreted alongside other supporting indices [14]. SAR quantifies the relative abundance of Na^+ to Ca^{2+} and Mg^{2+}, which control the soil's exchangeable Na^+ and infiltration capacity. Waters with SAR < 10 are generally suitable for irrigation, while values above 26 indicate a high sodium hazard (Richards, 1954). SAR was calculated using equation (1) [15].

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}} \text{ ....Equation (1)}$$

where all ionic concentrations are in meq/L.

Sodium Percentage

Sodium Percentage (Na%) signifies how much Na+ is available compared to other major cations in the water. When Na+ begins to dominate this balance, the soil may gradually lose its natural structure, especially under continuous irrigation. Na% remains a useful indicator when assessing the suitability of water for irrigation due to its sensitivity to early shifts in Na+ levels and is calculated using equation (2) [16].

$$Na\% = \frac{Na^+}{Ca^{2+}+Mg^{2+}+Na^++K^+} \text{ x } 100 \text{ … … …. Equation (2)}$$

Soluble Sodium Percentage (SSP)

Soluble Sodium Percentage (SSP) indicates how much of the readily exchangeable Na+ is present in the overall ionic mix of the water. When SSP becomes elevated, it often signals a gradual drift toward Na+ enrichment on the soil's exchange complex. Thus, SSP helps reveal sodicity risks that may not be noticeable based on broader indices alone [17]. SSP is computed based on the quantity of Ca2+, Na+, Mg2+ and K+ in irrigation water utilising Equation (3) [18]. SSP values above 50 are indications of unsuitable quality of the irrigation water since high values reduce the permeability of the soil.

$SSP = \frac{Na^{+}}{Ca^{2+}+Mg^{2+}+Na^{+}} \text{x } 100$ .... Equation (3)

This parameter expresses the contribution of sodium and potassium to total cations. According to Wilcox (1955), SSP < 20 % denotes excellent quality, whereas values exceeding 80 % suggest unsuitability for irrigation.

Kelly's Ratio (KR)

Kelley's Ratio examines whether Na+ outweighs the combined stabilising effect of Ca2+ and Mg2+ in irrigation water. When this balance tilts in the Na+ direction, soils will begin to lose their structural organisation over time. KR can therefore serve as an early-warning tool for identifying waters that may promote sodicity even when other parameters appear acceptable [19]. The KR values are determined by computing the total amount of Na+ against the sum of Ca2+ and Mg2+ ions as presented in Equation (4) [15].

$KR = \frac{Na^{+}}{Ca^{2+}+Mg^{2+}}$ .... Equation (4)

Values < 1 indicate permissible limits, while KR > 1 suggests excess sodium that could deteriorate soil structure (Kelly, 1963).

Magnesium Hazard (MH)

Magnesium Hazard examines how the concentration of Mg2+ in relation to Ca2+ might affect the soil. Elevated Mg2+ levels can deteriorate soil aggregates, thereby reducing infiltration, especially in fine-textured soils. MH provides a practical way to predict these structural challenges before they become evident in the field [20]. MH is computed using the Ca2+ and Mg2+ average concentrations by the following equation (5) [21]

$MH = \frac{Mg^{2+}\,X100}{Ca^{2+}+Mg^{2+}}$ .... Equation (5)

Irrigation Water Quality Index (IWQI)

The IWQI integrates several chemical indicators into a single measure that reflects the combined effect of salinity and sodicity on irrigation suitability. The index provides a balanced view of overall water quality by weighing each parameter based on its importance [22]. This makes IWQI particularly useful when individual parameters point in different directions. The IWQI is computed using equation (6) [21].

$IWQI = \sum(W_i \times Q_i)$ .... Equation (6)

where Wi represents the assigned weight of each parameter and Qi the corresponding sub-index value derived from normalised data ranges. The resulting IWQI values classify

Data Treatment and Statistical Analysis

All analytical results were subjected to descriptive statistical analysis, including mean, standard deviation, and coefficient of variation, to characterise the variability of hydrochemical parameters. Correlation analysis was used to examine interrelationships among ions, while Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) were applied to identify dominant geochemical processes and spatial groupings. The indices were evaluated using internationally recognised classification schemes to determine the overall irrigation suitability of groundwater in the Hadejia Basin.

III. RESULTS AND DISCUSSION

Irrigation Water Suitability Indices

Assessing the suitability of water for irrigation requires an integration of complementary chemical indices, whereby each highlights a different dimension of salinity and sodicity risk. In this study, seven commonly used indicators were applied: the Electrical Conductivity (EC), the Sodium Adsorption Ratio (SAR), which reflects the effect of sodium relative to calcium and magnesium on soil permeability; Sodium Percentage (Na%) and Soluble Sodium Percentage (SSP), both of which describe the proportional dominance of sodium within the overall cation balance; Kelley's Ratio (KR), a sensitive measure of sodium excess over divalent cations; Magnesium Hazard (MH), which assesses the relative influence of magnesium on soil structural behaviour; and the Irrigation Water Quality Index (IWQI), a composite tool that integrates these parameters into a single overall suitability rating. Together, these indices provide a coherent framework for interpreting both the immediate and long-term implications of irrigation water on soil stability, crop performance, and environmental sustainability.

