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Integrated approach for the investigation of groundwater quality using hydrochemical and geostatistical analyses in Wadi Fatimah, western Saudi Arabia

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The Wadi Fatimah area suffers from a lack of freshwater resources, so this study aimed to analyze the groundwater in this region and evaluate its quality for irrigation and drinking purposes. Eleven water quality parameters, including pH, total dissolved solids (TDS), Ca^{2+}, HCO^{-3}, NO^{-3}, F^{-}, Cl^{-}, K^{+}, Mg^{2+}, $SO_2{}^{-4}$, and Na^{+}, were utilized to evaluate the quality of the water and produce a water quality index (WQI). These parameters were measured at 100 different chosen locations. The spatial distribution map revealed that all parameters are high in the southern part except K^{+}. Using the correlation matrix, a high positive correlation is obtained among TDS, Cl^{-}, Mg^{2+}, and Ca^{2+} in addition to a high correlation among TDS with Cl^{-} and Na^{+}. From PCA analysis, PCA1, PCA2, and PCA3 represent about 52%, 12%, and 10% of all components along the study area, respectively. PCA1 has low variance than PCA2 and PCA3. The majority of the Southern region's sites went from having extremely poor to poor water classifications and from poor to unsuitable water. However, the center part possesses exceptionally high-quality groundwater. According to the results from the current study's water quality index, the presence of nitrate and fluoride in the groundwater samples was primarily responsible for their high WQI values. The statistics showed that a higher percentage of the population had poor drinking water due to direct pollutant release, agricultural effects, and excessive groundwater resource use. The study offers a groundwater quality modeling technique that is both affordable and replicable in other areas.

KEYWORDS

groundwater, Wadi Fatimah, remote sensing, physiochemical parameters, IDW, WQI

1 Introduction

Less frequent rainfall and high evaporation rates in arid regions, like Saudi Arabia's dry soil, can lead to fractionation processes that have a big impact on the chemistry of shallow groundwater (Reddy et al., 2012; Verma et al., 2020). This is true of the alluvium deposits in the Kingdom's western region (Sharaf and Hussein, 1996). Certain hydrochemical processes may have an impact on the ionic composition of groundwater as it moves from recharge areas to discharge areas and interacts with rock minerals. The majority of earlier studies on the major wadis in the Western Region noted that the main determinants of groundwater salinity are rock types and agricultural practices. Actually, the middle and lower reaches of the wadis were the focus of this research (e.g., Memon et al., 1984; A1-Kabir, 1985; Sharaf et al., 1988; Jamman, 1978; A1-Khatib, 1977; Alyamani and Hussain, 1995; Sharaf, 2013). However, studies on these locations have generally focused on evaluating the hydrochemical conditions, paying little attention to the groundwater chemistry or the main source of recharge in the higher catchment areas, where processes and products can be recognized with the greatest ease (Sharaf and Hussein, 1996). The groundwater composition in upstream regions would resemble that of rain that falls on recharge zones (Abdel-Sattar et al., 2017). Such investigations, which are essential, can offer extra valuable information regarding the chemistry of groundwater's evolution.

Due to the rapid urbanization process, population growth, and increase in anthropogenic activities, groundwater represents the most important freshwater for human drinking purposes. Agricultural, industrial, and domestic activities are major sources of groundwater pollution worldwide (Bi et al., 2021). Groundwater degradation is mostly caused by changes in its quality parameters beyond normal variations brought on by the addition or removal of various contaminants (Todd, 2001). Unfortunately, this resource is under threat from urban, modern agricultural, and industrial operations, as well as from the rising amount of soluble chemical input they produce (Aydi et al., 2013). As a result, the quality of the water is determined socially based on its intended or desired use. The continual monitoring of water quality is the most important phase in the management of water resources not only for human survival but also for the integrity of entire ecosystems. Different water quality requirements are established for various uses, and these standards are upheld through ongoing water quality monitoring (Shabbir and Ahmad, 2015). Determining the quality of the groundwater has become essential for the long-term development of fresh groundwater aquifers in Faisalabad because of the city's numerous enterprises. Understanding the spatial distribution of environmental characteristics is essential for assessing the water quality (Solangi et al., 2018). In order to support such monitoring efforts, accurate and flexible instruments are required because monitoring is expensive, especially for large groundwater areas (Wong et al., 2021). The potential cost is further reduced by using modular technologies, like a geographic information system (GIS), because fewer observation wells are needed to evaluate the groundwater quality throughout the entire region (Verma et al., 2020). One of the most often used methods for classifying and reflecting the condition of water quality in a particular location (WQI) is the GIS-based water quality index (Mahmood et al., 2011). A helpful method for maintaining water quality is the mapping of water quality indices within the GIS. It is useful to provide three-dimensional patterns in water quality variation in order to better comprehend the current situation regarding the numerous parameters of the water quality studied. Several researchers from different countries have utilized the WQI to evaluate the water quality in that area (Arkoç, 2016).

Facilitating the unified environmental simulation models using the GIS requires more effective data processing and specialized solutions. The internet, global positioning systems, and remote sensing, among other techniques for obtaining and producing data, have all advanced (Sweeney, 1997). In arid and semiarid regions of the world where the populace and industry are strongly dependent on this irreplaceable resource, the groundwater quality evaluation for public health is crucial. The study's objective is to assess the groundwater quality in the Wadi Fatimah area using various physiochemical indicators and then to use the WQI to produce a distributed-scale geospatial water quality map. The objectives of this work are to 1) conduct a laboratory-scale assessment of the groundwater quality by gathering physiochemical data for a few parameters and 2) weighted overlay the physiochemical features in ArcGIS to obtain the WQI.

