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Adoption of Water Quality Index and Multivariate Statistical Analyses to Appraise the Groundwater for Drinkable Purposes

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ABSTRACT

This research focused on assessing groundwater quality in the Alton Kopri, Kirkuk Province, northern Iraq. Twenty-two samples were selected from twenty-two wells randomly distributed in the study area to assess the subsurface water for drinking purposes. The samples were analyzed for parameters (pH, T.D.S, Na^+, Mg^{2+}, K^+, Ca^{2+}, NO_3^-, SO_4^{2-}, HCO_3^-, and Cl^-) to compute Water Quality Index (WQI). Pearson's correlation and principal components analysis (PCA) were adopted to study the physicochemical parameters sources in groundwater. The dominant cations were ordered as follows: Na > Ca > Mg > K, and the dominant anions were arranged as follows: SO_3 > Cl > HCO_3 > NO_3. The average concentrations of TDS, Ca, Mg, Na, SO_4, and Cl were 1118.45, 173.54, 132.59, 341.36, 873.63, and 414.50, respectively, surpassing the maximum permissible limits set by WHO. The average concentrations of K, NO_3, HCO_3, and pH were 5.90, 35.02, 172, and, 8.05 respectively, and were within acceptable limits. The WQI ranged from 33.3 to 1024. The findings designated that 23% of the samples were categorized as excellent, 27% as good, 18% as poor, 14% as very poor, and 18% as inappropriate for drinking purposes. The Pearson correlation matrix has been created and analyzed to appraise the important factors impacting groundwater quality. The PCA technique was adopted to analyze water quality parameters, resulting in the extraction of three components that together account for 81.574% of the total variance. The extracted components suggest that the predominant contributors to groundwater contamination include geological characteristics, agricultural practices, precipitation, domestic wastewater, and manufacturing activities. This study stands out from others due to various local factors that impact groundwater quality in the Alton Kopri area. Agricultural practices, including fertilizer and pesticide use, lead to chemical seepage into the aquifer, while pastoral activities contribute organic contaminants. Insufficient sewage infrastructure in some areas results in wastewater infiltration. The region's geology, dominated by limestone and clay, affects groundwater hardness and heavy metal levels. Additionally, the Little Zab River, which recharges groundwater, can transport pollutants during floods. Minor industrial activities may also introduce trace metals and oils. Understanding these influences is key to interpreting water quality variations and informing sustainable management strategies.