Electrical Conductivity (EC)

The Electrical Conductivity (EC) is known to be a principal indicator of salinity hazard in irrigation water. This is because EC reflects the total ionic strength of the water, which controls osmotic pressure in the soil solution, water uptake, salt accumulation in the root zone, as well as long-term soil permeability and infiltration stability [21]. The higher the salinity, the lower the ability of plants to absorb water due to osmotic stress, a phenomenon known as physiological drought [23] which is one of the most hazardous challenges in arid and semi-arid regions [24] such as northern Nigeria.

In this study, the EC values (in μS/cm) (Table 1) range was found to be within four categories, where G4, G9, and R2 (≈150 μS/cm) were characterized as Lowest, while G1, G5, G6, G7, R1, R3 (230–340 μS/cm) fall within the moderate category. Sampling points G2 (460 μS/cm) and G10 (430 μS/cm) were found to be within the high while G3 (680 μS/cm) and G8 (515 μS/cm) fall within the very high category. The water samples were further classified based on FAO/USSL standards and all the samples fall into two categories, C1 (Low salinity) to C2 (Medium salinity) in accordance with their values.

The result shows sampling points G4, G7, G9, R1, R2, R3 fall within C1 (Excellent) water for irrigation. The C1 water is known to have very low osmotic stress, good for sensitive crops (fruits, vegetables, legumes), and there is minimal risk of salt accumulation even with high intensity of irrigation [18]. While the sampling points G1, G2, G3, G5, G6, G8, and G10 fall under the C2 (Moderate Salinity) samples [25]. This water class is known to be suitable for most field crops (maize, millet, sorghum) common in arid areas such as Hadejia. However, C2 class are known to cause little yield reduction, especially when there is high evaporation [18]. Thus, there is a need for leaching fraction management and continuous monitoring of EC, particularly during the dry season, for sustainable development. On the environmental implications of high EC (C2), it has been established to increase the energy plants need to absorb water, especially under harmattan dry winds, or high evapotranspiration season or poorly drained clayey soils, thus leading to yield reduction [26]. Similarly, high EC has a stabilising effect on clay aggregates by compressing the electrical double layer and in the process, affecting soil permeability [21].

Sodium Percentage (Na%)

Sodium Percentage (Na%) represents the amount of Na^+ compared to total major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) [27]. Na% is a vital indicator of sodicity hazard, reflecting soil permeability reduction, clay dispersion and swelling, loss of aggregate stability, decline in hydraulic conductivity and reduction in water infiltration. Thus, Na% is principally significant in semi-arid regions due to high evaporation and insufficient rainfall that can dilute or flush accumulated salts [22].

The result shows three categories of Na% in the study area ranges between 55–83%, indicating varying sodicity hazards from permissible to unsuitable (Table 1 and 2). The sampling point G1 was found to have the highest Na% (83.12%) making it the most sodic water Unsuitable in the area. This class is known to promotes clay dispersion, disrupts cation exchange balance, lowers aggregate stability, creating compaction of soil surface thereby leading to poor infiltration and waterlogging during irrigation [28].

The second class which accounts for most of the remaining sampling points with the exception of (G10 and R3) falls within Doubtful Na% (60 - 80%). A sodicity class known for reduced water movement in the soil, gradual sealing of clayey soils leading to decreased aeration and root suffocation as well as increased energy demand for water uptake [29]. The remaining two sampling points G10 and R3 falls within Permissible (40 - 60%) Na% showing moderate sodium accumulation risk [30].

Table 1: Showing summary of water Quality Indies

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S/No	Sample	EC_dS_m	SAR	Na %	SSP	KR	MH %	EC Class	SAR Class	Wilcox Class	KR Flag	MH Flag
1	G1	0.32	3.64	83.12	29.56	1.75	11.82	C2 (Medium)	S1 (Low)	Unsuitable	Risk (>1)	OK (≤50 %)
2	G2	0.46	2.14	68.73	33.46	1.07	6.82	C2 (Medium)	S1 (Low)	Doubtful	Risk (>1)	OK (≤50 %)
3	G3	0.68	1.80	68.36	25.84	0.82	8.67	C2 (Medium)	S1 (Low)	Doubtful	OK (≤1)	OK (≤50 %)
4	G4	0.15	1.75	72.07	24.99	0.90	5.76	C1 (Low)	S1 (Low)	Doubtful	OK (≤1)	OK (≤50 %)
5	G5	0.34	1.70	63.91	31.88	0.88	4.32	C2 (Medium)	S1 (Low)	Doubtful	OK (≤1)	OK (≤50 %)
6	G6	0.27	2.11	73.79	26.50	1.01	9.09	C2 (Medium)	S1 (Low)	Doubtful	Risk (>1)	OK (≤50 %)
7	G7	0.23	1.66	67.25	27.17	0.83	7.48	C1 (Low)	S1 (Low)	Doubtful	OK (≤1)	OK (≤50 %)
8	G8	0.52	2.32	67.79	36.85	1.14	6.83	C2 (Medium)	S1 (Low)	Doubtful	Risk (>1)	OK (≤50 %)
9	G9	0.15	1.58	72.49	22.77	0.83	5.48	C1 (Low)	S1 (Low)	Doubtful	OK (≤1)	OK (≤50 %)
10	G10	0.43	1.68	55.78	35.84	0.81	7.36	C2 (Medium)	S1 (Low)	Permissible	OK (≤1)	OK (≤50 %)
11	R1	0.17	1.65	64.66	29.61	0.84	5.53	C1 (Low)	S1 (Low)	Doubtful	OK (≤1)	OK (≤50 %)
12	R2	0.15	1.57	58.25	34.50	0.83	5.54	C1 (Low)	S1 (Low)	Permissible	OK (≤1)	OK (≤50 %)
13	R3	0.16	1.57	59.61	32.08	0.79	5.51	C1 (Low)	S1 (Low)	Permissible	OK (≤1)	OK (≤50 %)