Together with population growth, groundwater demand is rapidly increasing and climate change is further taxing water resources. Notwithstanding the importance of drinking water to the local population's health in underdeveloped countries and the fact that groundwater is frequently the main source of drinking water, it is important to consider the water's chemical purity (Alsuhaimi et al., 2019; Ahmed et al., 2020; Metta et al., 2020; Nwankwo et al., 2020; Panneerselvam et al., 2020; Singh et al., 2020; Salem et al., 2022). The groundwater monitoring network provides data on potential measures and when to adjust the settings for our water management system. Comparative studies should highlight the various components of groundwater and their effects on human health. The study's objectives are to comprehend the existing groundwater quality conditions in the relevant locations, including the sources of pollution, and to develop a particular dataset for chemometric-based future research. The study also intends to grasp the ecological circumstances of the close-by regions while comprehending groundwater's appropriateness for irrigation and understanding its household and commercial application utilizing certain water quality indices. The results of the study will serve as a baseline for further research in Wadi Fatimah and surrounding areas, including the strengthening of groundwater management standards, leading to more sustainable decision-making and a reduction in the region's groundwater and environmental pollution issues.

2 Materials and methods

2.1 Study area

The western portion of Saudi Arabia's Makkah region is where Wadi Fatimah is located. The recharge zones are close to Taif province. Two examples of cities that are next to a wadi are Jamoum and Bahrah. Figure 1 illustrates the general area, which is approximately 4,050 km^2 in size and spans a distance of 250 km from the Taif mountains to the Red Sea coastal plain. According to Walter et al. (1975), Harnickell, and Mueller-Dombois, the study location is in a region with a subtropical dry climate, which is distinguished by hot summers and mild winters (1975). The maximum average temperature for the year is 31.2°C, with July being the hottest month with a maximum average temperature of 36.25°C. January is the coldest winter month with a maximum average temperature of 24.12°C. With an average annual precipitation of 84 mm/year and a monthly mean that varies from 0 mm in June to 25.5 mm in November, rainfall is scarce and unreliable. The Precambrian plutonic rocks that make up Wadi Fatimah are found inside the Makkah Quadrangle, along with some Tertiary volcanic rocks and Quaternary clastic deposits.

2.2 Hydrogeological settings

Since geology governs how aquifers recharge, geology is regarded as a key determinant of their hydrogeological properties (Ganapuram et al., 2009). Figure 2 shows the geology map of Wadi Fatimah. According to

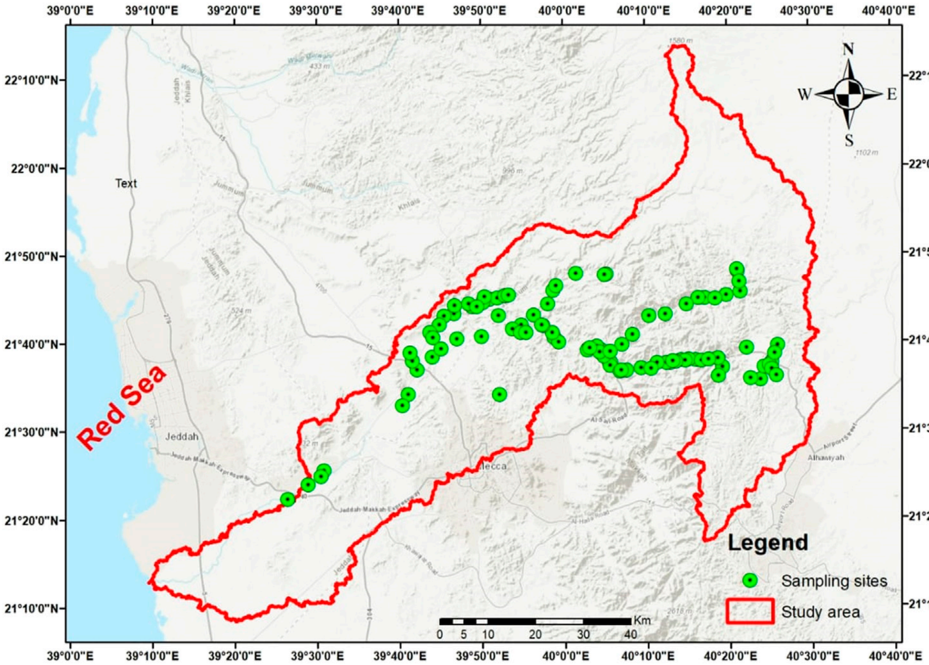

FIGURE 1
Geographical location of Wadi Fatimah, KSA, and sampling locations.