1. INTRODUCTION

Groundwater is an essential resource for all people across the globe. Due to the significance of this resource, nations worldwide face a significant challenge of water scarcity, particularly in arid and semiarid districts [1, 2]. Below rainfall and high evaporation rates in arid and semiarid districts lead to increased water salinity, which increases the toxicity of certain chemicals in groundwater [3]. The geology of the area and aquifer properties significantly influence the groundwater quality, which is impacted by various natural and human activities [4]. Groundwater contaminants primarily comprise inorganic salts, toxic metals, cations, and anions [5]. Concern about groundwater quality issues has become increasingly significant in the last years, and the assessment of groundwater quality and health risk evaluations has been studied extensively worldwide [6]. The Water quality index (WQI) is commonly used to appraise whether surface and groundwater are appropriate for watering and drinking [7]. The WQI method is a technique used to appraise and classify water quality. It is an effective tool for expressing water quality in a simple, stable, and reproducible manner. This method also effectively communicates information about water quality to both populations and policymakers [8]. Several researchers investigated the quality of groundwater for drinking and irrigation purposes. Ibrahim. Submitted a study to identify the appropriateness of groundwater in Jordan for drinking purposes. Sixteen samples were collected from sixteen stations. The WQI was used to appraise the quality. The findings revealed that most parameters used were below the permissible limit, while microbiological parameters, such as E. coli count, exceeded it. Specifically, 19% of the samples were categorized as excellent, 56% as good, 6% as poor, 12% as very poor, and 6% as unsuitable for drinking purposes. Sahab et al. [10] submitted a paper to appraise the groundwater quality for irrigation in the Al-Wafaa region west the Iraq. The sodium adsorption ratio (SAR) and the percent sodium (%Na) were computed. The United States Salinity Laboratory and Wilcox diagrams were utilized to appraise the appropriateness of the sub-water quality for watering. The findings indicated that the samples are inappropriate for irrigation due to raised salinity [10]. Ahmed et al. [11] evaluated the groundwater quality in the Bayji region of northern Salah al-Din province, Iraq, focusing on its appropriateness for drinking and irrigation. Drinking and irrigation water quality indices were used to appraise the sub-water. The drinking water quality index (DWQI) found that 96.67% of water samples were poor, while the irrigation water quality index (IWQI) ranged from medium to high [11]. Karakuş [12] Applied WQI values were determined using various water quality parameters, and spatial distribution maps of these values were created using Geographic Information System (GIS) technology to assess the groundwater quality in Sivas City, Turkey. The results revealed that 91.66% of the groundwater samples collected during the wet season and 77.07% collected during the dry season were suitable for drinking. Furthermore, the groundwater quality around the center of Sivas city was classified as excellent, also, the findings indicated that the total dissolved solids, nitrate, sulfate, chrome, and arsenic adversely impact groundwater quality. [12]. Ram et al. [13] applied the WQI to appraise and classify water quality in District Mahoba, Uttar Pradesh, India. This analysis provides information for both the public and policymakers regarding water quality. The WQI in the studied region varies from 4.75 to 115.93. Overall, the findings designate that the groundwater is secure and drinkable, excluding a few places in the study region [13]. Abbas et al. [14] utilized the Water Quality Indicator (WQI) to assess the sub-water quality in the Basrah province in southern Iraq. Samples were selected from 29 wells located in various districts, including Safwan, Zubair, and Um-Qasr. The findings designated that the WQI values range from low to inappropriate for human consumption [14]. Al-Mohammed et al. [15] applied water quality indicators to appraise groundwater quality for potable purposes in Kerbala. The findings indicated that WQI values for the groundwater of the study region varied from 432.6 to 184.5. This indicated that the water is severely polluted and inappropriate for potable purposes at all well sites [15]. Sahab et al. [16] used heavy metal pollution indexes to assess the Euphrates River in Ramadi City, western Iraq. The HMPI, HMEI, and CD were adopted for evaluation. The results showed that the Euphrates River experiences low levels of pollution. Sahab et al. [16] reinforced slab concrete measuring 500 mm × 500 mm with a thickness of 50 mm by incorporating fibers made from soft drink can strips. These fibers were added to the concrete in various ratios of 0.5%, 1%, and 1.5% by weight of cement, with lengths of 3 cm, 6 cm, and 9 cm, to enhance the concrete's resistance. Ten specimens were subjected to high-velocity impact loads from a distance of 15 m. The research indicated that using these fiber types in different percentages and lengths could significantly increase impact load resistance [17]. Previous studies lacked dependence on advanced statistical analysis, such as principal components analysis, and linking results to local factors. This study aims to fill these knowledge gaps by applying multiple methodologies and analyzing the latest data from the study region to assess the quality of groundwater for drinking purposes.

2. DESCRIPTION OF STUDY REGION

Figure 1. Geographical position of Alton Kopri Region

The Alton Kopri area is placed in the northeastern of Kirkuk province, north of Iraq as shown (Figure 1). Approximately 6.5 Km from the city center, positioned between 421362.95-466227.16m East and 3964586.46-3933367.08m North, covers approximately 826.4 Km^2. The research district is located in the foothill aquifer system within the Chamchamal-Klar sub-system. There are two aquifers present in the research region. The upper unconfined aquifer consists of Quaternary deposits located in the center of the basin and composed of gravel, sand, silt, and clay. The lower semi-confined aquifer is part of the Bai-Hassan Formation and includes a sequence of gravel, sand, and conglomerate, interspersed with layers of clay [18]. The natural renewal of groundwater occurs through a recharging procedure, which varies due to natural factors such as vegetation cover, intensity and period of precipitation, climate conditions, and type of soil [19, 20].

3. METHODOLOGY

3.1 Collection of groundwater sampling

Twenty-two groundwater samples were collected during June and July 2024 from the wells in the study area shown in (Figure 2) based on the standard procedures [21].

A portable GPS device was utilized to determine the location of the wells and document the coordinates as shown in (Table 1). The samples were composed in 1 liter capacity high-density polyethylene bottles and sterilized to prevent pollution and changes in groundwater characteristics. The samples were subsequently transported to the desert studies center at Anbar University for chemical parameters analyses.