Tables 2: Classification of Na% its Implications (Modified from [22])

Na%	Class	Soil/Agronomic Implication
< 20%	Excellent	No sodicity hazard
20 - 40%	Good	Suitable for irrigation
40 - 60%	Permissible	Moderate sodium buildup risk
60 - 80%	Doubtful	Significant sodicity hazard
> 80%	Unsuitable	Severe structural damage risk

Magnesium Hazard (MH%)

Magnesium Hazard (MH%) measures whether Mg^{2+} exceeds Ca^{2+} in irrigation water as high Mg^{2+} relative to Ca^{2+} can lead to soil alkalinity, loss of aggregate strength, increased clay swelling and decrease hydraulic conductivity among other things [31]. Interestingly, all the sampling points are within safe MH% (4.32 - 11.82%) (Table 1) far below the 50% [18, 22]. This means that Ca dominates over Mg and the Ca-Mg interaction supports good soil structure reduce the risk of clay swelling while neutralizing some effects of Na% [32, 33].

Soluble Sodium Percentage (SSP)

SSP is a good sodicity indicator that is closely related to Na% which is expressed specifically in terms of Na^+ against all soluble major cations in the irrigation water (Ca^{2+}, Mg^{2+}, Na^+, and K^+) [34]. Presence of high SSP means that sodium dominates the exchange complex, thereby increasing the dispersion of soil clay particles, loss of aggregate stability, surface crusting and sealing, reduced infiltration and hydraulic conductivity and causing poor aeration and root stress [35]. All the sampling points showed that the SSP values are within a 20 - 40% window (Table 1), placing the waters between “Good” and “Permissible” [36].

Looking at this result from a purely SSP perspective, the water is largely acceptable, but there is an underlying trend toward higher sodium contribution in G8, G10, G2, R2, R3, which approach the upper bound of the “Permissible” class. This is because, even when SSP values fall within the “Good - Permissible” range, readings above 30% indicate an early warning of gradual sodium accumulation on the soil exchange complex, particularly under repeated irrigation cycles. [37]. This may lead to a gradual decline in hydraulic conductivity in clayed soils, thereby leading to increased susceptibility to surface crusting, which affects germination and early seedling establishment [38]. Thus, continued use of such water for irrigation for an extended period of time can cause micro and macro porosity loss, which will directly affect the root penetration and oxygen diffusion [35].

Sodium Adsorption Ratio (SAR)

SAR is the most commonly used global index for sodicity hazard because it combines the activity (not just concentration) of Na^+ (monovalent dispersive ion) or Ca^{2+} and Mg^{2+} (divalent flocculating ions). Moreover, SAR gives an estimate of how sodium will behave when water interacts with soil clay minerals [39, 40].

Table 3: Standard FAO–USSL SAR Classification (Modified from [22])

SAR	Sodicity Class	Soil Behaviour
0 - 10	S1 (Low)	Safe; little sodium hazard
10 - 18	S2 (Medium)	Moderate hazard; structural decline possible
18 - 26	S3 (High)**	Severe hazard, requires gypsum or amendments
> 26	S4 (Very High) **	Unsuitable for irrigation

The result of SAR revealed that all the samples fall between 1.57 to 3.64 (Table 1 and 3), thus, S1 (Low sodicity) [40]. At first glance, one may assume the water is safe for irrigation, but this may be misleading without companion indices (Na%, SSP, KR) [41]. It is important to note that, based on these results, Na^{2+} is unable to dominate the soil exchange complex; instead, Ca^{2+} and Mg^{2+} continue to exert their flocculating effects to maintain structural stability [42, 43]. Therefore, irrigation with these waters may usually sustain acceptable infiltration and permeability. However, this is not always the case, because SAR might underestimate real sodicity hazard [44, 14].

The SAR limitation becomes evident when it is compared with other sodium-related indices such as Na% and Kelley's Ratio, which clearly indicate greater sodicity stress than SAR implies. The discrepancy arises because SAR evaluates Na^{2+} activity in relation to Ca^{2+} and Mg^{2+}, whereas proportion-based indices capture the broader imbalance in the cationic system and its implications for soil structure [45]. As a result, relying solely on SAR would mask the potential for soil dispersion, permeability loss, and long-term structural degradation. The coexistence of low SAR values with high sodium proportions exemplifies a classical scenario in which SAR fails to detect actual sodification hazards, particularly in semi-arid regions where low-hardness waters are common [46]. Given these complex hydrochemical conditions, SAR should not be used in isolation; rather, it must be interpreted alongside more sensitive indices that provide a more realistic picture of the soil structural risks and long-term sustainability implications of the irrigation water [47, 48, 14].

Kelley's Ratio (KR)

Kelley's Ratio (KR) provides a direct evaluation of whether Na+ concentrations exceed the combined levels of Ca+ and Mg+ two essential flocculating cations that maintain soil structural stability [49]. In this study, KR values revealed a clear distinction between safe and Na+ dominated waters. Four samples (G1, G2, G6, and G8) exceeded the critical threshold of KR > 1 (Table 1), indicating that Na+ is present in proportions capable of degrading the soil aggregates [30]. These same samples are also characterised by low Ca+ and Mg+ concentrations, a condition that magnifies sodium's dispersive effect and explains why KR is such a sensitive indicator in this hydrochemical context [50]. Though, the SAR values are low, but Na% and KR are high in several samples Na% up to 83%, KR > 1 in G1, G2, G6, G8 whereas SSP approaching 37% and many EC values were low, therefore, reduced flocculation which means, absolute Na^{+} concentrations are not dangerously high, but Ca^{2+} + Mg^{2+} concentrations are relatively low thereby causing proportion-based indices to show greater risk [22].

