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Evaluation of hydro-geochemical processes controlling groundwater quality in Balkh center (Mazar-e-Sharif), northern Afghanistan

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ABSTRACT

Background: Groundwater in Afghanistan stands as the predominant water source employed for potable consumption, household utilization, irrigation, and industrial applications. Major cities of Afghanistan are largely dependent on groundwater resources. However, the groundwater quality of major cities in Afghanistan, including Mazar-e-Sharif city was not investigated in detail.
Objective: This study aims to conduct a comprehensive analysis of the hydrochemical characteristics of the Mazar-e-Sharif groundwater, identify the factors influencing groundwater quality, and evaluate the groundwater contamination sources.
Methods: A total of 18 groundwater samples were collected during the dry season (June 2020) and analyzed for various physico-chemical parameters. Methods such as multivariate statistical analyses, geochemical modeling, water quality index (WQI), and spatial distribution of groundwater quality were employed to evaluate the hydrogeochemistry of the study area.
Results: The results reveal that **1)** The prevailing groundwater within the study area is predominantly characterized by Na-(Ca)-HCO_3 and Ca-(Mg)-SO_4 water types. **2)** Physicochemical variables such as NO_3^-, F^-, TDS, and SO_4^{2-} exceeded the World Health Organization (WHO) safe limits in many wells. **3)** Hydro-geochemical processes such as silicate weathering, cation exchange, and gypsum dissolution controls the groundwater chemistry. **4)** Cl/Br ratios reveal, that high salinity may originate from evaporitic lacustrine and evaporite deposits and found to be localized in nature. **5)** The Water Quality Index (WQI) classification suggests that approximately 60 % of the groundwater samples fall into poor to very poor water quality categories, highlighting substantial public health concerns. Major contaminants like nitrate and fluoride were found to be higher than the safe limit in nearly half of the samples.
Conclusion: The findings of this study hold value for decision-makers in formulating a proficient strategy for the management of groundwater resources in Mazar-e-Sharif City in achieving the UN sustainable goal (SDG) of providing sustainable water for all. Furthermore, new advanced techniques like environmental isotopes should be analyzed to evaluate groundwater hydro-chemical evolution in the future to enhance our understanding.

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1. Introduction

Groundwater plays a pivotal role in supplying drinking water to billions of individuals globally [1–4]. Preserving the cleanliness and safety of groundwater is of utmost importance for achieving sustainable social, and human development [5,6]. However, rapid urbanization, increased wastewater generation, and deterioration of groundwater quality have become a worldwide concern, given its widespread distribution and potential health implications [7–11]. Many cities worldwide, particularly those in arid, and semi-arid regions are currently confronted with the dual challenge vis-à-vis groundwater depletion, and degradation of water quality [12–15].

Globally, hydro-geochemical processes have been extensively studied, providing critical insights into the evolution and quality of groundwater. Investigations in arid environments, particularly in the Middle East regions, have underscored the significance of evaporation and mineral dissolution in controlling groundwater chemistry [16–19]. Research conducted in temperate and tropical regions highlighted the influence of anthropogenic activities, including agricultural practices and industrial discharge on groundwater chemistry [20,21]. Recent studies also incorporate isotopic and geochemical tracers to advance research on groundwater contamination assessments [22–25].Correlation analysis, ionic ratios, and assessment of saturation indices are regarded as efficient methodologies for investigating the hydro-chemical evolution of groundwater [26–28]. Additionally, researchers have integrated traditional methods like multivariate statistics and geochemical modeling to interpret complex hydro-chemical datasets for detailed characterizations of groundwater chemistry [29–31]. Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) are effective notable multivariate statistical methods used to categorize water samples containing intricate chemical datasets and diminish the dimensionality of multivariable chemical datasets by extracting fundamental components [32–35]. Geochemical modeling is extensively utilized for the quantitative evaluation of mass transfer magnitudes implicated in the geochemical progression of groundwater and its flow path from one point to another point [36,37]. Furthermore, a range of scientific techniques are employed to evaluate the quality of groundwater based on physicochemical parameters [38]. These techniques include Geographic Information Systems (GIS) methods such as Inverse Distance Weighting (IDW), Kriging, Cokriging, and Spline, as well as geo-statistical analysis and the Water Quality Index (WQI). Among these approaches, GIS and WQI methods are frequently used by numerous researchers to investigate groundwater quality [39–43].

Afghanistan is a landlocked country situated in the Central-South Asia, and characterized by an arid to semi-arid climate. The country is largely surrounded by mountains and covered with vast desert regions, reflecting its climate and environmental conditions [44]. Recently, the increased dependency on groundwater has led researchers to investigate water quality for drinking, and irrigation throughout Afghanistan. Although majority of research in the water domain in Afghanistan have been conducted by the US Geological Survey (USGS), the German Federal Institute for Geosciences and Natural Resources (BGR), and the Japan International Cooperation Agency (JICA). Few local researchers primarily focused their investigations mainly on the Kabul basin, the Capital of Afghanistan [44–53]. Therefore, limited studies on groundwater were conducted particularly in the plains of northern Afghanistan including Mazar-e-Sharif [54].

Mazar-e-Sharif is situated in the northern region of Afghanistan and is emerging as a significant urban center in the northern part of the country. The rapid development of residential areas and the subsequent population growth have led to significant challenges, notably groundwater pollution, and excessive extraction. The water level in Mazar-e-Sharif city experiences a considerable decline, particularly during the dry season. Consequently, the residents of Mazar-e-Sharif are confronted

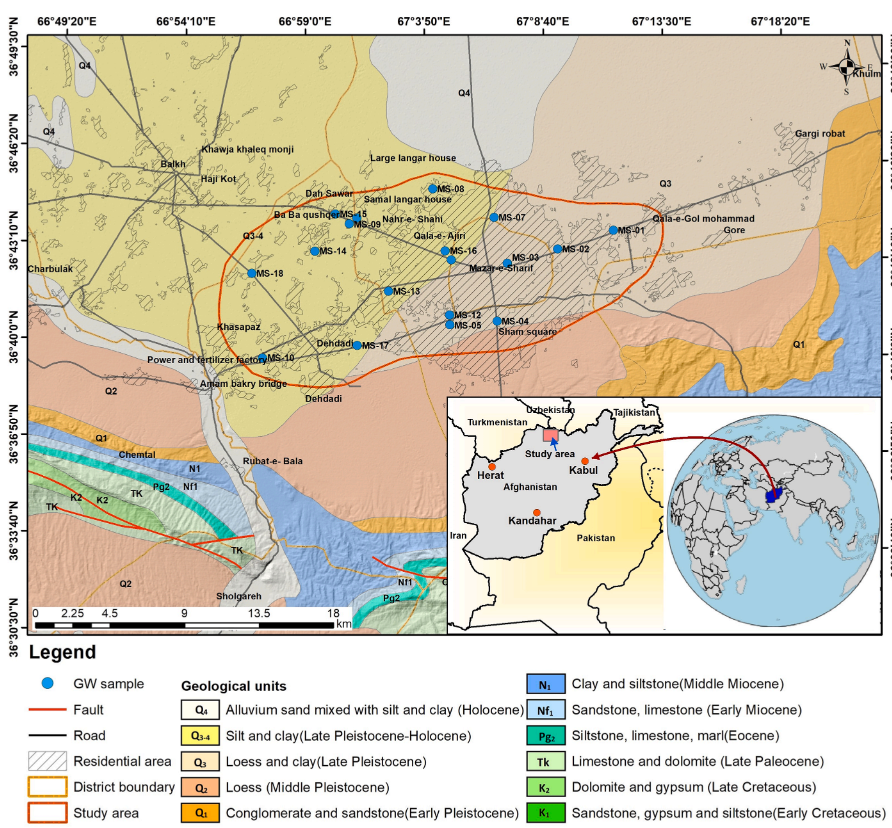

Fig. 1. Geological map of Mazar-e-Sharif city (USGS report by Doebrich and Wahl (2006); available at https://www.usgs.gov/; open access. The study area is shown as a red line; collected water samples localities are shown as blue points.