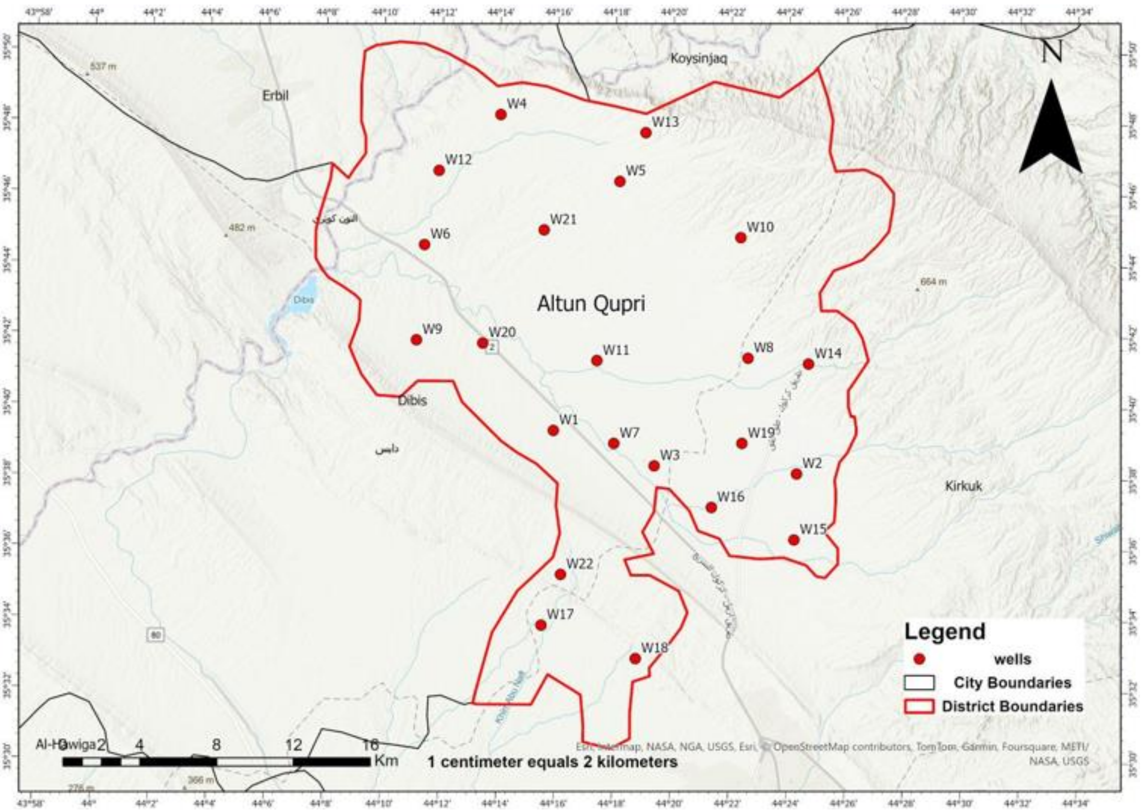

Figure 2. The position of wells in Alton Kopri Region

3.2 Laboratory analysis of samples

The quality of groundwater specimens was analyzed for various parameters, including pH, total dissolved solids (T.D.S), sodium (Na^+), magnesium (Mg^{2+}), potassium (K^+), calcium (Ca^{2+}), nitrate (NO_3^-), sulfate (SO_4^{2-}), bicarbonate (HCO_3^-), and chloride (Cl^-). The pH, and total dissolved solids (T.D.S.) of water samples were measured in the field directly after collection using a portable device multi-parameter (HANNA). Calcium (Ca^{2+}), sodium (Na^+), and potassium (K^+) concentrations were analyzed with a flame photometer (Jenway PFP7). Magnesium, bicarbonate, and chloride levels were determined using a titrimetric method, employing standard solutions of EDTA, hydrochloric acid (HCl), and silver nitrate ($AgNO_3$), respectively, as titrants [21]. Sulfate (SO_4^{2-}) and nitrate (NO_3^-) concentrations were measured using a spectrophotometer (SR 5000 HACH) as shown in Figure 3.

3.3 The Water quality index (WQI)

The WQI was utilized to appraise the combined impact of individual water quality parameters on overall water quality [22]. WQI is a mathematical formula used to summarize a huge amount of water quality data into a single value that is intelligible [23]. Ten criteria were used in the calculation of the Water quality index. WQI has been calculated using the drinking water quality standard proposed by (WHO) [24]. Four phases are required to calculate the Water quality index. In the first phase, each of the 10 parameters (pH, TDS, Cl, HCO_3, SO_4, NO_3, Ca, Mg, Na, and K) was assigned a weight (wi) based on their relative relevance in the overall quality of water for drinking purposes, as indicated in (Table 2), with values ranging from 1 to 5. The parameters SO_4, TDS, and Cl, are given a maximum weight of (5) for their relevance in water quality assessment, whereas the parameter K is given a minimum weight value of (1) since it plays no role in water quality assessment [25]. In the second phase, calculating the relative weight (RW) based on the following formula [26]:

$$\mathrm{RW} = \frac{Wi}{\sum_{i=1}^{n} Wi} \tag{1}$$

where, RW refers to the relative weight; Wi indicates the weight for each parameter; n indicates the number of parameters.