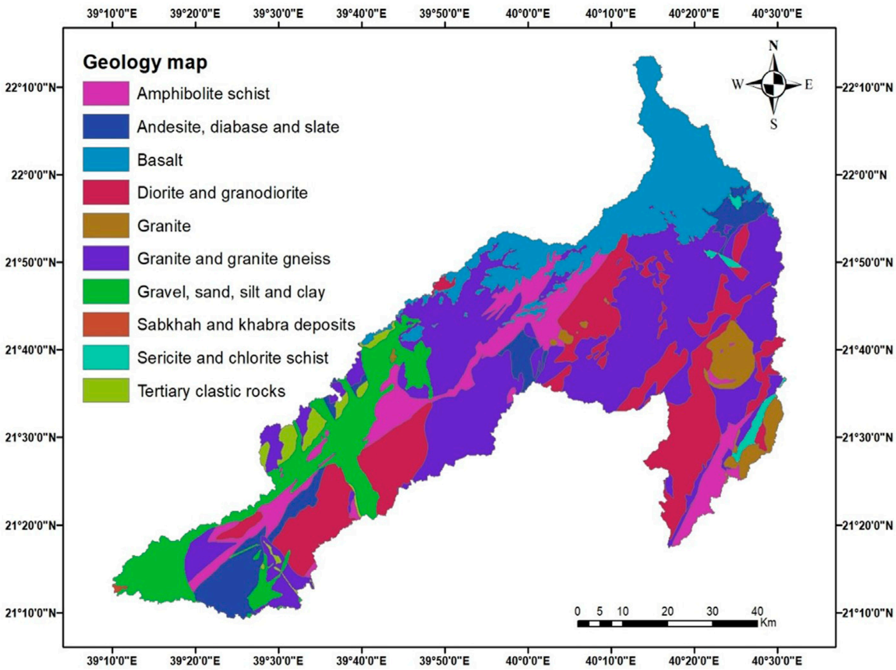

FIGURE 2
Geology map of Wadi Fatimah.

the thoroughly studied geological map, Wadi Fatimah is a sedimentary basin with a diversity of geological components, spanning from Quaternary to Jurassic formations with a predominance of Tertiary formations. The study area's center is taken up by granite. The Fatimah basin's Quaternary wadi fill deposits range in thickness from 10 to 20 m upstream to roughly 80 m downstream. These deposits are made up of mudstones, sandstones, and conglomerates. Another good location for groundwater preservation is Wadi Fatimah, whose bedrock is made up of severely worn, fractured Arabian Shield igneous and metamorphic rocks (Sharaf et al., 2004). Additionally, the porosity of this shallow aquifer ranges from 14% to 30%, and its average transmissivity is 140 m^2/day. Its average storativity is similarly 0.1 (Jamman, 1978; Es-Saeed et al., 2004). These characteristics collectively show that the aquifer is unconfined and shows moderate potential. As the geology affects groundwater penetration, the ranks were assigned accordingly. Quaternary, thus, obtained the best rating, whereas Jurassic received the worst.

The Fatimah catchment's entire surface area is approximately 4,650 km^2, and it almost perfectly parallels the Red Sea from east to west. Jado and Zotl (1984) claimed that following the intense rains that fall on the higher portions of the Arabian Shield, the deeply cut gorges serve as the gathering pathways for greater floods. In the southwest corner of this wadi, these chasms (deep fissures) rise to elevations of more than 2,000 m above sea level. Groundwater recharge spots can be found in main and sub-catchments because surface characteristics are among the most crucial controlling variables for rainwater dispersion across the catchment. The Fatimah catchment area is seen on the topographic map in Figure 3, and it is clear that the catchment's highest peaks are in its northeastern region, close to the Hijaz Escarpment. Different lithologies, tectonic movements, weathering, erosion, climatic influences, and geological formations are what determine the surface features. Additional elevational variations have been caused by the Harrat Rahat basalt explosions, particularly in the northeastern catchment zones.

In general, the catchment area can be thought of as having three distinct elevations: the coastal area, which has elevations less than 100 m; the middle area, which has elevations between 100 m and 600 m; and finally, higher elevations, which include the edges of the Hijaz Escarpment, which have elevations greater than 600 m. Groundwater flow routes also follow a similar pattern based on this classification. According to this structure, the shallowest alluvium fills are found at high elevations and include relatively coarse grains, whereas the alluvium thickness increases toward the lower reaches and contains smaller grains.

The sub-basins of the Fatimah catchment exhibit typical characteristics of arid or semiarid environments, including multiple segments of ephemeral flow systems that are shallow and narrow and have irregular recharges. In the region of the Harrat Rahat basaltic area in the northeast and close to the Hijaz Escarpment in the east, this catchment contains steep slopes with significant running water energy, which reduces toward the lowlands where thick silt accumulations occur. Since higher places are predicted to have larger values of hydraulic conductivity than other locations, these locations are predicted to have high groundwater seepages in the longitudinal direction. Along the whole wadi, the aquifer thickness in this location is the thinnest.

3 Data collection and analysis

A total of 100 sampling locations were selected to map the groundwater quality (Figure 1). A variety of wells were used to