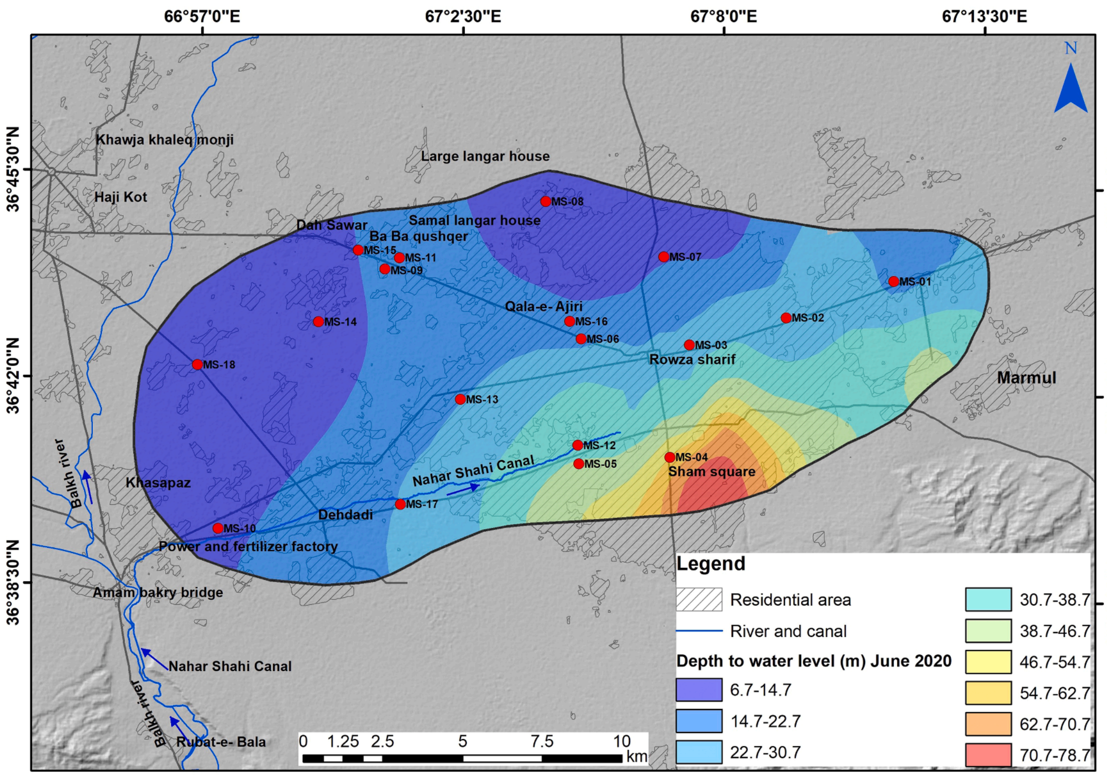

Fig. 2. Depth to groundwater levels of Mazar-e-Sharif city in June (dry) 2020.

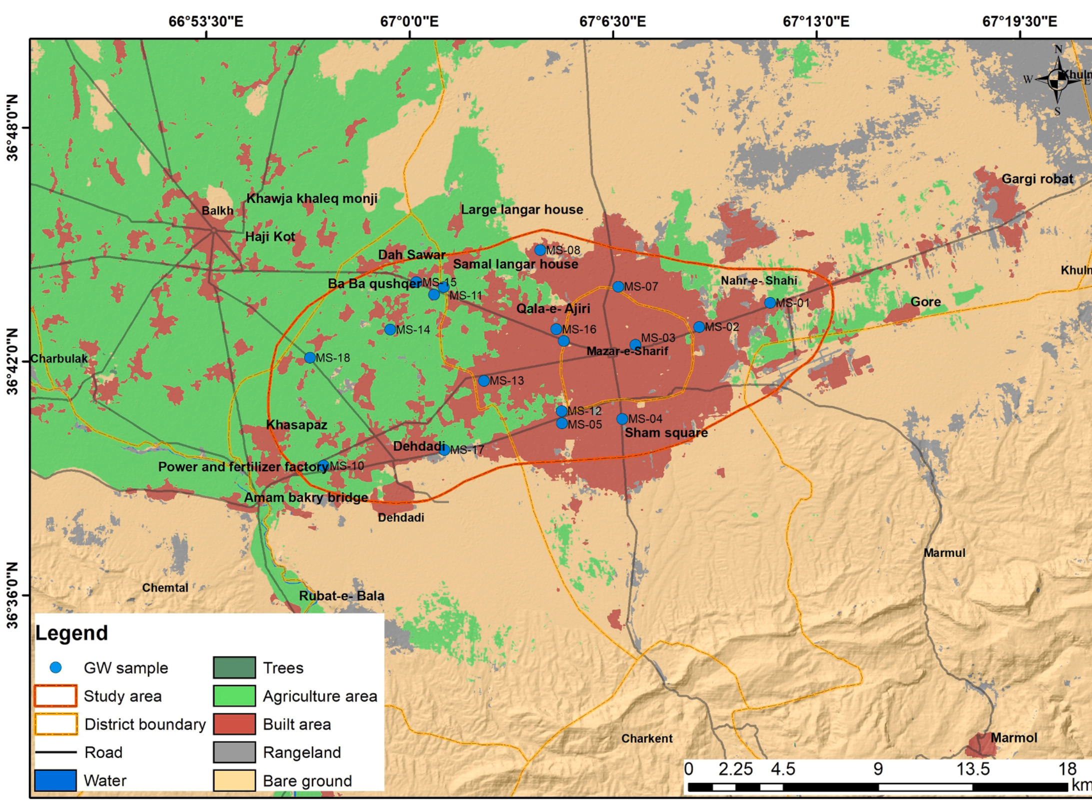

Fig. 3. The map depicting Land use/land cover within the study area (the study area is shown as a red line in the figure).

with severe issues related to access to safe drinking water [55].

Earlier, Mahaqi et al. [55] investigated the groundwater of Mazar-e-Sharif for drinking, and irrigation using only traditional empirical formulas. However, this study used an integrated approach involving hydrochemistry, geospatial analysis tools, geochemical modeling, and multivariate statistical analyses to investigate the

Table 1
Groundwater quality variables and their relative weights are applied to the groundwater quality index (GWQI) [84].

Chemical parameter (mg/L)	WHO (2022)	Weight (w_i)	Relative weight (W_i)
Fluoride	1.5	5	0.122
Nitrate	50	5	0.122
TDS	500	5	0.122
pH	7.5	4	0.098
EC	1500	4	0.098
Sulfate (SO_4)	250	4	0.098
Total Hardness	500	3	0.073
Bicarbonate (HCO_3)	500	3	0.073
Chloride (Cl)	250	3	0.073
Sodium (Na)	200	2	0.049
Potassium (K)	12	2	0.049
Magnesium	150	1	0.024
Total	-	$\sum w_i = 41$	$\sum W_i = 1$

Water quality classification according to the Water Quality Index (WQI) is as follows: When the WQI is below <50, it is classified as excellent, (50–100) is considered decent, poor (100–200), very poor (200–300), and if the WQI exceeds >300, the water is deemed unfit for drinking [74–77].

groundwater evolution of the study area.

The study's objective is to comprehensively analyze the hydrochemical characteristics of the Mazar-e-Sharif groundwater, identify the factors influencing groundwater quality, and evaluate the groundwater contamination sources. These techniques provide a more thorough assessment of groundwater evolution and facilitate the identification of both natural and anthropogenic factors influencing groundwater chemistry. The outcome of this study holds significant implications for local policy and strategy makers and will be a valuable insight for sustainable groundwater management and future research endeavors related to groundwater in Mazar-e-Sharif.

2. Study area

2.1. Description

Mazar-e-Sharif city, located in the northern region of Afghanistan and falls within the geographical coordinates 66° 54′ 10″ E to 67° 18′ 20″ E longitude and 36° 36′ 50″ N to 36° 46′ 20″ N latitude, and serves as the capital of Balkh province. It is the fourth largest city in the country, covering an area of about 83 km^2, and shares its borders with Nahar-shahi, Balkh, and Marmol districts. National Statistics and Information Authority reported that the estimated population of Mazar-e-Sharif city is approximately more than half a million [56]. Notable population growth can be seen in the last five years in the city. The city is located at a relatively lower altitude compared to other cities of Afghanistan (average height 357 m above the mean sea level; m asl). The climate in the study area is characterized as semi-arid to arid. Precipitation is minimal throughout the year. The average annual temperature in the study area stands at 21 °C, and the annual precipitation measures approximately 170 mm. July experiences the highest mean temperature, reaching an average of 36.5 °C. Conversely, December records the lowest average temperature of around 4.3 °C. The majority of the rainfall occurs from February to April during winter [57].

2.2. Geology and hydrogeology

The study area is entirely covered by alluvial, prolluvial, and colluvial deposits of the Quaternary age, as well as salt marsh sediments, and non-marine sediments. These deposits have originated from the accumulation of runoff in swamp-like regions, facilitated by high temperatures, and subsequent precipitation and extensively covered the Afghan North Plain (Fig. 1). Quaternary deposits within the study area can be classified into two primary units [58,59]. Firstly, there are alluvium deposits in the hilly region, consisting of terrace sands and gravels, occasionally mixed with cobbles. Secondly, prolluvial deposits dominate the majority of the area. The geological formations present in the study area exhibit a wide range of compositions.