Figure 3. The devices utilized for analyzing the samples

Table 1. The coordinate of samples

Well Number	Northing (m)	Easting (m)
W1	3945970	433473
W2	3943708	446150
W3	3944130	438735
W4	3962435	430761
W5	3958942	436952
W6	3955660	426777
W7	3945290	436635
W8	3949735	443620
W9	3950691	426353
W10	3956011	443244
W11	3949605	435749
W12	3959525	427530
W13	3961487	438312
W14	3949421	446779
W15	3940267	446011
W16	3941956	441715
W17	3935836	432830
W18	3934090	437751
W19	3945290	443302
W20	3950528	429808
W21	3956413	433002
W22	3938472	433845

Table 2. Standard specification for drinkable (WHO) and requiring values to determine water quality indicators

Parameters	Unit	Standard Specification for Drinking (WHO)	Assigned Weight (wi)	Relative Weight (RW)
pH	-	8.5	4	0.118
T.D.S	mg/L	500	5	0.147
Mg^{2+}	mg/L	50	3	0.088
Ca^{2+}	mg/L	75	3	0.088
Na^{+}	mg/L	200	2	0.059
K^{+}	mg/L	12	1	0.029
Cl^{-}	mg/L	250	5	0.147
SO_4^{2-}	mg/L	250	5	0.147
HCO_3^{-}	mg/L	500	2	0.059
NO_3^{-}	mg/L	45	4	0.118
			Σ = 34	**ΣRW = 1**

In the third phase, determining the quality rating (QR) utilizing the following formula:

$$\mathrm{QR} = \frac{ci}{si} \times 100 \tag{2}$$

Where, QR refers to the quality rating; ci indicates the concentration of each parameter; si indicates the recommendation of the value by WHO for each parameter.

Table 3. Classification of the water based on the WQI [27]

Range	Type of Water
$<$ 50	Excellent water
50-100	Good water
100.1-200	Poor water
200.1-300	Very poor water
$>$ 300	Water unsuitable for drinkable

In the fourth phase, calculating the WQI for each well using the following formula [25]:

$$\mathrm{WQI} = \sum_{i=1}^{n} \mathrm{RW} \times \mathrm{QR} \tag{3}$$

Where, WQI refers to the Water quality index; RW refers to the relative weight of ith parameter; QR refers to the quality rating depending to the concentration of ith parameter.

The WQI values are classified into different categories: excellent, good, poor, very poor and water unsuitable for drinkable as revealed in Table 3.

3.4 Statistical analyses

In this paper, the program SPSS Statistics version 26 software was used to perform Pearson's correlation and principal components analysis (PCA) to study the physicochemical parameters sources in groundwater. The Pearson correlation matrix has been employed to analyse the link between physical and chemical characteristics in water samples. Pearson's correlation was used due to its simplicity and suitability for normally distributed, continuous data. It was preferred over Spearman's correlation, which is better suited for ordinal or non-linear data. PCA is a method for converting original variables into new, uncorrelated variables known as principal components, which are linear combinations of the original variables [28]. PCA gives information on the momentous parameters that describe the entire data set interpretation and data reduction, as well as a summary of the statistical association between components in drinking water samples with little loss of original information [29]. It explains variance efficiently without requiring complex assumptions like those in factor analysis. PCA was also favoured over clustering methods, which classify samples rather than explore inter-variable relationships. These methods align with the study's objectives and the structure of the dataset.

4. RESULT AND DISCUSSION

4.1 Parameters concentration

Recognizing groundwater quality is crucial for safe drinking water consumption [30]. Table 4 displays the statistical analysis of physicochemical properties in groundwater samples, including minimum, maximum, and mean values. The analysis of the physicochemical properties of groundwater samples in the study region revealed that the pH values ranged from 7.18 to 8.40, with an average of 8.05. These values fall within the WHO guideline limit of (6.5-8.5), suggesting alkaline groundwater. The total dissolved solids (TDS) ranged between 184 and 4112 mg/L, with an average value of 1118.45 mg/L. Based on the recommended limit for TDS (500 mg/L), 54.5% of the groundwater samples are considered unhealthy and undrinkable for anthropological consumption. The pattern of cation dominance is as follows: Na > Ca > Mg > K, and the order of anion dominance is as follows: SO_4 > Cl > HCO_3 >NO_3.

