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A survey on spatial variations of groundwater quality in Kabul, Afghanistan and its evaluation for different uses

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Abstract

Groundwater is one of the most important sources of freshwater supply in arid and semi-arid regions. The purpose of this research is to investigate the chemical quality of Kabul's groundwater using statistical description methods, statistical classification, quality indices, graphical methods, and also to examine the spatial variations of effective physicochemical parameters of 54 bore wells water using geostatistical methods with the help of GIS tools. The chemical quality evaluation shows that due to the influence of rivers on Kabul's groundwater, a large part of the city's groundwater quality is of the Mg-HCO_3^{-1} and Mg-Ca-HCO_3^{-1} types, which is considered inappropriate for industrial use based on the International Association of Hydrogeologists method . The United States Salinity Laboratory diagram shows that the groundwater in this city is in the average range, C3S1, and in some cases good and inappropriate for agricultural and irrigation purposes. In terms of drinking, according to the Schuler diagram, water quality is salty the groundwater in the region is categorized as brackish for drinking purposes, with moderate conditions in some areas. The spatial variations of key physicochemical parameters influencing the quality of Kabul's groundwater were analyzed using various interpolation methods. Then, using the mutual evaluation criterion, the best variogram model was selected to draw the estimation map. The results show that for the zoning of EC, TH, TDS, Mg^{+2}, Ca^{+2}, and SO_4^{-2} parameters, the inverse distance weighting method, and for Na^{+1}, K^{+1}, HCO_3^{-1} the indicator kriging method were appropriate. The estimation maps of the spatial variations of effective parameters on Kabul's aquifers show that the groundwater quality is moderate towards the west of Kabul and becomes suitable as it progresses towards the west. In contrast, the quality of groundwater decreases from the center of the city towards the east, and the salinity of the water has increased.

Introduction

Groundwater serves as a crucial resource for various uses, including drinking and agriculture, contingent upon its appropriate chemical quality. Effective management and utilization of groundwater require comprehensive and informed planning, which is only feasible through a precise understanding of its quantity and quality. Groundwater plays a vital role in global water supply, particularly as a primary source of potable water. However, increasing population pressures and over-exploitation have contributed to both a reduction in groundwater levels and a decline in its quality. Consequently, researchers have directed efforts towards optimizing groundwater usage, recognizing the limited nature of this resource. In addition to the challenges posed by water scarcity, groundwater pollution has emerged as a significant threat. Effective control and prevention of groundwater pollution necessitate the identification of pollution sources, crisis zones, and an understanding of pollution movement pathways. This information is essential for implementing measures to protect and enhance groundwater quality (Askari et al., 2009; Dehshibi et al., 2022). The indiscriminate extraction of groundwater in many parts of the world has resulted in a significant decline in the groundwater table (Akbari et al., 2009; Ghasemi Ziarani & Faryadi, 2009). The mean annual decrease in groundwater levels in Kabul city has between 2008 and 2016 is 1.7m. The primary cause of this decline is the uncontrolled use of water and the population increase in this city, which is indeed a cause for concern (Noori and Singh, 2021). Although the vulnerability of groundwater to surrounding environments may be less compared to surface water sources, research indicates that, in conjunction with surface sources, the quantity and quality of groundwater are also influenced by environmental factors, and in some cases, these impacts can be more severe and persistent (Xiao et al., 2007). Among these impacts, water pollution affecting the potable water supply and intoxications resulting from their usage can be mentioned (Pond, 2005). Recent advancements in the introduction and development of non-classical methods have led to an increased inclination towards utilizing geostatistical techniques for the purpose of further exploration and understanding of these changes Geostatistics, a branch of applied statistics, offers a range of statistical estimators to estimate properties in spatial domains with limited sampling data by utilizing information from sampled points. Geographic Information System (GIS) plays a crucial role in this process by enabling the efficient storage, retrieval, and analysis of large datasets, facilitating geostatistical analyses for users (Ahmadi & Sedghamiz, 2008). Geostatistical estimation involves two main stages: first, understanding and modeling the spatial structure of the variable, and second, estimating the desired variable. To ensure accurate mapping, an adequate number of data points is necessary to maintain estimation errors within acceptable limits (Farhadian and Maleki, 2023) . Typically, every geostatistical analysis begins by calculating the semi-variogram of the variable under investigation. The semi-variogram indicates the spatial correlation between measured data points as a function of the distance between these points. The set of geostatistical methods used to estimate unmeasured variables based on measured values is referred to as kriging. One of the fundamental techniques in kriging involves associating an error value with each estimation. Consequently, not only can the average error values be computed, but also the distribution of errors across the entire study area can be examined (Farhadian and Nikvar Hassani, 2020)