The majority of groundwater in Afghanistan occurs within alluvial deposits of Quaternary and Neogene ages along the primary water courses and valleys located between mountain ranges [54,60]. The groundwater can be largely found within basin-like depressions bounded by minor faults resulting from tectonic movements.

The groundwater recharge is expected to be high during peak

Table 2
Statistics analysis of the physicochemical parameters of groundwater samples within the designated study area.

Sample ID	pH -	Temp. °C	TDS mg L^{-1}	EC µS/cm	Ca^{2+} mg L^{-1}	Mg^{2+} mg L^{-1}	Na^+ mg L^{-1}	K^+ mg L^{-1}	HCO_3^- mg L^{-1}	Cl^- mg L^{-1}	SO_4^{2-} mg L^{-1}	NO_3^- mg L^{-1}	F^- mg L^{-1}	Br^- mg L^{-1}
MZ-01	7.34	18.1	3240	4710	222.4	188	90	3.8	210	370	680	85.00	5.44	0.62
MZ-02	7.41	18.2	899	1306	76.8	55	193	3.1	345	144	240	28.88	4.22	0.79
MZ-03	7.39	23.3	896	1302	57.2	60	164	4.3	375	97	218	39.52	1.80	0.29
MZ-04	7.67	17.5	2745	3990	144	74	352	7.1	126	600	390	63.6	3.7	0.46
MZ-05	7.78	17.9	2401	3490	232.8	76	288	5.2	145	470	380	80.08	2.95	0.44
MZ-06	7.12	23.3	2477	3600	224	120	99	3.6	480	255	410	31.64	5.48	0.57
MZ-07	7.43	17.7	1555	2260	68.8	94	325	5	335	290	480	37.04	1.5	0.39
MZ-08	7.27	19.5	1658	2410	111.2	120	127	4	330	205	410	6.65	2.28	0.42
MZ-09	7.56	18.8	979	1423	97.6	65	160	12	360	145	254	44.38	1.31	0.81
MZ-10	7.34	17.6	833	1283	140.8	47	57	15.2	175	57	270	52.9	1.35	0.75
MZ-11	7.72	26.2	1085	1577	94	55	173	6.2	400	135	228	53.4	1.37	0.44
MZ-12	7.68	25.8	519	754	72	29	52	2.1	300	35	52	32	0.99	0.33
MZ-13	7.87	26.4	786	1142	80	44	123	2	480	40	97	22.2	2.6	0.41
MZ-14	7.65	26.5	863	1254	76	35	170	3.8	370	93	190	42.1	1.33	0.52
MZ-15	7.78	26.7	607	882	64	34	94	3.6	290	57	114	40.88	1.23	0.41
MZ-16	7.68	26.4	2229	3240	168	110	78	3.7	390	132	400	71.04	5.60	0.56
MZ-17	7.78	26.3	1610	2340	220	100	4	2.4	360	82	440	53.32	5.35	0.53
MZ-18	7.62	26.2	736	1070	78	38	104	2.7	270	98	155	40.7	1.12	0.36
Min	7.12	17.50	519	754	57.20	29	4	2	126	35.00	52	6.65	0.99	0.29
Mean	7.56	22.36	1451	2112.94	123.76	74.67	147.39	4.99	318.94	183.61	300.44	45.85	2.76	0.51
Max	7.87	26.70	3240	4710	232.80	188	352.00	15.20	480	600	680	85.00	5.60	0.81
SD	0.21	3.88	807.81	1171.38	61.24	39.91	91.56	3.35	99.26	153.34	155.29	19.41	1.69	0.15
WHO (2022) Permissible Limit	6.5–8.5	-	1000	1500	200	150	200	12	500	250	250	50	1.5	0.5
Percentage of samples above the safe limit	0.00	-	50	50	16.6	5.55	11.1	5.5	0.00	27.8	55.5	38.8	44.4	44.4

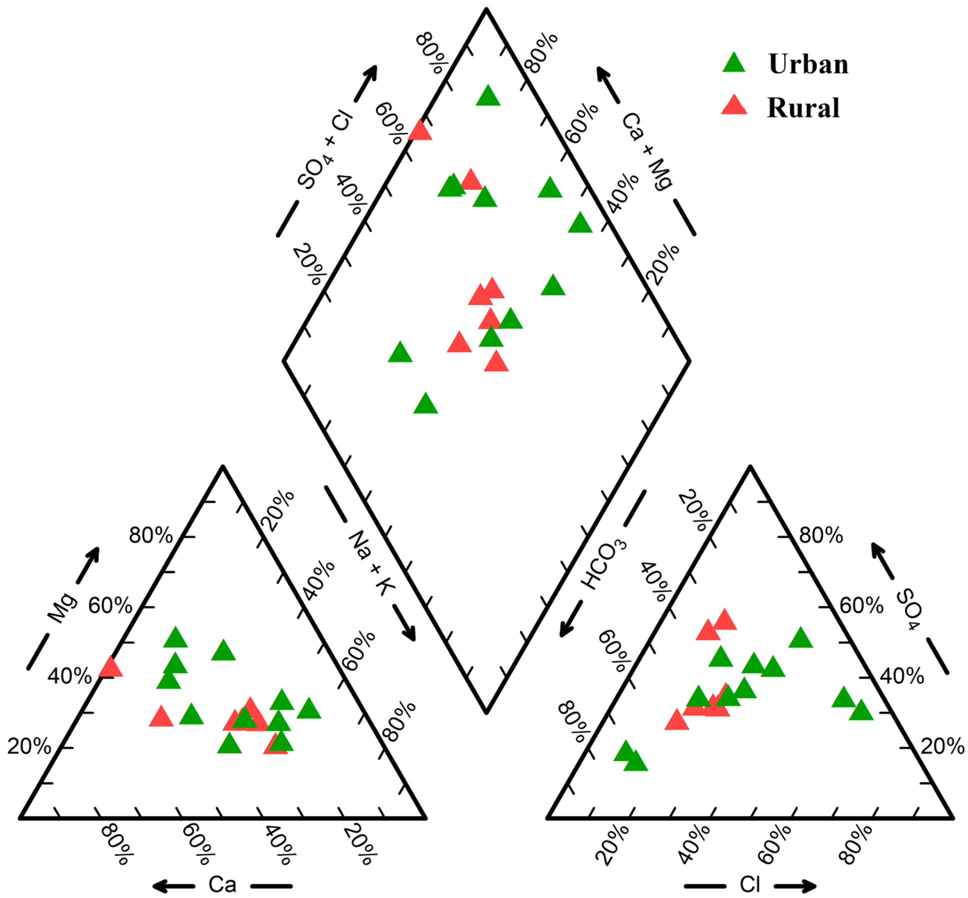

Fig. 4. Piper diagram depicting the chemical compositions of groundwater samples from the Mazar-e-Sharif alluvial aquifer.

snowmelt season. Consequently, the recharge to groundwater is significantly influenced by the amount of snowfall during the winter period [61]. Additionally, groundwater is also recharged by irrigation to return flow water, especially in the irrigated area. The study area consists of a single, unconfined, and unconsolidated aquifer system, functioning as a phreatic aquifer. Given the absence of a confined aquifer in the study area, this aquifer is the sole and critical resource for water supply, making its sustainable management essential.

2.2.1. Depth to groundwater level

For this study, groundwater levels were collected from the Afghanistan Ministry of Energy and Water (MEW). The depth to groundwater level map is demonstrated in Fig. 2. The depth to groundwater levels in the study area ranges from 6.7 m to 78.7 m below the ground surface. The shallow groundwater levels were observed in the west and north of the region, while the deeper groundwater levels were observed in the south of the Mazar-e-Sharif urban area. The Balkh River, which is the primary groundwater recharge source of the aquifer, flows from the southern region towards the northern, and north-western portions and is the only perennial river in the study area (Fig. 2). Also, the river water is widely utilized for irrigation in the aforementioned areas. Therefore, irrigation return flow also primarily contributes to groundwater recharge in the western and north-western regions of the study area. The deeper groundwater level in the southern region is most likely due to over-exploitation.

2.2.2. Land-use/ land cover

This study utilizing the Sentinel 2 satellite image captured in 2020 generated the land-use/land cover (LULC) map of Mazar-e-Sharif. The area is broadly categorized into six distinct classes through the maximum likelihood classification algorithm, employed within the Google Earth Engine platform (Fig. 3). The major six classes identified in the LULC map are; water bodies, forest, agricultural land, urban land, rangeland, and bare ground. The classification was determined by considering field observations as well as satellite imagery. The findings reveal that a significant portion of the study area are covered by agricultural land (28.9 %), followed by built-up area (40 %), rangeland (2.5 %), and bare ground (28.6 %). However, water bodies and forests were found to be negligible (<1 %). Built-up area and agricultural land can be found mainly in the western part of the study area (Fig. 3).