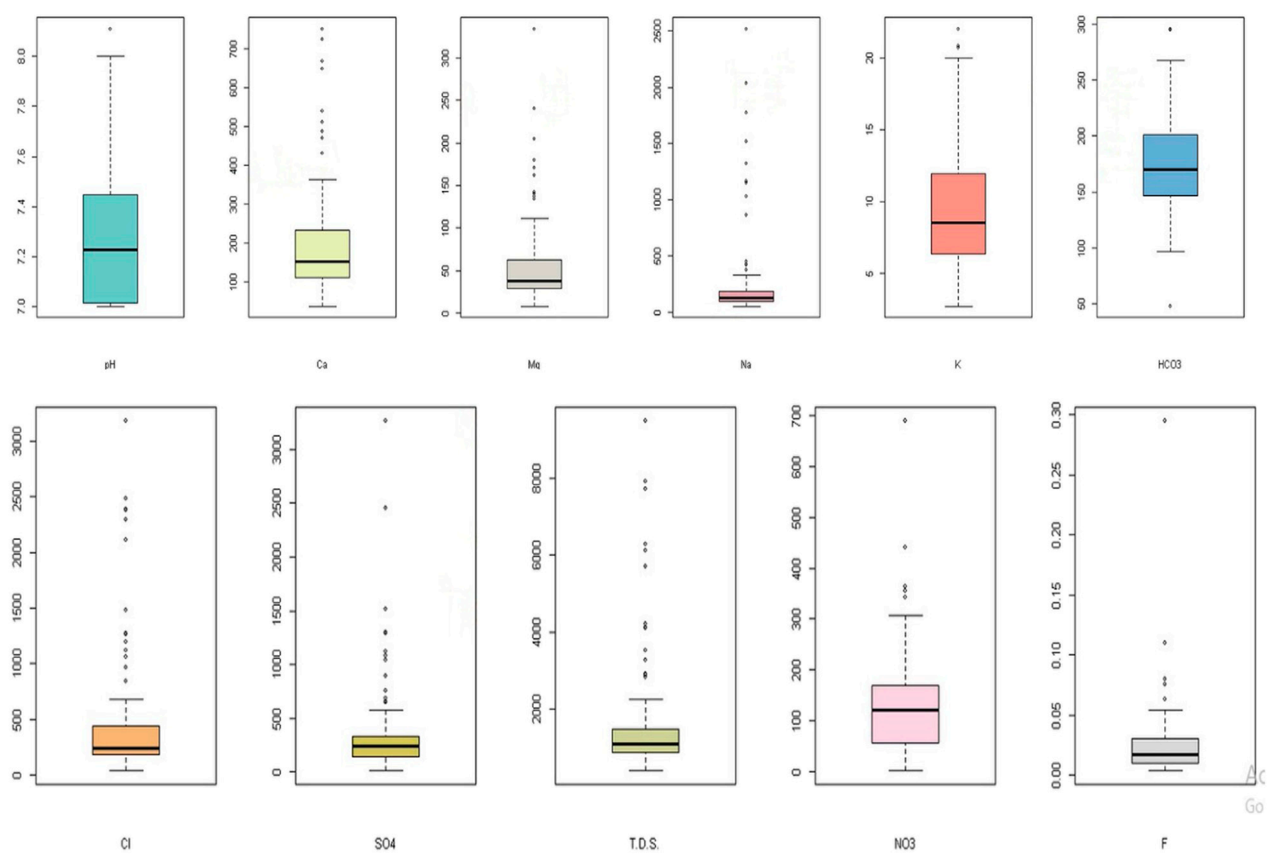

FIGURE 3
Box diagram of all parameter concentrations in groundwater.

collect samples of the groundwater used for agriculture, drinking water, and other domestic and industrial uses. Prior to collecting the samples, polypropylene containers were thoroughly washed multiple times with the sample water. All of the water samples were kept in a cooler filled with ice while the fieldwork was being performed. The samples were stored in a refrigerator in the lab, which was kept at a temperature of 2°C–4°C. The increased temperature of the circulation, which causes a greater degree of mineral breakdown, and the mixing of fresh, shallow groundwater with deeper saline water, as can be observed on Piper and Durov plots, can be linked to the high TDS of the geothermal samples (Alshehri et al., 2022). All reasonable measures were made to reduce contamination during sample collection and processing. According to the American Public Health Association, these samples were collected and examined for several physiochemical factors (APHA, 1998) using standard methods. The parameters which were analyzed included pH, total dissolved solids (TDS), Ca^{2+}, HCO^{-3}, NO^{-3}, F^{-}, Cl^{-}, K^{+}, Mg^{2+}, Na^{+}, and SO_2^{-4}. K^{+} and Na^{+} were determined using a flame photometer. Ca^{2+}, Mg^{2+}, Cl^{-}, and HCO^{-3} were analyzed by the titrimetric method. SO_2^{-4} was determined using a digital spectrophotometer.

3.1 Data analysis using the GIS

The sampling sites were taken using portable GPS. Through a point layer, the various sampling sites were loaded into GIS software. A unique code was given to each sample point and entered into the point attribute table. All chemical parameter values and sample codes for each sampling site were separated into separate columns in the database file. The geodatabase was used to construct the spatial distribution maps for a number of water quality metrics, including the water quality index (WQI) for drinking water. Using the inverse distance weighted (IDW) raster interpolation method, the spatial analyst module of ArcGIS 10.8 was used to depict the spatial distribution of various water pollutants (Kumar et al., 2007).

TABLE 1 Relative weight for the chosen parameters and the weight assigned.

Parameter	Standard	W_i (weight)	W_i (relative weight)
pH	6.5–8.5	3	0.09
TDS (mg/L)	1,000	3	0.09
SO_2^{-4} (mg/L)	250	3	0.09
Cl^{-} (mg/L)	250	3	0.09
K^{+} (mg/L)	12	1	0.03
Ca^{2+} (mg/L)	75	2	0.06
Mg^{2+} (mg/L)	50	2	0.06
Na^{+} (mg/L)	200	4	0.12
HCO^{-3} (mg/L)	120	3	0.09
NO^{-3} (mg/L)	45	5	0.15
F^{-}(mg/L)	1.5	5	0.15
		$\sum wi = 33$	$\sum wi = 1.000$

3.2 Water quality index

The water quality index (WQI) has been calculated in three steps using weighed arithmetic index techniques (Ramakrishnaiah et al., 2009; Akter et al., 2016). First, as shown in Table 1, the water quality parameters that have been selected and given weights are essential for establishing the quality of drinking water. The metrics MPN and nitrate both received the maximum weight of five because of their significant roles in the WQI. When calculated with a minimum weight of 1, it was found that potassium and total hardness cannot be damaging to people's health. The next step involves calculating Wi (relative weight) using the following formula.