The environmental implications of the KR results are extensive. Waters with KR > 1 pose a genuine risk of progressive sodification, particularly in soils with fine textures or those prone to poor drainage, such as clay [51]. Continued use of such water is likely to induce clay dispersion, surface sealing, thereby causing reductions in infiltration and eventual loss of pore continuity, which may aggravate waterlogging or increased alkalinity [52]. These findings are consistent with the patterns observed in Na%, SSP, Wilcox, and IWQI classifications (Table 1), all of which identify G1, G2, G6, and G8 as the most sodicity-prone waters. In contrast, samples with KR < 1, most notably R1, R2, and R3, emerge as high-quality irrigation sources, characterised by a good infiltration pattern and a low risk of structural impairment. The equilibrium among Ca2+, Mg2+ and Na+ ions support long-term irrigation sustainability and further confirms that surface water in the area is more suitable for irrigation than the groundwater. Overall, KR emerges as the most dependable single index for diagnosing sodicity risk in this environment [53, 15].

Wilcox Classification

The Wilcox diagram is a standard method used to evaluate irrigation water quality through a bivariate plot in which Electrical Conductivity (EC) represents the salinity hazard placed on the X-axis, while Sodium Percentage (Na%) represents the sodicity hazard on the Y-axis. Each water sample is positioned within one of the established quality zones: Excellent, Good, Permissible, Doubtful, and Unsuitable depending on the collective influence of its EC and Na% [22].

In this study, the Wilcox classification was used in grouping the samples into three categories (Table 1). G1 was identified as Unsuitable, G10, R2, and R3 fell within the Permissible class, while the remaining samples: G2, G3, G4, G5, G6, G7, G8, G9, and R1were classified as Doubtful. The classification of G1 as unsuitable is explained by its unusually high Na% (83.12%) in combination with a moderate EC value (0.32 dS/m). Although its EC falls within the C2 (medium salinity) range and its SAR was low (S1), the very high Na% shifts the water into the "Unsuitable" region of the Wilcox plot [54]. This reflects a strong dominance of Na in the cationic composition, which substantially increases the likelihood of soil erosion, crust formation, and loss of permeability effects that are particularly severe in fine-textured soils [55]. Hence, a continues irrigation with G1 would require significant management interventions such as gypsum application, regular leaching, and close soil monitoring to avoid long-term degradation [56].

The Wilcox results further reveal that all the water samples are somewhat influenced by Na^+ since none of the samples qualify as Excellent. Most groundwater samples and one river sample fall into the "Doubtful" zone. This suggests that, although salinity levels remain within acceptable limits, Na^+ already presents a concern [54]. From an environmental standpoint, long term use of water designated as Doubtful or Unsuitable categories may lead to increased soil sodicity, reduced infiltration rates, greater runoff and erosion, and progressive alkalinity build-up. These changes collectively threaten soil structure, reducing its agricultural productivity over time [56]. Thus, such waters may be safely used only under specific conditions namely, well - drained, coarse-textured soils, where the risk of sodification is considerably lower. However, when applied to clay-rich or poorly drained soils, these waters can gradually impair soil structure, decrease infiltration thereby, promoting waterlogging and surface compacting. Consequently, the Wilcox interpretation underscores the need for careful irrigation scheduling, soil monitoring, and, where necessary, the adoption of sodicity-mitigation strategies [54].

Integrated Irrigation Water Quality Index (IWQI)

The IWQI provides a consolidated assessment of the suitability of the sampled waters by merging the behaviour of several key chemical parameters into a single, interpretable score and the final values obtained reflect a clear hierarchy across the area. Threshold - based IWQI scores range from approximately 57 in G1 to nearly 72 in R3, placing all groundwater samples within the Permissible category, while the river waters attain Good to Excellent quality. This outcome arises from the collective contribution of the Qi sub-indices, whose individual responses to salinity, sodium balance, and the broader cation chemistry shape the overall IWQI score (Table 1 and 4). Thus, the moderate EC (152-682 µS/cm), uniformly low SAR values (1.57-3.64), and favourable MH helps in controlling the effects of high Na^+ in many samples. The percentile-based IWQI further refines this picture [22]. The IWQI delineate G1, at roughly 17% as the poorest water, whereas R2 and R3, both exceeding 94% were identified as the most suitable for irrigation. This simultaneous application of absolute thresholds and within-dataset ranking creates a more complete and context-appropriate assessment than either global guidelines or single-parameter measures can provide [16].