3. Materials and methods

3.1. Groundwater sampling and analyses

A total of 18 groundwater samples were collected from an unconfined aquifer during the dry season (June 2020) by the Ministry of Energy and Water (MEW) and analyzed for physicochemical parameters at the Danish Committee for Aid to Afghan Refugees (DACAAR) Laboratory in Kabul. A set of ten samples were collected from monitoring wells monitored by MEW, while 8 samples were obtained from wells utilized for various purposes such as domestic, irrigation, and industrial utilizations (Fig. 2). In-situ parameters such as temperature, pH, and electrical conductivity (EC) of each sample were measured on-site using the hand-held meter (Multi 340i, WTW, Germany). Some field blanks and duplicates were also collected and analyzed for quality control. Water samples intended for hydro-chemical analysis, including cations such as Ca^{2+}, K^{+}, Na^{+}, Mg^{2+}, and anions like HCO_3^-, Cl^-, SO_4^{2-}, NO_3^-, and F^-, were collected in clean polyethylene bottles. To uphold the integrity of the analysis, field blanks, and duplicate samples were systematically collected as part of rigorous quality control protocols, ensuring the precision, accuracy, and reliability of the analytical results throughout

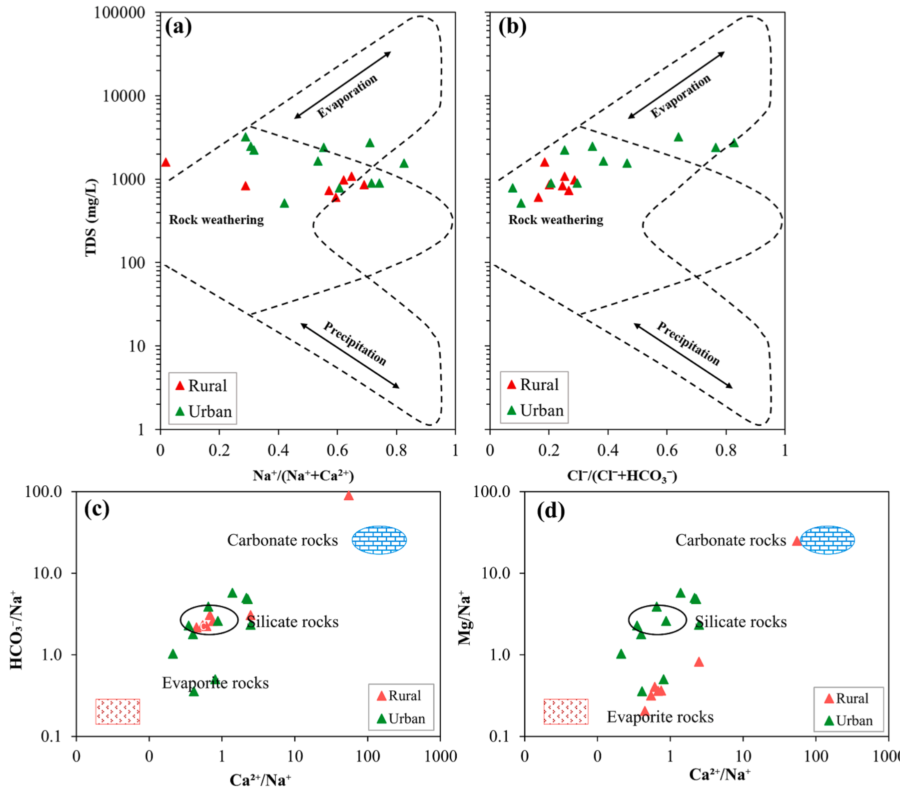

Fig. 5. The graphs display the main processes controlling water chemistry. **(a)** TDS against $Na^+/(Na^+ + Ca^{2+})$. **(b)** TDS against $Cl^-/(Cl^- + HCO_3^-)$. **(c)** Scatter diagrams (HCO_3^-/Na^+) vs (Ca^{2+}/Na^+), **(d)** (Mg^{2+}/Na^+) vs (Ca^{2+}/Na^+).

the entire testing process. The samples were transported to the DACAAR Laboratory in Kabul under controlled conditions, ensuring their chemical integrity during transit. The physicochemical properties were analyzed using the Photometer 8000 for precise determination of both cations, and anions. To ensure statistical reliability, all analyses were conducted in triplicate, and rigorous quality control was maintained by including field blanks and duplicate samples. The assessment of the accuracy and reliability of the chemical analyses was conducted by employing the computation of charge balance error (CBE). Except for two groundwater samples that exceeded the ±5 % threshold, the charge balance error (CBE) values of all other groundwater samples were within the acceptable range. This outcome confirms the praiseworthy accuracy and reliability of the conducted chemical analyses.

3.2. Multivariate statistical analyses

The mechanism governing groundwater control can be determined through hydro-chemical analyses and multivariate statistical techniques, such as ion ratios, Gibbs plots, and Piper plots. Multivariate statistical methods, including principal component analysis (PCA) and correlation analysis, assisted by GIS and Origin software, play a crucial role in identifying pollution sources [62–64].

3.3. Geochemical modeling

The saturation index (SI) is of paramount importance in assessing the equilibrium and reactivity between groundwater and minerals [33,65]. The hydro-geochemical state and the occurring reactions in groundwater are assessed by utilizing the ratio between the activity product and the solubility product. The SI indices are employed to assess the level of equilibrium between water and minerals. Alterations in saturation state serve as valuable indicators for distinguishing various stages of hydro-chemical evolution, and aid in identifying the primary geochemical reactions that govern water chemistry [66–68].

Through the analysis of the values of SI, the states of saturation were classified as follows: saturated (indicating equilibrium, SI = 0), unsaturated (indicating dissolution, SI < 0), and over-saturated (indicating precipitation, SI > 0). PHREEQC version 2.8 was utilized to determine the values of SI of minerals such as calcite, dolomite, gypsum, halite, and fluorite in this study Eq. (1).

$$SI = \log IAP/Ksp \tag{1}$$

where, IAP and K_{SP} represent the activity product and solubility product, respectively.

3.4. Water quality index (WQI)

For assessing the overall quality of groundwater Water Quality Index (WQI) method is widely used. It simplifies the evaluation process by combining multiple important water quality parameters into a single index and is utilized widely [69–73]; Eq. (2):

$$WQI = \sum_{i=0}^{n} W_i \times Q_i \tag{2}$$

The quality rating assigned to the i parameter is represented as Q_i, and the weight assigned to each parameter in the W_i is equal to the total number of parameters, represented as 'n' Eq. (4).

$$Q_i = \left[\frac{C_i}{S_i}\right] \times 100 \tag{3}$$

The determination of the quality rating (Q_i) is based on the concentration (C_i) of each parameter, measured in mg L^{-1} in relation to the corresponding standards set by the WHO, denoted as (S_i) Eq. (3).