Table 4. Chemical and physical properties

Number of Well	pH	TDS mg/L	Ca^{2+} mg/L	Mg^{2+} mg/L	Na^+ mg/L	K^+ mg/L	SO_4 mg/L	Cl^- mg/L	NO_3 mg/L	HCO_3 mg/L
W1	8.20	184	34	17	13	5.3	20	5	14	210
W2	8	3077	536	130	223	3.6	1950	150	50	120
W3	8.12	400	35	20	40	0.8	66	71	1.3	85
W4	8.07	232	56	14	9	10.3	25	10	15	210
W5	8	893	112	78	71	7.2	422	96	3	226
W6	8	2071	244	129	198	1.8	1188	151	46	116
W7	8.13	1589	640	924	3496	12.3	5600	4473	104	268
W8	7.74	945	489	370	1285	8.29	2874	1873	238	187
W9	8.2	680	52	36	78	1.2	93	137	2	173
W10	8.25	467	42	25	50	19	84	102	1.1	104
W11	8.35	390	130	56	305	9.7	720	240	6	178
W12	7.18	2492	272	15	310	0.7	1340	240	19	185
W13	8.4	297	26	95	56	0.2	62	22	0.1	104
W14	8.4	366	36	140	41	0.8	82	85	1.1	92
W15	8.1	533	53	132	79	8	89	138	3	180
W16	7.87	463	100	19	36	10.3	180	36	12	163
W17	8.1	433	89	23	50	7.6	127	12	34	87
W18	8	4112	416	175	656	11	1688	959	75	104
W19	8.1	1327	118	101	138	2.2	763	62	24	235
W20	8	248	52	18	14	1.6	17	9	15	213
W21	8	1117	84	70	163	4.2	499	43	50	256
W22	8	2290	202	330	199	3.8	1331	205	57	288
Max.	**8.20**	**4112**	**640**	**924**	**3496**	**19**	**5600**	**4473**	**238**	**288**
Min.	**7.74**	**184**	**26**	**14**	**9**	**0.2**	**17**	**5**	**0.1**	**85**
Average	**8.05**	**1118.45**	**173.54**	**132.59**	**341.36**	**5.90**	**873.63**	**414.50**	**35.02**	**172.00**
Standards value (mg/L)	**8.5**	**500**	**75**	**50**	**200**	**12**	**250**	**250**	**45**	**500**

Sodium is an essential nutrient element. A specific quantity of sodium is very vital for maintaining proper health; however, exceeding the maximum satisfactory intake can lead to adverse health risks such as hypertension high blood pressure, and spew [31-33]. In this study, the concentration of sodium in groundwater ranges from 9 to 3,496 mg/L, with an average value of 341.36 mg/L. Based on the findings in Table 4, 72.72% of the groundwater sampling in the study area falls within the allowable limit of 200 mg/L for sodium. Calcium and magnesium are vital for human health. Insufficient calcium in drinking water can lead to various health issues, including kidney stones, hypertension, stroke, osteoporosis, and colorectal cancer [34]. In the current study, calcium concentrations ranged from 26 to 640 mg/L, with an average of 173.54 mg/L (Table 4). However, 41% of groundwater samples were less than the maximum recommended limit of 75 mg/L for drinking purposes. Magnesium is an essential ion for cellular functions, particularly in enzyme activation. However, at higher concentrations, it can act as a laxative [35]. The maximum permissible limit for magnesium in drinking water is 50 mg/L. Groundwater samples magnesium levels in the study region ranged from 14 to 924 mg/L, with an average concentration of 132.59 mg/L. The findings indicate that only 41% of the groundwater samples fall within the acceptable range for drinking water. Many minerals and rocks contain potassium, which can dissolve over time, increasing potassium concentration in groundwater [36]. The potassium concentrations ranged from 0.2 to 19 mg/L, with an average of 5.90 mg/L as shown in Table 4. The result indicated that 91% of groundwater samples fall within the satisfactory range for drinking water.