Tables 4 showing Classification Matrix of all the indies

Sample	EC	Na%	SSP	SAR	KR	Wilcox	IWQI	Final Verdict
G1	C2	Very High	High	Low	>1	Unsuitable	Worst	Unsuitable
G2	C2	Very High	High	Low	>1	Doubtful	Permissible	Moderate risk
G3	C2	Very High	High	Low	<1	Doubtful	Doubtful	Risky (salinity + sodicity)
G4	C1	High	Moderate	Low	<1	Doubtful	Good	Conditionally safe
G5	C2	High	Moderate	Low	<1	Doubtful	Good	Acceptable
G6	C2	Very High	High	Low	>1	Doubtful	Permissible	Sodicity risk
G7	C1	High	Moderate	Low	<1	Doubtful	Good	Good but sodium-influenced
G8	C2	Very High	High	Low	>1	Doubtful	Doubtful	Significant sodicity risk
G9	C1	High	Moderate	Low	<1	Doubtful	Good	Marginally acceptable

Tables 4 showing Classification Matrix of all the indies

Sample	EC	Na%	SSP	SAR	KR	Wilcox	IWQI	Final Verdict
G10	C2	Lowest Na%	Moderate	Low	<1	Permissible	Good	Better-quality groundwater
R1	C1	High	Moderate	Low	<1	Doubtful	Good	Good quality river water
R2	C1	Moderate	Low	Low	<1	Permissible	Excellent	Excellent water
R3	C1	Moderate	Low	Low	<1	Permissible	Excellent	Best water in dataset

The broader interpretive power of the IWQI becomes evident when its outcomes are compared with the sodium related indices. Waters with more balanced Ca - Mg - Na compositions, such as R2 and R3, consistently present a higher composite scores, reflecting their good infiltration potential and low structural hazard. On the other hand, samples dominated by Na^+ especially G1 (Na% = 83 and KR = 1.75) alongside other samples with high-Na like (G2, G6, and G8) are downgraded despite their low SAR, revealing the limitations of SAR as a stand-alone measure in low Ca^{2+} waters [44]. Through aligning more closely with Na%, SSP, and KR, the IWQI captures sodicity risks that SAR overlooks (Table 4), offering a more accurate representation of how the soil is likely to respond under irrigation [57]. Its strength lies in synthesising multiple dimensions of risk into a single classification that is both scientifically defensible and practically meaningful for irrigation decision-making [22].

Hydrochemical Characteristics of the Groundwater

Table 5 shows that the Electrical conductivity (EC) ranged from 152.9 to 682 µS cm^{-1} (mean = 311 µS cm^{-1}), indicating low to moderate salinity. Total dissolved solids (TDS) varied between 97.9 and 436 mg L^{-1}, classifying the water as fresh according to standard irrigation guidelines. These low EC and TDS values imply limited mineralization, reflecting active recharge and minimal evaporative concentration. The pH (7.42- 9.58; mean = 8.35) revealed slightly to strongly alkaline conditions, primarily governed by carbonate equilibria and CO_2 degassing.

Table 5: Descriptive Statistic of the analytical data for irrigation water suitability

Variable	Minimum	Maximum	Mean	Std. deviation
Mg	0.94	3.13	1.73	0.61
Ca	34.21	44.60	37.59	2.63
Na	34.23	87.07	44.86	13.75
K	14.32	276.30	103.41	61.37
EC	152.90	682.00	311.02	164.76
TDS	97.86	436.48	199.05	105.45
PH	7.42	9.58	8.35	0.71
NO3	0.00	0.08	0.03	0.03
Cl	23.69	38.49	30.02	4.47

Calcium (34-45 mg L^{-1}) dominated the cation composition, followed by sodium (34-87 mg L^{-1}), magnesium (0.9-3.1 mg L^{-1}), and potassium (39-270 mg L^{-1}). Chloride (23.7-38.5 mg L^{-1}) was the major anion. This composition typifies a Ca-Mg-Cl-HCO_3 water type, common in shallow alluvial aquifers influenced by silicate and carbonate weathering. The dominance of divalent cations (Ca^{2+}, Mg^{2+}) over Na^+ underscores low sodium exchange and fresh recharge signatures.

Correlation Analysis of Hydrochemical Parameters

The correlation matrix (Table 6) was employed to explain the interdependence among the parameters and to pinpoint the dominant processes controlling the hydrochemistry of the area. The correlation is set at (α = 0.05) significant to show the geochemical interactions and possible sources or reactions controlling ion distributions within the study area.

Table 6: Correlation matrix of the hydrochemical parameters

Variables	EC	TDS	PH	NO_3^-	Cl^-	Ca^{2+}	K	Mg^{2+}	Na^+
EC									
TDS	1.0000	1							

PH	-0.1936	-0.1936	1						
NO3	-0.0441	-0.0441	-0.2339	1					
Cl	0.6711	0.6711	-0.1961	-0.2087	1				
Ca	0.5974	0.5974	-0.3484	-0.1913	0.3685	1			
K	0.0779	0.0779	0.0129	-0.1913	0.1053	0.0779	1		
Mg	0.2338	0.2338	-0.0903	-0.1618	0.3421	0.4416	0.3766	1	
Na	0.4516	0.4516	-0.2821	-0.2339	0.5361	0.3742	0.4258	0.6323	1

Values in bold are different from 0 with a significance level alpha=0.05

A perfect positive correlation (r = 1.000) exists between EC and TDS, confirming that major ions are the main variables controlling these parameters, indicating mineralization of water through dissolution and other related processes. The strong connection between EC and TDS suggests progressive evaporation, solute minerals accumulation and rock–water interactions as the major processes causing salinity [58]. Cl^- exhibits a strong correlation with EC (r = 0.67) and TDS (r = 0.67), indicating that salinity is largely controlled by Cl^- enrichment. This pattern typically indicates multiple processes such as evapoconcentration, leaching of halite minerals, or agricultural runoff causing salts to accumulate due to evapotranspiration [59].