$$W_i = \frac{w_i}{\sum_i^n w_i} \tag{4}$$

The calculations involve utilizing the relative weight of each

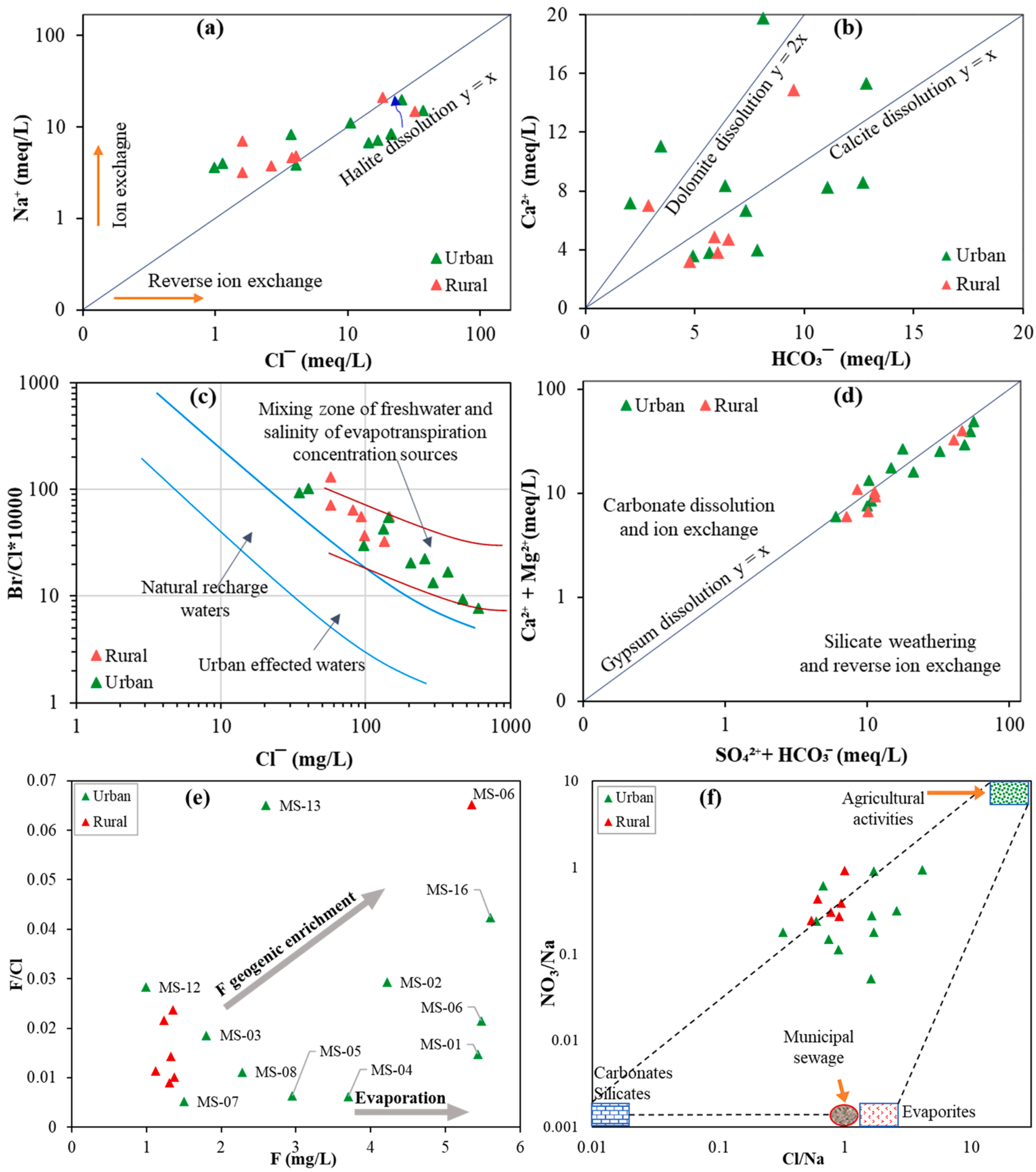

Fig. 6. Diagrams depicting the interrelationships among major cations/anions to differentiate various hydro-geochemical processes. (a) Na^+ versus Cl^-; (b) HCO_3^- versus Ca^{2+}; (c) Cl^- versus Br/Cl^-; (d) (SO_4^{2-} + HCO_3^-) versus (Ca^{2+} + Mg^{2+}); (e) F^- versus (F^-/Cl^-); (f) Cl^-/Na^+ versus NO_3^-/Na^+.

sampled parameter, denoted as W_i, in conjunction with the weight assigned to each parameter (w_i) and the total number of parameters (n) Eq. (4). Table 1

3.5. Spatial distribution of groundwater quality mapping

The geospatial method known as Inverse Distance Weighting (IDW) interpolation is extensively utilized to portray and analyze the spatial distribution patterns of groundwater quality parameters. The original formulation of this interpolation method can be attributed to the work of Shepard, Bartier, and Keller [78]. The IDW method has demonstrated satisfactory outcomes in numerous comparable investigations. Various researchers have effectively employed this method to assess the regional destruction of groundwater quality [79–82]. To evaluate the spatial distribution of groundwater quality in Mazar-e-Sharif, the IDW interpolation method was implemented using ArcGIS 10.6 software.

4. Results and discussion

4.1. Major ions chemistry

The Na^+ and K^+ concentrations in the analyzed samples exhibit significant variability, ranging from 4 mg L^{-1} to 352 mg L^{-1} and 2 mg L^{-1} to 15.2 mg L^{-1}, respectively, with average values of 147.4 mg L^{-1} and 4.99 mg L^{-1} (Table 2). The presence of Na^+ within the study area can be attributed to various processes such as silicate weathering, gypsum dissolution, and also from anthropogenic sources [68]. The Ca^{2+} and Mg^{2+} concentrations in the analyzed samples exhibited in the range of 57.2 mg L^{-1} to 232.8 mg L^{-1} and 29 mg L^{-1} to 188 mg L^{-1}, respectively, with average values of 123.8 mg L^{-1} and 74.7 mg L^{-1}. The release of Ca^{2+} and Mg^{2+} into the groundwater is facilitated by the ion-exchange mechanism during the interactions between water and rock, as well as through mineral dissolution [83]. The prevailing anions

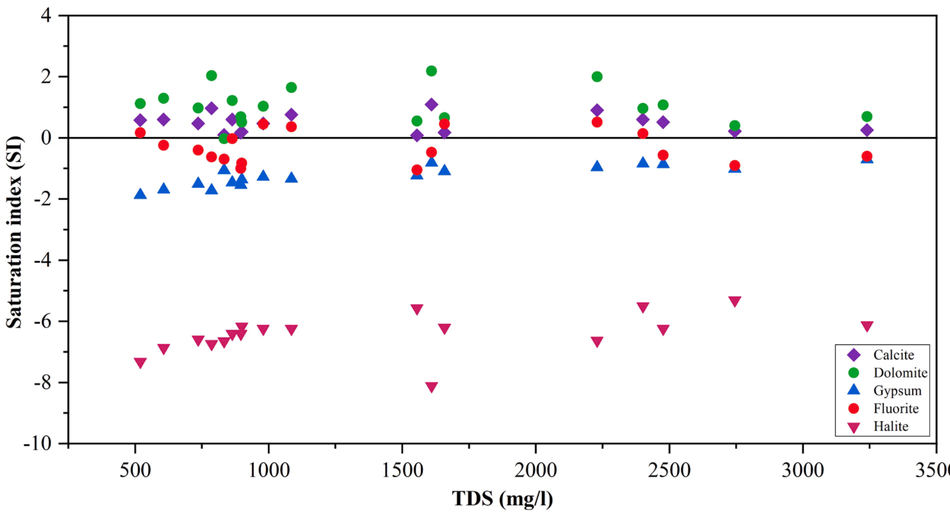

Fig. 7. Saturation indices of the different minerals as a function of TDS.

Table 3
Correlation matrix between groundwater variables (shown as heat map for better visualization).

	pH	Temp.	TDS	EC	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	Cl^-	SO_4^{2-}	NO_3^-	F^-
pH	1												
Temp.	0.499*	1											
TDS	-0.274	-0.460	1										
EC	-0.288	-0.491*	0.998*	1									
Ca^{2+}	-0.071	-0.301	0.752*	0.767*	1								
Mg^{2+}	-0.415	-0.388	0.907*	0.913*	0.678*	1							
Na^{+}	-0.024	-0.396	0.245	0.224	-0.174	0.030	1						
K^{+}	-0.304	-0.616*	0.354	0.372	0.170	0.229	0.463	1					
HCO_3^-	0.063	0.568*	-0.074	-0.095	-0.139	0.053	-0.069	-0.306	1				
Cl^-	-0.363	-0.644*	0.841*	0.835*	0.488*	0.704*	0.599*	0.499*	-0.278	1			
SO_4^{2-}	-0.429	-0.5*	0.855*	0.865*	0.625*	0.923*	0.031	0.323	-0.129	0.683*	1		
NO_3^-	0.259	-0.163	0.453	0.457	0.507*	0.245	-0.036	0.446	-0.358	0.312	0.326	1	
F^-	0.311	0.586*	-0.218	-0.240	-0.106	-0.149	-0.143	-0.131	0.329	-0.247	-0.322	-0.067	1

in the groundwater were HCO_3^- and Cl^-, which exhibited concentrations ranging from 126 mg L^{-1} to 480 mg L^{-1} and 35 mg L^{-1} to 600 mg L^{-1}, respectively (mean 318.94 mg L^{-1} and 183.61 mg L^{-1}). The presence of HCO_3^- in groundwater is likely due to weathering of silicates and dissolution of carbonates from the atmosphere [84]. The SO_4^{2-} concentration in the samples varied in the range of 52 mg L^{-1} to 680 mg L^{-1} (mean value; 300.5 mg L^{-1}; Table 2). The primary origin of SO_4^{2-} in the groundwater is associated with the dissolution of anhydrite and gypsum, although human activities such as improper sewage disposal and the application of fertilizers in agriculture may also contribute to its presence [85].

NO_3^- concentration in the study area varies from 6.7 mg L^{-1} to 85.7 mg L^{-1} (average 45.85 mg L^{-1}). The eastern and southern regions of the study area exhibit the highest concentrations of NO_3^-. Generally, elevated levels of NO_3^- indicate the presence of anthropogenic influences within a specific area [86]. The higher concentrations of NO_3^- in groundwater could be attributed to unscientific agricultural practices involving the wider application of fertilizers, and poor sewage drainage systems [87,88]. Field observations and land use indicated that sewage and chemical fertilizer are more likely to be the main origin of elevated NO_3^- levels in the study area.