$$W_{i=}\frac{wi}{\sum_{i=1}^{n} wi}.$$

In this case, Wi denotes relative weight, Wi denotes the weight of each chosen water quality parameter, and n is the total number of water quality parameters. Table 1 displays the computed Wi (relative weight) values for each water quality indicator. In the third stage, the qi (quality rating scale) for each specific water quality parameter is computed by dividing the observed value in the relevant water sample by the standard specified in the (BIS, 2012) drinking water guidelines and then multiplying the result by 100.

$$q_i = \frac{Ci}{Si}*100.$$

Quality rating is determined by qi, and the concentration of specific chemical (Ci) traits in each sample of water measured in mg/L, as well as SI, is based on the WHO standard (BIS, 2012) recommendations. First, SI is calculated for each chemical parameter in order to calculate the WQI by multiplying the quality rating by the relative weight. Next, the sum of the sub-indices is used to calculate the WQI using the following formula:

$$SIi = w_i{}^* q_i,$$

$$WQI = \sum_{i}^{n} SIi.$$

Here, the *i*th water quality parameter is the sub-index (SIi) and the rating qi is based on the concentration of the *i*th parameter and the total number of water quality parameters (n) used to calculate the GWQI. According to Table 2, the GWQI values are divided into five categories, from "Excellent water" to "Water unsuitable for drinking."

TABLE 2 Groundwater classification using the water quality index.

WQI value	Water quality
<50	Excellent
50–100	Good water
100–200	Poor water
200–300	Very poor water
>300	Water unsuitable for drinking

TABLE 3 Physico-chemical parameter statistics for groundwater samples.

	pH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^{-}	Cl^{-}	SO_4^{2-}	TDS	NO^{-3}	F^{-}
Min.	7	36.4	7.8	50	2.7	47.8	41.8	18.5	411	2.04	0.004
Max.	8.11	750.2	334	2,520	22	295.5	3,180	3,264	9,488	690	0.295
Mean	7.2	202	58	281	9.7	175.6	482.03	385.85	1,714.29	137.14	0.03
SD	0.2	152.2	57.7	472.8	4.7	42.61	638.0	537.6	1,789.6	114.9	0.04

3.3 Statistical analysis

In environmental studies, multivariate statistics are typically used to categorize and evaluate soil characteristics. The data can be condensed, unified, and categorized using multivariate approaches in order to extract meaningful information. The method can also be used to explain temporal and spatial variations caused by connections between seasonality and outside factors, both natural and artificial. The data gathered for the groundwater samples were evaluated using principal component analysis. The most popular method for converting the original variables into new, uncorrelated variables (axes), or principal components is principal component analysis (PCA). PCA allows for the straightforward accounting of data variations (Pop et al., 2009). PCA has been used to evaluate the salinity and alkalinity of soil (Mohamedou et al., 1999). The relationships in the original data are maintained while providing essential information for the entire data set.

4 Results and discussion

4.1 Physicochemical parameters

According to the physicochemical analysis of major groundwater quality parameters of the 100 groundwater samples in Wadi Fatimah, the WQI was calculated, as shown in Table 3. The value of pH ranges from 7 to 8.11 with a mean value of 7.2. The pH level was largely constant due to the low S.D. value (0.2). The groundwater quality is important because it is the main factor in determining whether it is suitable for drinking (Kumar et al., 2007). Although it has no direct impact on consumers, one of the most important indicators of water quality is often its pH. Typically, the needed optimal pH ranges from 7.0 to 8.5 (World Health Organization, 2004). The value of **Ca^{2+}** ranges from 36.4 to 750.2 with a mean value of 202. The value of **Mg^{2+}** ranges from 7.8 to 334 with a mean value of 58. The value of **Na^{+}** ranges from 50 to 2,520 mg/L with a mean value of 281 mg/L. The value of **K^{+}** ranges from 2.7 to 22 mg/L with a mean value of 9.7 mg/L. The value of **HCO_3^{-}** ranges from 47.8 to 295.5 with a mean value of 175.6. The value of **Cl^{-}** ranges from 41.8 to 3,180 mg/L with a mean value of 482.03 mg/L. The value of **SO_4^{2-}** ranges from 18.5 to 3,264 mg/L with a mean value of 385.85 mg/L. The value of **TDS** ranges from 411 to 9,488 mg/L with a mean value of 1714.29 mg/L. The value of **NO^{-3}** ranges from 2.04 to 690 mg/L with a mean value of 137.14 mg/L. The value of **F^{-}** ranges from 0.004 to 0.295 mg/L with a mean value of 0.03 mg/L. The box diagram of all parameters in the groundwater of Wadi Fatimah water is shown in Figure 3. Based on Figure 4, there is a high positive correlation among TDS, Cl^{-}, Mg^{2+}, and Ca^{2+} in addition to a high correlation among TDS with Cl^{-} and Na^{+}.

4.2 Principal component analysis

From PCA analysis, PCA1, PCA2, and PCA3 represent about 52, 12, and 10% of all components along the study area, respectively. PCA 1 has low variance than PCA2 and PCA3. Based on these data, three components were selected for further analysis, as shown in Figure 5. In addition, it was shown that TDS, Cl^{-}, Mg^{2+}, Na^{+}, and Ca^{2} are correlated with each other and less correlated with K^{+} in the present study; seawater intrusion is the source of high release of cations and anions in Wadi Fatimah.