On the other hand, NO_3^- shows weak and negative correlations with most ions (r = - 0.04 to - 0.23), implying site-specific anthropogenic inputs, such as fertilizer applications or leaching of organic waste [60]. $Ca^{2+}$and Mg^{2+} were found to show moderate correlation (r = 0.44), indicating a common source most likely a carbonate dissolution and cation exchange equilibria. Similarly, Ca^{2+}aexhibit a moderate correlation with EC (r = 0.56) suggesting that weathering is significantly contributing to total salinity. Moderate correlations between Na^+ and Mg^{2+} (r = 0.63) and between Na^+ and Cl^- (r = 0.54) imply minor cation exchange and silicate weathering contributions. K^+ shows moderate correlations with Na (r = 0.43) and weak correlations with Mg (r = 0.38) indicating a likely slight influence of fertilizer application [61].

Principal Component Analysis (PCA)

The resulting output of the PCA shows that only 3 components passed the eigenvalue bench mark of ≥1 [62] after varimax-rotation explaining over 80% of the total variance:

Table 7. Factor pattern after Varimax rotation:

Parameters	PC1	PC2	PC3
EC	0.96	0.04	0.04
TDS	0.96	0.04	0.04
PH	-0.22	-0.19	-0.81
NO3	-0.14	-0.31	0.73
Cl	0.78	0.23	-0.08
Ca	0.67	0.29	0.17
K	-0.06	0.76	-0.14
Mg	0.23	0.80	0.03
Na	0.44	0.75	0.06

Values in bold correspond for each variable to the factor for which the squared cosine is the largest

Values in bold correspond for each variable to the factor for which the squared cosine is the largest

The first component (Table 7), PC1 accounts for the highest proportion of variances (44 %) mainly associated with EC, TDS, Cl, Ca all of which display high positive loadings 0.96, 0.96, 0.77 and 0.67 respectively. This component reflects ion enrichment originated from water–rock interactions, representing a salinity–hardness factor [63, 64]. The implication of this component to irrigation is that, elevated salinity is known to impair soil structure, reduce osmotic potential, and limit water uptake by plants, thereby reducing the crop yield [65].

The second component PC2 is responsible for about 28% of the total variance, characterized by high positive loadings for Na^+ (0.75), Mg^{2+} (0.80) and K^+ (0.75). This component is accumulated by cations most likely influenced by a combination of silicate mineral weathering and cation exchange processes taking place when the groundwater interacts with the aquifer matrix [66].

Generally, this component reflects the groundwater flows through silicate-rich geological formations, thereby causing breakdown of Na^+ and K^+ bearing silicate minerals in to the water [64]. Whereas, the increase in magnesium concentrations is likely attributable to cation exchange processes that arise as a result of interaction between groundwater with clay minerals along the groundwater flow path [67]. The practical implication of this component from an irrigation perspective is that, high concentration of these minerals can affect soil quality and crop performance. Moreover, elevated Na^+ concentrations can contribute to soil sodicity, thereby reducing the soil permeability, thus, limits water infiltration and affects the ability of crops to absorb moisture [68]. Noticeably, this component highlights the need for continuous monitoring of groundwater in the area for a sustainable irrigation activities and better agricultural productivity.

The third component PC3 explains 11% of the total variance characterized strong inverse relationship between pH (-0.81) and NO_3 (0.73) showing redox reaction likely caused by anthropogenic activities, most likely application of nitrogen-based fertilizers. This component has important consequences, as increasing NO_3^- levels in irrigation water is known to enhance nutrient availability in the short term. However, continuous nitrate enrichment may lead to soil acidification, altering nutrient balance in the process, reducing microbial activity, thus, negatively affecting soil fertility over time [21].

Similarly, from an environmental point of view, the presence of high NO_3^- concentrations signal potential contamination from agricultural runoff or poor fertilizer management, increasing the risk of nitrate leaching into groundwater. This would likely lead to a chain of environmental consequences: eutrophication of surface waters, causing algal blooms, oxygen depletion, and biodiversity loss in addition to deteriorating drinking water quality posing risks such as methemoglobinemia ("blue baby syndrome") [69]. Hence, there is an urgent need for best management practice particularly with respect to fertilizer application, regular monitoring, and integrated nutrient-water management to protect both agricultural sustainability and environmental health in general.