The F^- concentrations in several wells exceed the World Health Organization's (WHO) maximum permissible limit of 1.5 mg L^{-1}, with values ranging from 0.99 mg L^{-1} to 5.6 mg L^{-1} (average 2.75 mg L^{-1}) [89]. Approximately, 56 % of the groundwater samples have elevated F^- levels in the study area. The high concentration can be attributed to the presence of fluorine-bearing rocks in the aquifer and could be linked to long water-rock interactions. In addition, this study for the first time reported elevated levels of F^- in the area and also in Afghanistan which was undocumented earlier. However, an in-depth evaluation of F^- sources can be taken up in the future.

4.2. Hydro-chemical facies

The identification of hydro-chemical facies within an aquifer has the potential to elucidate the mechanisms underlying the occurrence and provide insights into the palaeo-environmental history of the groundwater system. The analysis of Piper's diagram indicates that the major water types in the Mazar-e-Sharif region are predominantly Na-HCO_3, Na-Ca-HCO_3, Ca-Mg-SO_4, and Na-Cl (arranged in descending order of occurrence; Fig. 4). The hydro-chemical facies of groundwater in the Mazar-e-Sharif region are significantly influenced by land use and land cover (LULC) patterns. The predominance of Na-HCO_3 and Na-Ca-HCO_3 water type facies reflects active cation exchange and silicate weathering processes typically linked to groundwater interaction with agricultural soils and natural mineral deposits. While agricultural activities, particularly the extensive use of fertilizers, can further accelerate these processes by enhancing ion availability and intensifying ion exchange in the

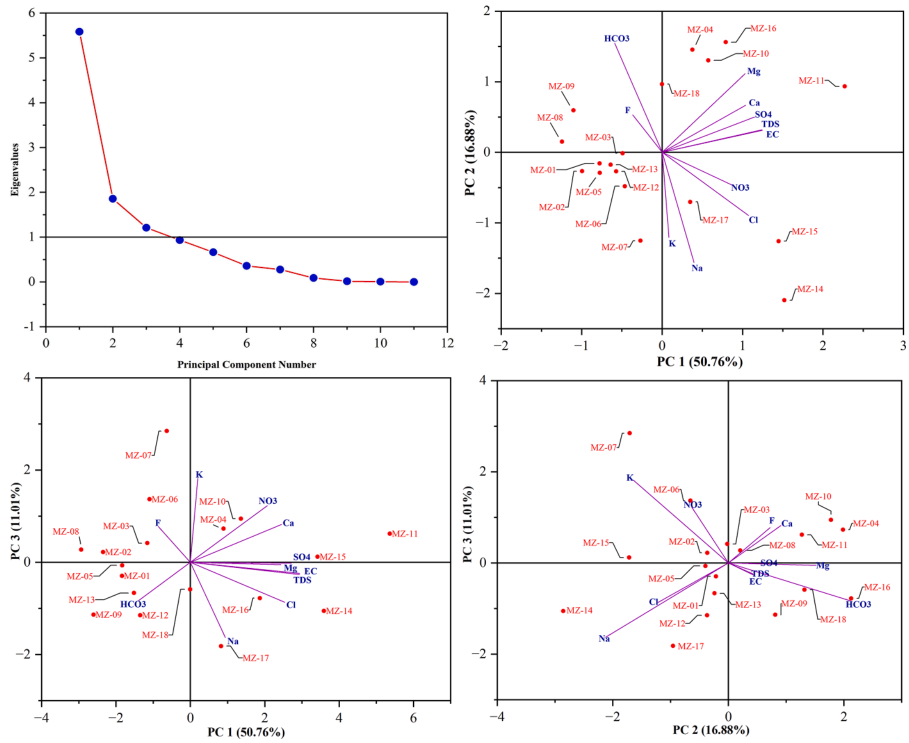

Fig. 8. Outcomes of principal component analysis displaying three PCs.

Table 4
Results of principal component analysis of hydro-chemical data of groundwater samples from Mazar-e-Sharif aquifer.

Chemical Variable	Principal component loading		
	PC1	PC2	PC3
TDS	**0.411**	-0.103	-0.083
EC	**0.412**	-0.100	-0.075
Ca	**0.344**	-0.214	0.256
Mg	**0.341**	-0.357	-0.017
Na	0.132	**0.501**	**-0.508**
K	0.028	**0.387**	**0.566**
HCO_3	-0.195	**-0.496**	-0.258
Cl	**0.356**	0.287	-0.270
SO_4	**0.380**	-0.160	-0.007
NO_3	0.290	0.150	**0.382**
F	-0.121	-0.170	**0.242**
Eigenvalues	5.913	1.966	1.282
% Variance	50.765	16.882	11.011
Cumulative %	50.765	67.647	78.658

groundwater [90,91].

Urban expansion and other anthropogenic activities have a pronounced impact on groundwater chemistry, as evidenced by the increased prevalence of Na-Cl facies in urban areas (Fig. 4). The shift towards Cl^--rich waters indicates geogenic as well as anthropogenic influences, such as domestic wastewater infiltration, industrial effluents, and urban runoff, which may introduce Cl and Na ions into the aquifer system. Additionally, the presence of Ca-Mg-SO_4 facies in recharge zones suggests contributions from both natural sources, such as gypsum dissolution, and anthropogenic inputs, including agricultural runoff enriched with sulfate-based fertilizers [92].

The spatial distribution of hydro-chemical facies, particularly the enrichment of Na-Cl facies in urbanized areas, highlights the direct influence of land use changes on groundwater quality. The findings underscore the need for sustainable land-use planning, and groundwater management strategies to mitigate anthropogenic contamination and preserve water quality in the region.

4.3. Factor governing water chemistry

In this study, the Gibbs diagram is employed to quantitatively assess the primary mechanisms governing the chemistry of groundwater (Fig. 5a, and b) Within the Gibbs diagram, three distinct mechanisms can be noted namely, rock dominance, precipitation dominance, and evaporation dominance [93]. Fig. 5 depicts that the prominent mechanisms influencing groundwater chemistry are due to evaporation dominance, and rock weathering. The influence of rock weathering dominance on groundwater chemistry arises from the fact that groundwater traverses the porous medium of the aquifer, wherein interactions between water and rock alter the chemical attributes of the groundwater. Additionally, the presence of evaporation dominance is evident in Fig. 5a, and b, highlighting the notable contribution of groundwater evaporation in the specific study area. This is very likely that in arid and semi-arid areas, evaporation influences hydro-geochemical processes. To comprehend these processes, the local geological characteristics of the research area and the ionic composition of the groundwater samples are assessed. Furthermore, isotopic studies on this aspect should be taken up in future research for a better understanding of salinity sources.

The bivariate diagrams depicting the relationships between HCO_3^-/Na^+ and Ca^{2+}/Na^+, as well as Mg^{2+}/Na^+ and Ca^{2+}/Na^+, were utilized to gain deeper insights into the specific rock types that exert a substantial influence on the hydro-geochemical evolution of water (Fig. 5c, and d). According to Fig. 5c, and d, only one sample plotted between carbonate dissolution. This finding suggests that within the aquifer, carbonate dissolution plays a negligible role in the hydro-chemical evolution of water. The significant portion of the groundwater samples shown in Fig. 5c, and d are plotted between silicate weathering predominance, and evaporate rock area. These findings suggest that the hydro-chemical evolution of water within the Mazar-e-Sharif aquifer is predominantly governed by the dissolution of evaporate rock, and silicate weathering.

Fig. 6**a** indicates that both cation exchange, and reverse cation exchange have occurred in the aquifer. Fig. 6b, implies that a considerable dissolution of calcite and partial dissolution of dolomite were operated