4.3 Spatial analysis of groundwater quality

Figures 6A–C present the spatial distributions of pH, total dissolved solids (TDS), Ca^{2+}, HCO^{-3}, NO^{-3}, Cl^{-}, K^{+}, Mg^{2+}, Na^{+},

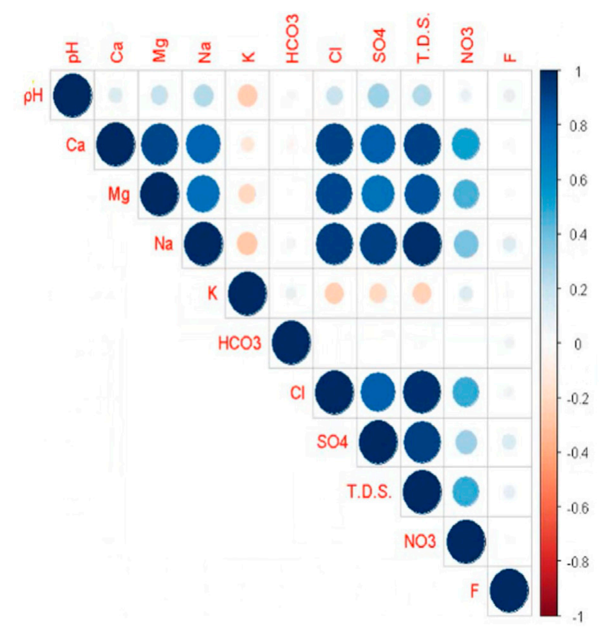

FIGURE 4
Correlation among all parameter concentrations in groundwater.

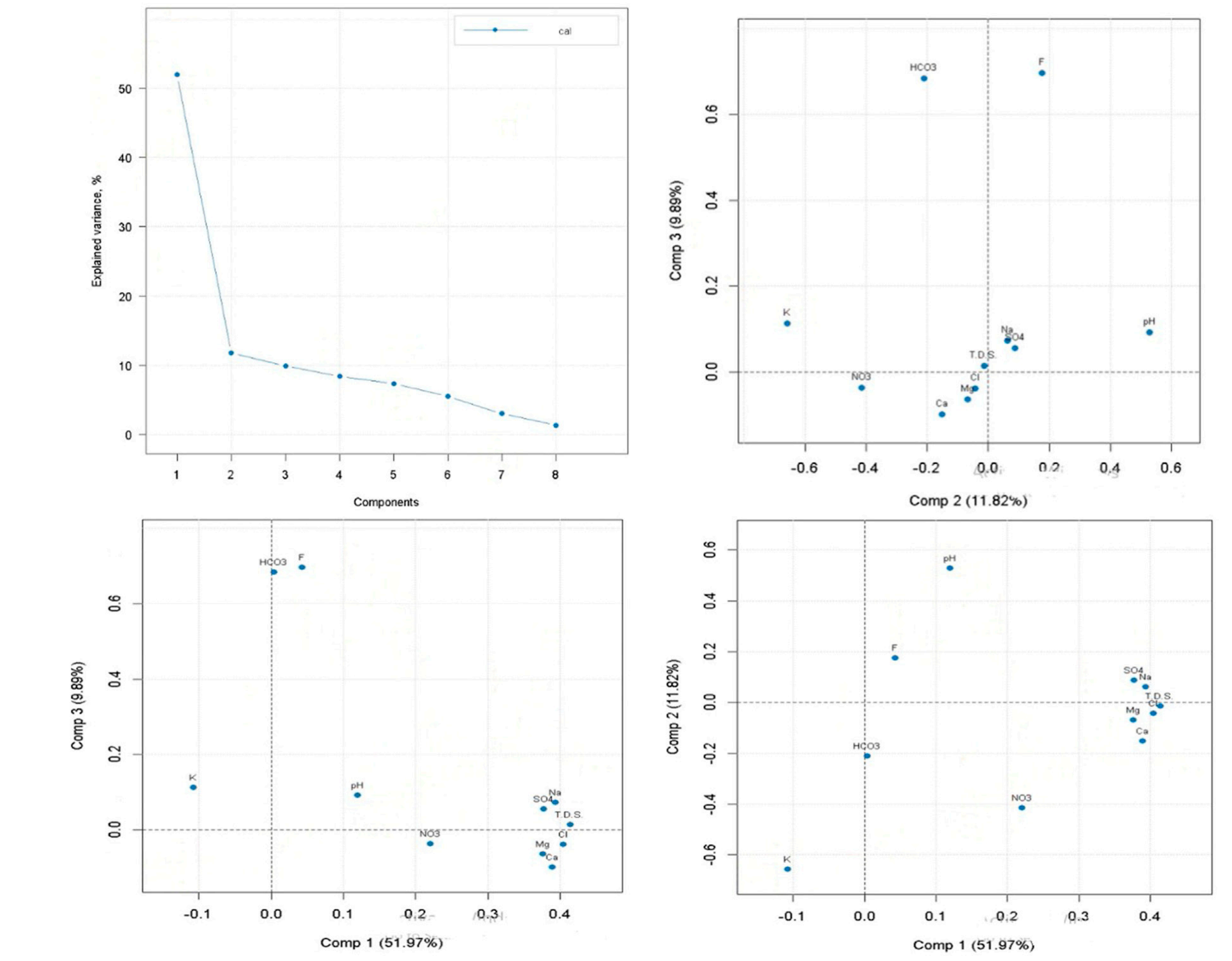

FIGURE 5
PCA components of all parameters in the groundwater of Wadi Fatimah.

and SO_2^{-4}. The pH values are very spatially heterogeneous in the present study as it tends to increase in the southern part of Wadi Fatimah. The southern portion of Wadi Fatimah was mostly home to regions with high TDS, Mg^{2+}, Na^{+}, and SO_2^{-4} concentrations; on the other hand, K^{+} concentrations were low. It was shown that chloride concentrations exceeded the standard limit in some sampling locations. Cl^{-} contamination from anthropogenic sources like industrial discharge may also be related to the high concentration of Cl^{-} in water samples. Furthermore, nitrate exceeded the standard limit in some locations. Anthropogenic pollution is shown by the greater NO^{-3} content. Additionally, agricultural practices add NO^{-3} to groundwater, which lowers its quality (Cardona et al., 2004). Regular fertilizer applications on crop fields and a process that causes the nutrients to build up in groundwater are the two main causes of agricultural contamination of groundwater (Chae et al., 2004). Finally, due to greater groundwater extraction near the shore, seawater intrusion is more prevalent and a source of high cations and anions.