Sulfate concentrations vary from (5600) mg/L to (17) mg/L, with a mean value of 873.63 mg/L. The high concentration of sulfate in some groundwater samples from the research region might be attributed to the presence of Miocene sediments including gypsum and limestone [36]. The results show that 59% of samples are within the permitted threshold (250 mg/L). Chloride is commonly regarded as an indicator of water contamination. Elevated concentrations can give water a salty taste and may have a laxative impact. Additionally, chloride primarily originates from domestic wastewater, industrial discharge, and municipal effluents [37, 38]. The chloride concentrations in the present study ranged from 4473 to 5 mg/L, with an average of 414.50 mg/L, as shown in Table 4. The findings indicate that 86% of the groundwater samples fall within the acceptable range for drinking water. Bicarbonate concentration varied from 85 to 288 mg/L, with a mean of 172 mg/L as shown in Table 1. However, all groundwater samples fall within the safe limit for drinkable water. Nitrate is a major contaminant of groundwater in agricultural districts worldwide [39]. The nitrate concentrations in the present study ranged from 238 to 0.1 mg/L, with an average of 35.02 mg/L as shown in Table 4. The findings indicate that 68% of the groundwater samples fall within the acceptable range for drinking water. The presence of nitrate in groundwater is mostly due to human activity, resulting from soil interaction with nitrate fertilizers, animal wastes, home sewage, and septic tank leakages [40].

4.2 Water quality index

The Water quality index was utilized to appraise the rank of groundwater for drinkable purposes in the study region. The WQI is classified into different classification: it is considered excellent when the value is less than 50; good if it ranges from 50 to 100; poor if it falls between 100 to 200; very poor if it is between 200 and 300; and not appropriate for drinkable if it exceeds 300 as shown in Table 3. The WQI values in the study area ranged from 33.3 to 1024 as shown in Table 5.

The findings shown in Table 5 and Figure 4 revealed that 23% of samples were classified as excellent, 27% of samples were classified as good, 18% of the samples were classified as poor, 14% of samples were classified as very poor, and 18% of samples were classified as unsuitable for drinkable purposes. The Water quality index was found to be high in samples with elevated total dissolved solids (TDS) and Total Hardness (Mg and Ca), indicating significant biological contamination. This pollution may stem from household activities, wastewater and industrial discharges, improper waste disposal, extensive agricultural and urban runoff, excessive fertilizer use, and a lack of maintenance in the sanitation system. Over recent years, the quality of water in Iraq has deteriorated rapidly, likely due to population growth and increased human activities. Household drainage, agricultural practices, and drought are major threats to water quality in Iraq.

Table 5. WQI classification range and types in the study region

Sample	WQI	Type of Water	Sample	WQI	Type of Water
W1	33.3	Excellent	W12	227.14	Very Poor
W2	332.60	Unsuitable	W13	48.03	Excellent
W3	41.41	Excellent	W14	63.84	Good
W4	38.24	Excellent	W15	76.85	Good
W5	101.3	Poor	W16	60.89	Good
W6	220.71	Very Poor	W17	59.84	Good
W7	1024	Unsuitable	W18	410.11	Unsuitable
W8	544.63	Unsuitable	W19	144.02	Poor
W9	62.46	Good	W20	36.39	Excellent
W10	52.97	Good	W21	119.9	Poor
W11	119.59	Poor	W22	275.62	Very Poor

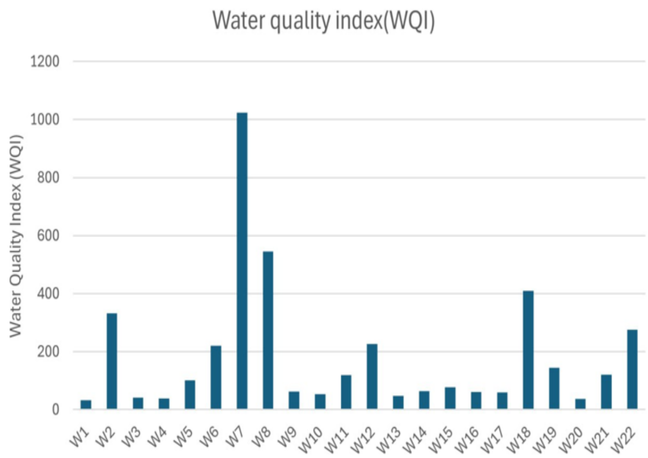

Figure 4. The Water quality index

Table 6. Pearson correlation

	pH	TDS	Ca	Mg	Na	K	SO_4	Cl	NO_3	HCO_3
pH	1									
TDS	**-0.444**	1								
Ca	-0.368	**0.694**	1							
Mg	0.008	0.28	**0.733**	1						
Na	-0.085	0.244	**0.761**	**0.941**	1					
K	0.109	-0.029	0.205	0.245	0.331	1				
SO_4	-0.25	**0.494**	**0.921**	**0.916**	**0.939**	0.242	1			
Cl	-0.075	0.227	**0.755**	**0.94**	**0.996**	0.354	**0.927**	1		
NO_3	-0.335	0.328	**0.732**	**0.603**	**0.6**	0.192	**0.704**	**0.629**	1	
HCO_3	-0.229	0.008	0.142	0.39	0.326	0.032	0.322	0.301	0.207	1