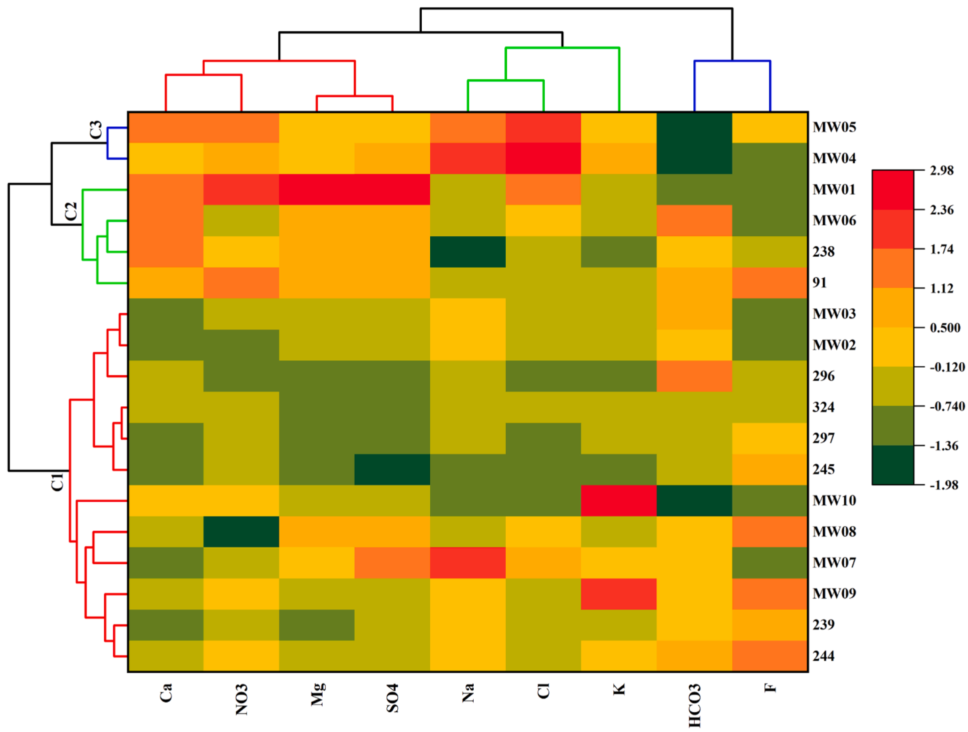

Fig. 9. Heat map with a two-way hierarchical clustering dendrogram. The color gradient from dark green to dark red displays the span from the lowest similarity to the highest similarity of each hydro-chemical parameter, respectively.

in the aquifer. The ratios of Cl/Br are widely employed for identifying the origin of groundwater salinity because both elements are chemically conservative and can predict various hydro-geochemical processes that have occurred in the groundwater system. The Cl/Br ratios suggest that the primary origins of groundwater salinity in the Mazar-e-Sharif urban aquifer are likely to be evaporite, and lacustrine deposits (Fig. 6**c**) [94, 95]. Fig. 6**d** indicates that dissolution of gypsum has remarkably occurred in the aquifer. Further, Fig. 6**e** suggests geogenic dominance influenced by evaporation. Also, most of the samples from urban areas were plotted in the evaporation region. Fig. 6**f** shows anthropogenic activities are responsible for the elevated levels of NO_3^-.

4.4. Geochemical modeling

Saturation indices (SI) are employed to assess the level of equilibrium between water and minerals. Alterations in saturation state serve as valuable indicators for distinguishing various stages of hydro-chemical evolution and assist in identifying the primary geochemical reactions that govern water chemistry [66–68].

Fig. 7 illustrates the SI values for various minerals, such as dolomite, calcite, gypsum, fluorite, and halite. According to Fig. 7, the dolomite and calcite were noted to exhibit an over-saturated condition, whereas gypsum, anhydrite, and halite were found to be dissolved in almost all water samples. The values of SI for dolomite and calcite in most water samples exceeded 0.25, suggesting their potential to precipitate due to being in a supersaturated state. Moreover, the increased values of SI for dolomite, and calcite suggest the predominance of diffuse flow within the investigated region. Conversely, the values of SI for halite in all sampled sites are below -4, indicating the significant ability of water samples to dissolve halite within the aquifer. Lower SI values for halite indicate a lesser influence on the chemical composition of water. Fig. 7 demonstrates the positive correlation between values of SI for gypsum and halite with total dissolved solids (TDS) in all groundwater samples, implying that the salinity of water samples will increase over time, leading to higher TDS levels. Furthermore, the geochemical modeling of fluorite suggests that approximately half of the samples are under-saturated, indicating a likelihood of increased F^- concentration over time.

4.5. Statistical correlation

In this study, descriptive statistics were calculated for the 12 hydro-chemical variables (Table 3). Analysis of Spearman's correlation coefficient matrix for the hydro-chemical parameters reveals significant associations between EC and TDS with Mg^{2+}, Cl^-, SO_4^{2-}, and Ca^{2+} concentrations (Table 3). The results suggest that evaporation and irrigation return flow are the main components attributing to groundwater salinity. There is a good correlation among Mg^{2+}, Ca^{2+}, and SO_4^{2-}, which highlights gypsum dissolution ($CaSO_4 \cdot 2H_2O$). Additionally, the correlation between Cl^- and Na^+ suggests the dissolution of halite (NaCl) as a contributing factor. Furthermore, statistical correlation shows a negative correlation between F^- with NO_3^- suggesting the possibility of geogenic contamination over anthropogenic.

4.6. Principal component analysis (PCA)

Principal component analysis was applied to ascertain the primary hydro-geochemical processes controlling groundwater chemistry in the Mazar-e-Sharif aquifer. The varimax rotation technique and the Kaiser's criterion were employed for PCA analysis. According to Fig. 8, PCA gathered three main principal components such as PC1, PC2, and PC3. The eigenvalues for all three PCs are greater than one, and the total cumulative variance contribution rate was 78.7 %. PC1 accounted for 50.76 % of the total variance with strong loading on EC, TDS, Ca^{2+}, Mg^{2+}, SO_4^{2-}, and Cl^-, representing the dissolution gypsum, halite, weathering of silicates, and reverse cation exchange were the key factors [96]. PC2 contained 16.84 % of total variance with strong loadings on K^+, Na^+, and HCO_3^- which play a crucial role in cation exchange, and weathering of silicates. PC3 accounted for 11.01 % of the total variance with strong loadings on NO_3^-, Na^+ and K^+, indicating aquifer was likely influenced by anthropogenic activities. Table 4

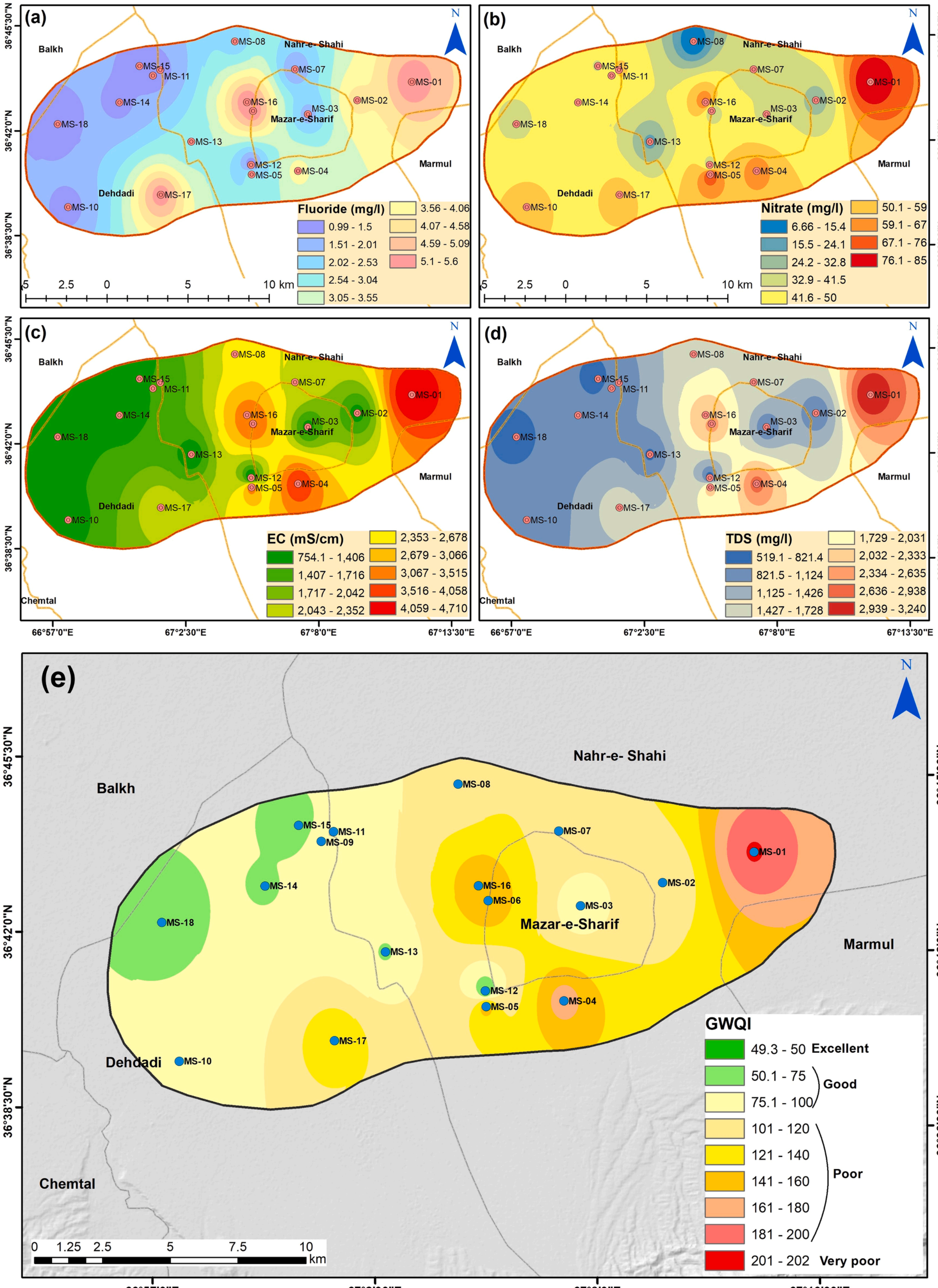

Fig. 10. Showing spatial distribution concentrations of (a) Fluoride; (b) Nitrate; (c) EC; (d) TDS; and (e) Water quality index map of Mazar-e-Sharif urban aquifer.