4.4 Water quality index

The quality of groundwater characteristics has been utilized to forecast the irrigation and drinking water quality (Subba Rao, 2006). In the current study in Wadi Fatimah, KSA, the WQI was chosen to ascertain whether the water is fit for drinking. For the computation of the WQI, many parameters were chosen and weights were assigned to each parameter based on the perceived influence on human health (Saeedi et al., 2010). Nitrate and fluoride have been assigned a maximum weight of 5 in accordance with WHO regulations (Srinivasamoorthy et al., 2008). According to how important they were in influencing the water quality, many other criteria were assigned a weight between 1 and 5. The groundwater samples' computed WQI values were categorized, as stated in Table 2. As indicated in Figure 7, none of the groundwater samples were "excellent water," only 33% were "good water," and the remainder were "poor, extremely poor, and unsuitable for drinking water." the spread of polluted water in Wadi Fatimah's southern section. Groundwater quality is at risk due to industrial and municipal

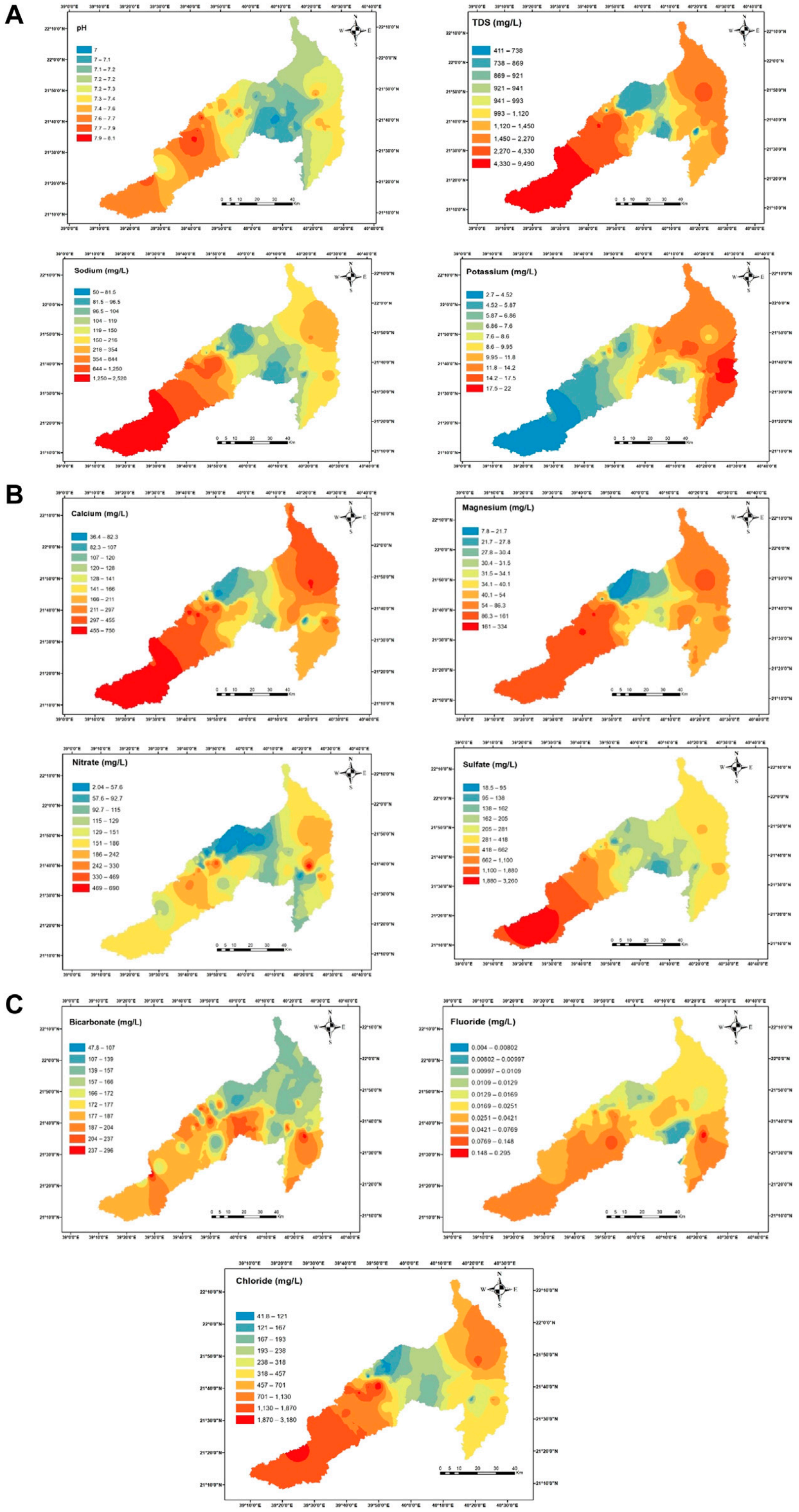

FIGURE 6
(A–C) Spatial distribution of physico-chemical parameters along the study area.

waste, according to Haq and Cheema (2011). The administration and authorities of Makkah City might utilize the created map to supervise a plan for discharging sewage water into Wadi Fatimah.