Correlation is significant at the 0.05 level

4.3 Contamination sources

The Pearson correlation matrix was utilized to analyze the link between physical and chemical characteristics in water samples. Principal component analysis and varimax rotation were employed to analyze water components such as pH, TDS, Ca^{2+}, Na, Mg^{2+}, K^+, So_4^2, Cl^-, SO_4, NO_3, and HCO_3^- In the Pearson correlation matrix (Table 6), the r values of either 1 or -1 indicate a strong association coefficient, signifying a complete correlation. Conversely, if the r values are close to zero, it suggests there is no association between the two parameters at the level of $P < 0.05$ [41]. If r is more than 0.7 and if it is between 0.4 and 0.7, the parameters are strongly and moderately associated respectively. In this investigation, a correlation matrix is employed to comprehend any link between the experimentally measured parameters, allowing for the discussion of factor loading using principal component analyses PCA. The pH has a poor negative association with Ca^{2+}, Na^+, SO^-_4, Cl^-, NO_3^-, and HCO_3, and a poor positive correlation with K^+ ($r < 0.4$), exception of TDS, which has a moderate correlation. The TDS has a moderate association with Ca^2 ($r = 0.694$) and SO4 ($r = 0.494$). The Ca^{2+} has a strong correlation with Mg^{2+}, Na^+, SO_4, Cl^- and NO_3. The Mg has a strong correlation with Na^+, SO_4, Cl and a moderate correlation with NO_3. The Na has a strong correlation with SO_4, Cl and a moderate correlation with NO_3. The significant positive association between Na and Cl^- with (r = 0.996) displayed the possibility of the meeting of two groundwater sources with differing end-member compositions, such as fresh and salty, which are known to be impacted by the presence of saline matrices [42]. Moderate association between SO_4 and TDS (r = 0.494), additionally strong associations were found between SO_4 and Ca (r = 0.921), SO_4 and Mg (r = 0.916), SO_4 and Na (r = 0.939). The high correlation between SO_4 and Mg indicates the existence of calcareous material in the research region. Based on Table 6 a moderate correlation between Cl and NO_3 has been found (r = 0.629). The positive correlation between these ions reveals a common source and highlights the impact of both human and natural activities on groundwater. K and HCO_3 displayed poor associations with the other parameters suggesting that K and HCO_3 are from different sources than other ions.

Table 7. Factor loading and varimax rotated component matrix

Parameters	Factor 1	Factor 2	Factor 3
Mg	**0.965**	-0.013	0.162
Na	**0.957**	0.032	0.141
Cl	**0.956**	0.024	0.123
SO_4	**0.940**	0.299	0.085
Ca	**0.800**	0.545	-0.114
NO_3	**0.644**	0.417	0.090
pH	0.047	**-0.867**	-0.324
TDS	0.312	**0.773**	-0.262
HCO_3	0.243	0.055	**0.920**
K	0.208	-0.060	-0.027
Eigen value	5.519	1.589	1.05
Variance explained %	55.186	15.891	10.497
Cumulative variance %	55.186	71.007	81.574

Three factors were sequentially extracted based on the eigenvalues greater than one, which cumulatively accounted for 81.574% of total variances in groundwater in the research region. The whole variation is explained by factors 1, 2, and 3, which account for 55.186%, 15.891%, and 10.497%, respectively. The first factor (Table 7 and Figure 5) represented 55.186% of the total variation with the highest eigenvalue of 5.519. It has extremely high loadings of Mg, Na, Cl, SO_4, and Ca, which might be attributable to household wastewater that is high in Na, Mg^2, and Cl^- and geological processes like weathering and dissolution of minerals [43]. Also, the first factor displayed the moderate loading of NO_3, indicating agricultural activity in the studied region [44]. Factor 2 represented 15.891% of the total variation with the eigenvalue of 1.589 (Table 7 and Figure 5). The high pH loading likely indicates it may originate from organic or biogenic sources. [45]. Factor 3 describes 10.497% of the total variation with the eigenvalue of 1.05 (Table 7 and Figure 5).