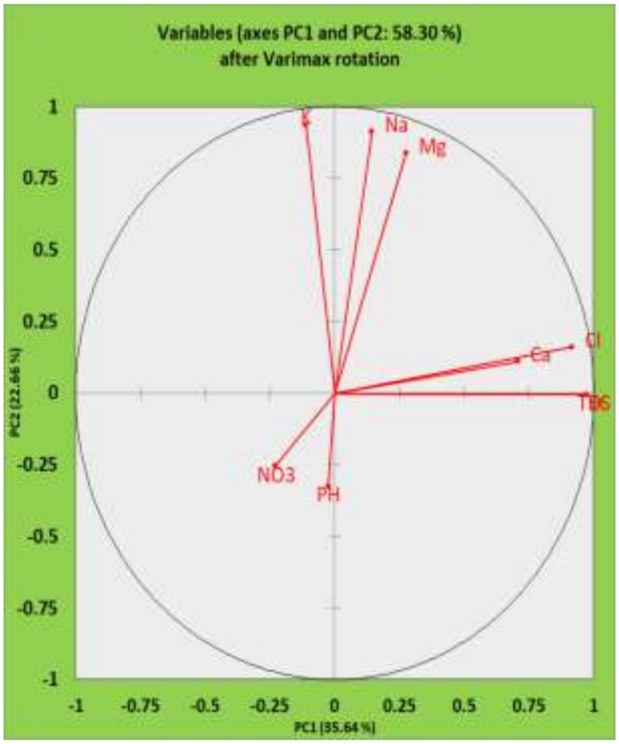

Figure 2: PCA biplots showing dominant water quality parameters for irrigation

The loading plot after Varimax rotation (figure 2) suggests a clear separation of the major hydrochemical variables along the first two PCs, which collectively explain 58.30% of the total variance (PC1 = 35.64%, PC2 = 22.66%). The first axis is strongly controlled by TDS, Cl^-, and Ca^{2+}, all of which cluster tightly on the positive side of PC1. This suggests that the dominant slope captured by PC1 reflects a general salinity mineralisation pattern, where samples with higher ionic strength are mainly influenced by Cl- and Ca2+ contributions, in conjunction with overall dissolved solids. The close alignment of these parameters indicates a shared geochemical origin or a consistent set of processes likely related to water rock interaction or evaporative concentration which elevate the background salinity of the samples [70].

The second axis reflects a separate geochemical influence dominated by K^+, Na^+, and Mg^{2+}, whose positive loadings suggest the role of cation exchange and the selective enrichment of these ions, likely linked to clay–water interactions [71]. In contrast, NO_3^- and pH show weak loadings and plot in the lower quadrants, indicating limited contribution to the main hydrochemical pattern and possible control by localized agricultural inputs [72]. The near-orthogonal separation between the salinity group (TDS, Ca^{2+}, Cl^-) and the NO_3^- and pH suggest minimal interaction, pointing to different processes acting simultaneously [73]. The PCA plot indicates two main controls on water chemistry: a salinity driven component and a secondary cation-exchange process involving Na^+, K^+, and Mg^{2+}. Overall, the dominance of PC1 underscores natural geochemical control on groundwater quality, whereas PC2 highlights ion exchange and PC3 captures localized anthropogenic inputs.

Hierarchical Cluster Analysis (HCA)

A total of three clusters are identified within the dendrogram of hydrochemical parameters (Figure 3) indicating distinctive geochemical processes controlling the water quality of the area.

Cluster I (Ca-Mg-Na-EC-TDS-Cl)

The first cluster consists of (Ca-Mg-Na-EC-TDS-Cl) representing the salinity–hardness family. This group is characterized by ionic components which explain the total mineralization and salinity hazard of the water. The strong correlation between electrical EC and TDS suggests that the ionic composition and solute concentration of the groundwater are predominantly controlled by enrichment mechanisms such as evaporative concentration, mineral dissolution through water–rock interaction, and ion exchange processes [72]. The coming together of Ca, Mg and Na in same group further highlights the role of carbonate and silicate weathering, alongside cation exchange dynamics, in governing the groundwater chemistry [36].

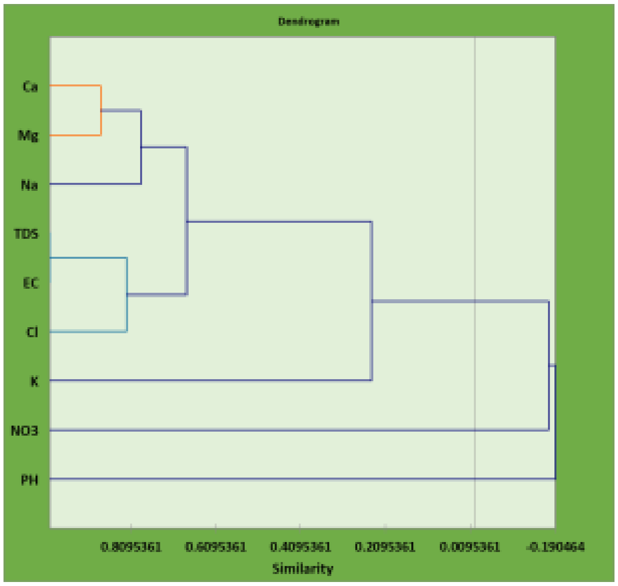

Figure 3: Cluster Analysis (CA) for hydrochemical parameters physicochemical across the study area

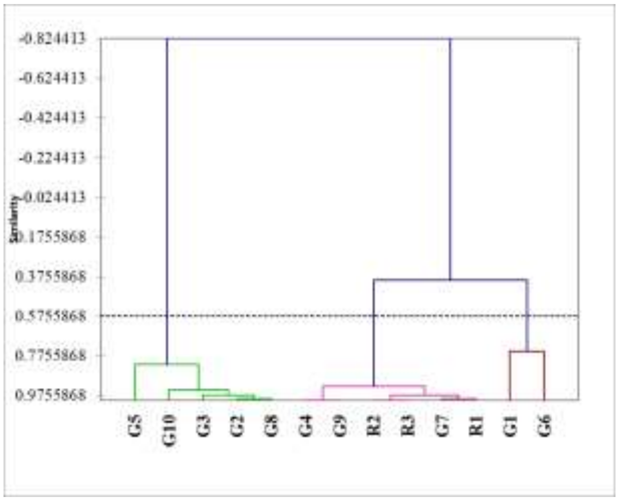

Figure 4: Cluster Analysis identifying the hydrochemical similarity for sampling points across the study area

Cluster II (K+)

The second cluster containing K+ shows a relatively autonomous behavior within the dataset, integrating with the principal salinity cluster (CA1) only at higher similarity thresholds. This marginal association suggests minimal influence from both natural (geogenic) [68] as well as anthropogenic sources, particularly those arising from agricultural practices such as fertilizer application and irrigation runoff [74]. It has been established that elevated concentrations of K+ are associated with intensified farming activity in farmlands [75].