Hydrologically, Wadi Fatimah and the nearby lands get sporadic rainfall, with the uppermost part of the wadi receiving a significant amount (170 mm/year) and the average annual rainfall not exceeding 60 mm. The Wadi

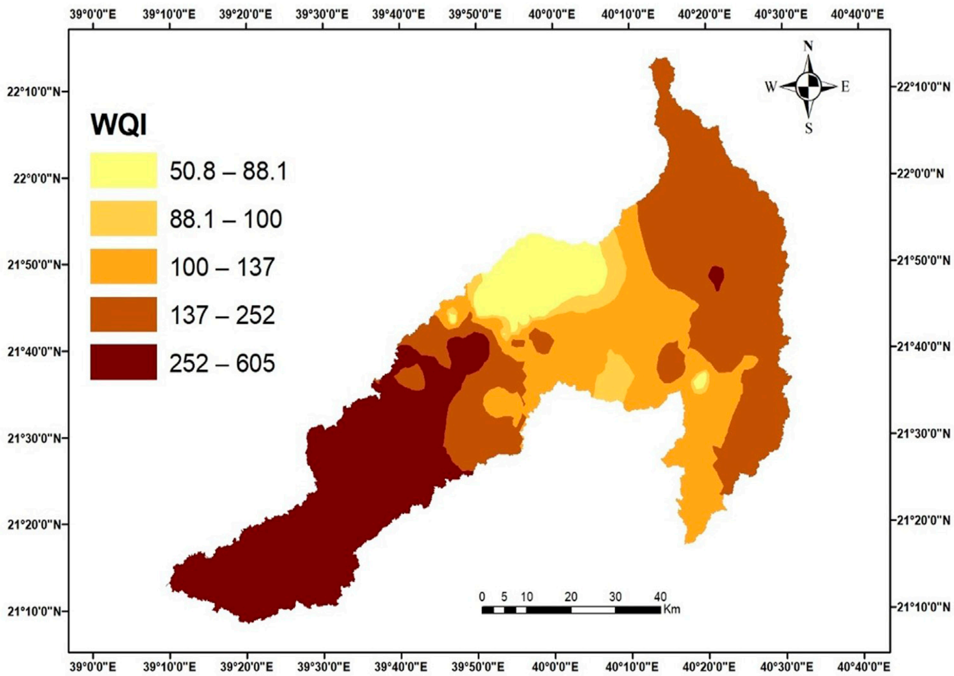

FIGURE 7
Water quality index spatial distribution.

Fatimah basin is filled with Quaternary sediments, whose thickness varies from 10 to 20 m upstream to roughly 80 m downstream (Sharaf, 2013). Both the underlying weathered Precambrian bedrock and the shallow Quaternary alluvial layers contain Wadi Fatimah's groundwater. According to Hem (1970), Drever (1982), Appelo and Postma (1993), and Sharaf and Subyani (2011) found that the distribution of trace elements in the groundwater of Wadi Fatimah is primarily regulated by various processes and the groundwater has a wide range of chemical compositions. Wadi Fatima's southern part was made up of areas with high concentrations of TDS, Mg^{2+}, Na^{+}, and SO_2^{-4}; on the other hand, K^{+} concentrations were low. The high content of Cl^{-} in water samples may also be attributed to Cl^{-} contamination from anthropogenic sources like industrial effluent. Because of the impending seawater intrusions, these samples show significantly salinized water (Sharaf et al., 2001). The groundwater in the Wadi Fatimah upstream sections has a normal salinity and is acceptable for irrigation purposes. The primary mechanisms changing the chemical composition of groundwater include evaporation, irrigation water recycling, and chemical weathering reactions of silicate minerals.

5 Conclusion

Most of the components of general water chemistry are somewhat provided by rainfall chemistry, which is also thought to be a significant source of Cl^{-} and SO_4^{2-} ions. The primary rock-forming minerals' chemical weathering reactions can be a substantial long-term neutralizing process of the groundwater's chemical composition, resulting in Mg^{2+}, Ca^{2+}, Na^{+}, K^{+}, and HCO_3^{-} ions and being significant for Mg^{2+} and Ca^{2+} ions. For irrigation and other human uses, groundwater is a significant source of freshwater. However, recently, the socioeconomic and health effects of groundwater contamination brought on by human activities from both point and non-point sources have gotten worse. The WQI is particularly effective and efficient when it comes to summarizing and reporting observed effects to policy authorities so they may better understand the state of groundwater quality today and have the chance to use it in the future in a more advantageous way. The results and analysis demonstrated the value of using the GIS to produce digital thematic layers and maps that display the spatial distribution of various water quality parameters. In the study area, the quality of the drinking water has significantly declined. The continuous discharge of industrial effluents from various firms, especially those without sewage treatment facilities, is thought to be the main reason for the prevalence of nitrate and fluoride. As a result, proper planning is necessary. A variety of treatment techniques should be utilized to get rid of heavy metals and other contaminants before releasing effluents into the environment. The current focus of the study is mostly on the groundwater quality; additional investigation is needed to examine the consequences for socioeconomics and health. The study's conclusions can serve as a roadmap for groundwater management and pollution control in the study area and other places, according to water system operators and authorities.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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