4.4 Sensitivity analysis and uncertainty considerations

The calculated Water quality index (WQI) values are based on standardized methods and measured parameters, but the small variations in input concentrations could influence the final WQI results. A detailed sensitivity analysis is recommended for future studies to assess how slight fluctuations in key water quality parameters (such as pH, heavy metal concentrations, and total dissolved solids) may impact the overall WQI classification. Conducting such an analysis would provide insights into the robustness and reliability of the WQI estimates and help quantify the uncertainty associated with water quality assessments.

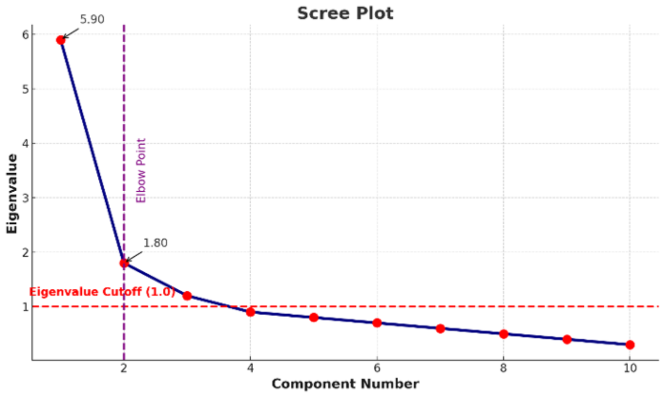

Figure 5. Scree plot graph

5. CONCLUSION

The Water Quality Indicator (WQI) is adopted to appraise water quality in the Alton Kopri region, which is a crucial factor for testing groundwater quality for drinkable purposes. Based on the WQI findings, 23% of the samples are classified as excellent, 27% as good, 18% as poor, 14% as very poor, and 18% as inappropriate for drinkable purposes. Half of the wells are contaminated and need to be treated before they can be safely used to be drinkable or provided to households. The findings of this study, along with spatial distribution maps of water quality indices, can be used for effective groundwater resource management in the region. The average concentrations of TDS, Ca, Mg, Na, SO_4, and Cl exceed the maximum permissible limits set by WHO, while K, NO_3, HCO_3, and pH are within acceptable limits. Multivariate statistical approaches, including the Pearson correlation coefficient and PCA for the water quality dataset of the study region, designated that variations in groundwater quality are primarily influenced by geological processes such as the weathering and dissolution of minerals. Other significant factors include chemical fertilizers and organic matter from the agriculture sector, industrial pollution from non-agricultural sources, rainfall, anthropogenic activities, and domestic wastewater. Based on the results of this study, an analytical framework or more generalizable model can be developed based on water quality indicators and local geological and environmental data, which can be used as a tool for assessing groundwater quality in other areas with similar characteristics. The outcomes of the research recommend the importance of conducting regular analyses of the physical and chemical parameters of water sources to identify any unhealthy conditions. It is essential to educate populations about these issues. Furthermore, it is vital to avoid overconsumption of water from wells and to encourage rational water usage. This approach will help prevent water depletion and protect against salinity. The research recommended that future studies include an assessment of the impact of climate change on groundwater quality, particularly in semi-arid areas such as the Alton Kopri region. Long-term climate data (such as rainfall, temperature, and evaporation) should be combined with hydrogeological models to analyze how groundwater recharge rates and contaminant concentrations change over time. Incorporating these climate factors will contribute to a more accurate and predictive assessment of future risks to water resources in the region. This study suggests using several indicators to appraise groundwater quality, providing essential information for water and environmental managers in making informed and effective decisions about groundwater management. To build upon the findings of this study, future research could focus on the following specific aspects: It is recommended to conduct periodic groundwater quality monitoring at a higher frequency to monitor seasonal changes and contamination dynamics, which enhances the accuracy of future assessments. Investigating the effectiveness and feasibility of different groundwater remediation techniques suited to the local hydrogeological conditions, such as membrane filtration, ion exchange, or chemical precipitation methods. Joint studies with microbiologists and public health scientists are recommended to examine the impact of chemical pollutants on microbial communities and water quality from an integrated environmental and health perspective.

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NOMENCLATURE

WQI	Water Quality Index
IWQI	Irrigation Water Quality Index
PCA	Principal Components Analysis
TDS	Total Suspended Solids
WHO	World Health Organization
HMPI	Heavy Metals Pollution Index
HMEI	Heavy Metals Evaluation Index
CD	Contamination Degree