Table 5
Classification of groundwater intended for consumption according to the GWQI.

GWQI range	Type of water	Number samples	Samples (%)	Area (%)
<50	Excellent	1	1.00	0.11
50–100	Good	8	44.44	39.92
100–200	Poor	8	44.44	59.82
200–300	Very poor	1	5.56	0.16
>300	Unsuitable for drinking	Nil	Nil	Nil

4.7. Dendrograms and heat map

For this study, two dendrograms displayed by heat map, were carried out using Euclidean distance and Word's linkage method to categorize groundwater samples into distinguished groups based on their hydro-chemical characteristics and sampling locations. The outcome of dendrogram classification and heat map visualization is exhibited in Fig. 9. According to Fig. 9, three main hydro-chemical integrations exist between 10 chemical parameters. R-mode dendrogram of the sampling locations is grouped into three clusters, and the clusters are shown as C1, C2, and C3. R-mode HCA displays that the majority of groundwater samples (66 %) are related to cluster C1. According to the heat map, the green color represents the minimum concentrations and the red color depicts the highest concentrations of chemical parameters. Samples with the highest EC values are classified into clusters C2 and C3.

4.8. Drinking water quality evaluation

The study area was assessed using the Water Quality Index (WQI), and the corresponding findings are presented in Fig. 10**e** and Table 5. The computed WQI values varied from 49.3 to 201.5, with an average value of 107.9. These values can be broadly classified into four categories, namely very poor, poor, good, and excellent water quality. It is noteworthy that more than 44 % of the water samples were categorized as poor water quality. These findings can be attributed primarily to the combined effect of relatively elevated concentrations of F^-, NO_3^-, and high salt levels. Specifically, WQI values for MS-01, MS-04, and MS-06 were calculated as 201.5, 168.2, and 156.7, respectively. Results further indicated that TDS, F^-, EC, and NO_3^- are the major contributors to the WQI. The distribution of WQI values, as illustrated in Fig. 10**e**, clearly demonstrates that the poor WQI level is predominantly concentrated in the western and central parts of the study area. Moreover, the spatial distribution of GWQI reveals that around 39.9 % of the study area is characterized by good water quality. Conversely, poor water quality and very poor water quality occupy 59.82 % and 0.16 %, respectively, and are primarily located in the central and eastern parts. These areas primarily correspond to the brackish zone, characterized by high concentrations of TDS, F^-, EC, and NO_3^-. These variables exhibit the strongest spatial correlation with the GWQI map (Fig. 10**a-d**). Overall, GWQI analysis demonstrates that a significant portion exhibits poor and very poor water quality, suggesting the urgent need for timely management actions (Fig. 10**e**).

4.9. Hydro-geochemical conceptual model

A schematic conceptual model has been developed to illustrate the hydro-geochemical processes governing water quality variations in the Mazar-e-Sharif aquifer system (Fig. 11). The model represents that the aquifer primarily consists of sand, gravel, and fine to very fine sediments, interspersed with discontinuous clay lenses of varying thickness, and spatially distributed. Groundwater is extensively abstracted from the study area for drinking, domestic, and industrial purposes, exerting significant pressure on the aquifer system.

The conceptual model delineates the mechanisms driving changes in groundwater quality. Anthropogenic activities, including over-extraction and improper waste disposal notably influenced groundwater quality in Mazar-e-Sharif City.

These hydro-geochemical interactions underscore the necessity for sustainable groundwater management strategies to mitigate contamination risks and ensure long-term water security. Implementing integrated water resource management (IWRM) practices is essential to align groundwater utilization with the United Nations Sustainable Development Goals (SDGs), particularly those related to clean water and sanitation (SDG 6).

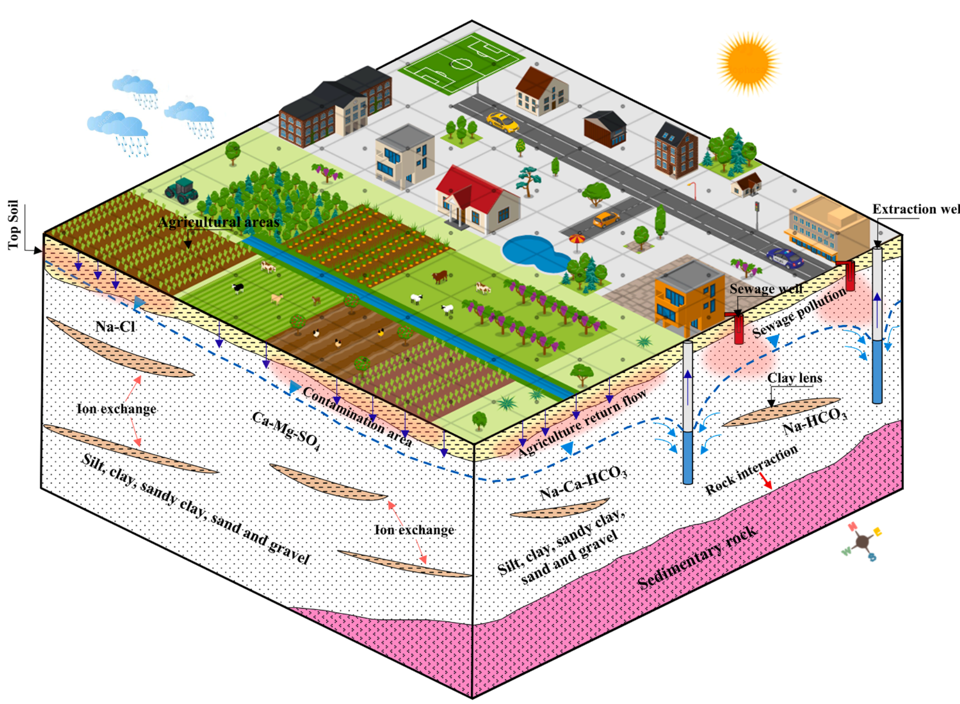

Fig. 11. Schematic hydro-geochemical conceptual model of Mazar-e-Sharif alluvial aquifer.

5. Conclusion

This study provides a comprehensive evaluation of groundwater quality in the Mazar-e-Sharif aquifer, in northern Afghanistan. The hydro-chemical analysis reveals that groundwater is predominantly of Na-HCO_3 (36 %), Ca-HCO_3 (28 %), and Ca-Mg-SO_4 (22 %) water facies, with key geochemical processes controlled by carbonate dissolution, halite and gypsum dissolution, and silicate weathering.

Hydrogeochemistry shows that about 39 % of groundwater samples exceed the WHO limit for NO_3^- (50 mg/L), with concentrations reaching up to 85.7 mg/L, and primarily contaminated by anthropogenic sources. F^- concentrations surpass the WHO standard (1.5 mg/L) in more than half of the samples, indicating longer water-rock interaction with fluorine-bearing minerals. Cl/Br ratios and geological data reveal groundwater salinity primarily originates from evaporitic and lacustrine deposits and is localized in nature.

The Water Quality Index (WQI) assessment classifies 60 % of the study area as poor to very poor water quality, making it unsuitable for direct consumption. Spatial analysis reveals that groundwater contamination is more severe in urban and agricultural areas, indicating the influence of anthropogenic activities.

The findings from this study underscore significant public health risks and highlight the urgent need for periodically groundwater quality monitoring and adopting effective management strategies. Future research should integrate advanced isotopic, and geochemical techniques to precisely identify the sources of NO_3^- and F^- contaminations in Mazar-e-Sharif's aquifer.

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Data availability

All data are presented in this article.

Consent to participate

The study does not involve the use of animals or humans in the experiments and therefore requires no consent to participate or ethical approval.

Consent publish

All the authors gave their consent to publish this article.

Ethical approval

Ethical approval is not required since this study does not involve the use of animals or humans in the experiments.

CRediT authorship contribution statement

Asadullah Farahmand: Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Abdulhalim Zaryab:** Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Nasrullah Ameri:** Methodology, Investigation, Data curation, Conceptualization. **Shakir Ali:** Visualization, Validation, Supervision, Methodology, Formal analysis. **Mohammad Naim Eqrar:** Visualization, Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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