Cluster III (NO_3-pH):

The third cluster C3 exhibits isolation of NO_3 which reflects localized nitrate contamination from surface infiltration or agrochemical leaching [21]. The dominance of NO_3^- in this group indicates fertilizer-derived inputs and leaching under low rainfall but occasional recharge which is common in arid environments undergoing irrigated agriculture. Whereas the association of NO_3^- with K^+ here, further reinforces a fertilizer/soil-amendment signal rather than a salinity-control axis [76].

The environmental implication of this is that, in a short-term, availability of NO_3^- guarantee nutrient supply, but continuous or long-term increase may lead to nutrient imbalance, soil acidification, and contamination of groundwater [77]. Thus, there is need to adopt 4R nutrient stewardship (right source, rate, time, place) as a management strategy among other measures to minimize leaching of the nutrients [78]. In contrast, pH displays minimal association with other ions, functioning more as a prevailing chemical conditions indicator rather than a determinant of cluster formation. This group signals anthropogenic enrichment and biochemical alteration [79]. This group further reflect the PCA3.

Cluster Analysis of Sampling Points

The site-based dendrogram (Figure 4) divides the twelve sampling points into three hydrochemical facies, showing spatial differences in water quality and irrigation suitability.

Cluster I

The first cluster here comprises five sampling sites (G5, G10, G3, G2, G8, G4). The chemical composition of these sites is generally characterized low EC and TDS. Similarly, these sampling points portray dominance of Ca and Mg with low Na% and SAR. The process controlling the hydrochemistry of these sites is predominantly freshwater recharge from rainfall or shallow aquifer systems [67]. These sites fall within the excellent to good irrigation water class, suitable for various soil types and crops and mostly doesn’t require salinity management

Cluster II

The second cluster II constitute six sampling sites three surface and three groundwater sampling points (G4, G7, G9, R1 R2, R3). The predominant process controlling the chemistry of these sites is moderate salinity with some Na and Cl enrichment and balanced Ca and Mg levels portraying water–rock interaction with slight evaporation showing mixed water type [68]. Sampling sites in this group falls between suitable or marginally suitable for irrigation as shown by moderate SAR, Kelley Index (KI), and sodium percentages (Table 1). Hence, these sites may need controlled leaching and Ca amendments, such as gypsum, for sustainable irrigation [27].

Cluster III

Two sampling sites namely (G1, G6) (figure 4) shows high EC and TDS values, with a strong Na-Cl presence, indicating evaporation, ion exchange, or human contributions like irrigation return flows thereby causing salinity and sodicity [80]. As shown in (Table 1 and 4) these sampling sites have high SAR, SSP, and KI values indicating significant sodicity hazard, which can affect the soil permeability and crop productivity [68]. The samples in this cluster falls within the classes of as doubtful to unsuitable for irrigation and therefore, there is need for best management strategy in these areas such as controlled application of gypsum [27]. The clustering pattern aligns with the spatial flow regime from recharge to discharge, confirming progressive mineralization along the hydrological gradient.

IV. CONCLUSION

This study integrated hydrochemical modeling and multivariate statistical analysis to assess the suitability of irrigation water in Hadejia, Northern Nigeria. Overall salinity is low to moderate, with EC values placing all samples in C1- C2 classes, suggesting that the waters are broadly suitable for common field crops in semi-arid northern Nigeria. However, the sodium-based indices reveal a more restrictive picture. Na% ranges from permissible to clearly unsuitable, and KR identifies four samples (G1, G2, G6, G8) with KR > 1, signalling genuine sodicity risk despite uniformly low SAR (S1) and safe MH values. G1 stands out as the poorest water, combining very high Na% with KR = 1.75 and an "Unsuitable" Wilcox class. The IWQI helps to sort out these mixed signals revealing a clear hierarchy of suitability.

Threshold-based IWQI scores classify all groundwaters as Permissible and the river samples as Good to Excellent, while percentile IWQI separates G1 as the worst-performing water and R2-R3 as the best quality sources. Waters with a balanced Ca-Mg-Na composition, especially the river sites, reliably show higher IWQI scores and better irrigation prospects, whereas Na-dominated waters are downgraded even where SAR appears safe. PCA and HCA support this interpretation by distinguishing a salinity hardness component (EC, TDS, Cl^-, Ca^{2+}), a second component linked to Na^+-K^+-Mg^{2+} enrichment and cation exchange, and a third related to NO_3^- and pH, pointing to localised agricultural inputs.

From a management perspective, most waters in the basin can be used for irrigation, however, high Na, KR > 1 sources require careful use especially on fine-textured or poorly drained soils. Priority actions include routine monitoring of EC and sodium indices, application of leaching fractions where feasible, and targeted Ca2+ amendments in sodicity prone areas. The result also highlights the need for better fertiliser management to limit nitrate loading. Overall, the work demonstrates that integrating traditional indices with IWQI, PCA, and HCA offers a more robust and process-based understanding of irrigation water quality than reliance on any single index and provides a useful model for managing semi-arid irrigation schemes under growing climatic and land-use pressures.

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