Kriging interpolation introduced by Kresic (2006) as the best and most powerful tool for interpolating data to generate maps of groundwater levels. Mehrjardi et al. (2008) conducted a study in the Yazd-Ardakan plain, analyzing the spatial distribution of some groundwater quality parameters, such as Cl^{-1}, $\mathrm{SO_4}^{-2}$, Sodium Absorption Ratio (SAR), Total Hardness (TH), Total Dissolved Solids (TDS) using three methods: Kriging, Inverse Distance Weighting (IDW), and co-Kriging. The evaluation of the results based on the mean square error criterion showed that the Kriging method had superiority over the other two methods and was ultimately selected as the final and suitable method for mapping the groundwater quality parameters in the region (Mehrjardi et al., 2008). Dhanasekarapandian et al. (2016) conducted an examination of the spatial and temporal variations in the groundwater quality and its suitability for agriculture and drinking purposes using GIS, Water Quality Index (WQI), and AqQa. The results indicated that the groundwater in the region is not suitable for agriculture and drinking due to human activities, exploitation of groundwater, and changes in land use patterns for agricultural purposes (Dhanasekarapandian et al., 2016). Zhou et al. (2017) investigated the spatial distribution of arsenic in groundwater sources in the northern, eastern, and southern regions of Xinjiang, China. The results of the study showed that more than 12% of groundwater sources have arsenic concentrations exceeding 10 μg/L, and the concentration of arsenic increases with the depth of sampling. Pande and Moharir (2018) conducted a spatial analysis and zoning of groundwater quality in the regions of Akola and Buldhana in India. They collected parameters including Cl^{-1}, TDS, Mg^{+2}, pH, $CO_3{}^{-2}$ and $HCO_3{}^{-1}$ from 35 bore wells. Using interpolation tools, they obtained the spatial distribution of groundwater quality parameters in the ArcGIS software environment. The analysis of groundwater quality revealed that a significant volume of water in the area, especially in regions with basaltic hard rocks, is suitable for drinking and agricultural purposes, Jawadi et al. (2020) utilized the WQI method and concluded that groundwater in the Kabul basin is generally very hard due to high levels of calcium and magnesium. The WQI indicates that no groundwater is of excellent quality, and more than 50% of groundwater is rated as poor to very poor quality. Groundwater in certain areas is not suitable for drinking and irrigation due to significant contamination with dissolved solids and nitrates. Kamoun et al. (2022) assessed the groundwater quality of the Aquifer of Endfidas in Tunisia, focusing on agricultural and drinking purposes. In this study, they employed statistical methods and graphical representation to evaluate the suitability of groundwater for agricultural and drinking purposes. Additionally, they utilized the Wilcox classification to examine the appropriateness of samples for agricultural use.

The decline in both quantity and quality of groundwater in Kabul, Afghanistan, presents a significant challenge to the city's water resources. Groundwater is essential for drinking, agriculture, and industry, making its management crucial for sustainable development. This study aims to investigate the chemical quality of Kabul's groundwater, model and classify physicochemical parameters using GIS and geostatistical methods, and evaluate various geostatistical approaches to estimate groundwater quality. Accurate selection of geostatistical techniques and understanding spatial variations in groundwater parameters are critical for effective water resource management in the region.

Study Area

Kabul serves as the administrative and political center of Afghanistan, located in the eastern part of the country. It is both the capital city and the capital of Kabul Province, with an estimated population of around 4.2 million people and covering an area of approximately 1,023 square kilometers, according to the 2020 estimate. This city is situated at an elevation of 1800 meters above sea level, along the southern course of the Kabul and Panjshir rivers. It is surrounded by the Paghman mountains to the west and the Safi mountains to the east. The city of Kabul is located at geographical coordinates 34 degrees 32 minutes north latitude and 69 degrees 10 minutes east longitude. Its time zone is UTC+4:30. Administratively, the city is divided into 22 urban districts within the national divisions (Mack et al., 2010). The climate of Kabul city is influenced by the general weather conditions of Afghanistan. In the regional climate classification of Afghanistan, Kabul is situated in the steppe (grassland) region. The meteorological records from 1956 to 1983 indicate that the monthly temperature variations in Kabul range from a minimum of -7.1 degrees Celsius in January to a maximum of 32.1 degrees Celsius in July (Broshears et al., 2005). In recent years, urbanization expansion and the return of migrants in Afghanistan have brought about rapid changes in the development trajectory and population levels of cities. The rapid and substantial urban population growth has posed significant challenges to urban development, particularly in Kabul. This includes the expansion of impermeable surfaces compared to natural permeable surfaces, where the majority of precipitation turns into runoff. Additionally, the discharge of domestic wastewater onto the city streets, coupled with the absence of proper urban sewage collection systems, results in the transport of pollutants from urban surfaces, creating various issues in urban areas. However, effective management measures have not been implemented to address these challenges (Mohammadi and Jafarbeglou, 2016).

The Kabul region has four main aquifers, generally consisting of sand and gravel deposits. The Paghman-Darulaman basin contains two aquifers along the Paghman River and the upstream section of the Kabul River. The other two aquifers are located in the Logar basin and the southern part of the Kabul basin, along the Logar River and the lower reaches of the Kabul River. The groundwater flows from the western or southwestern part of the basin towards the eastern margin of the basin. The aquifers primarily consist of gravel and sand layers, covered by thicker layers of clay and silt. The local thickness of the aquifers can exceed 80 meters. Their permeability ranges from 2.3×10^{-5} m/s to 1.3×10^{-3} m/s. Therefore, according to DIN-18-130 standard, their permeability is classified into permeable to highly permeable categories (Tünnermeier et al., 2005). The study area along with the locations of 54 bore wells is illustrated in Fig. (1).

Materials and Methods

In order to investigate the chemical quality and spatial variations of physicochemical parameters of groundwater in Kabul city, water data (August 2017) from 54 bore wells belonging to the Ministry of Energy and Water (Groundwater Department) were collected and analyzed at the General Laboratory of Water. In this study, a comprehensive investigation of the chemical quality and spatial variations of physicochemical parameters of groundwater in Kabul city was conducted using samples collected from 54 bore wells. After chemical analysis, the types of parameters were identified. These parameters include Ca^{+2}, Mg^{+2}, Na^{+1}, K^{+1}, $\mathrm{HCO_3}^{-1}$, Cl^{-1}, F^{-1}, $\mathrm{SO_4}^{-2}$, electrical conductivity (EC), acidity (pH), total dissolved solids (TDS), total hardness (TH), manganese, and total alkalinity (T Alkalinity). Nine parameters from the mentioned list, which were effective in determining water type and had more variation within the study area, were selected for analysis. Spatial variations of these parameters were also analyzed and investigated using geostatistical methods.

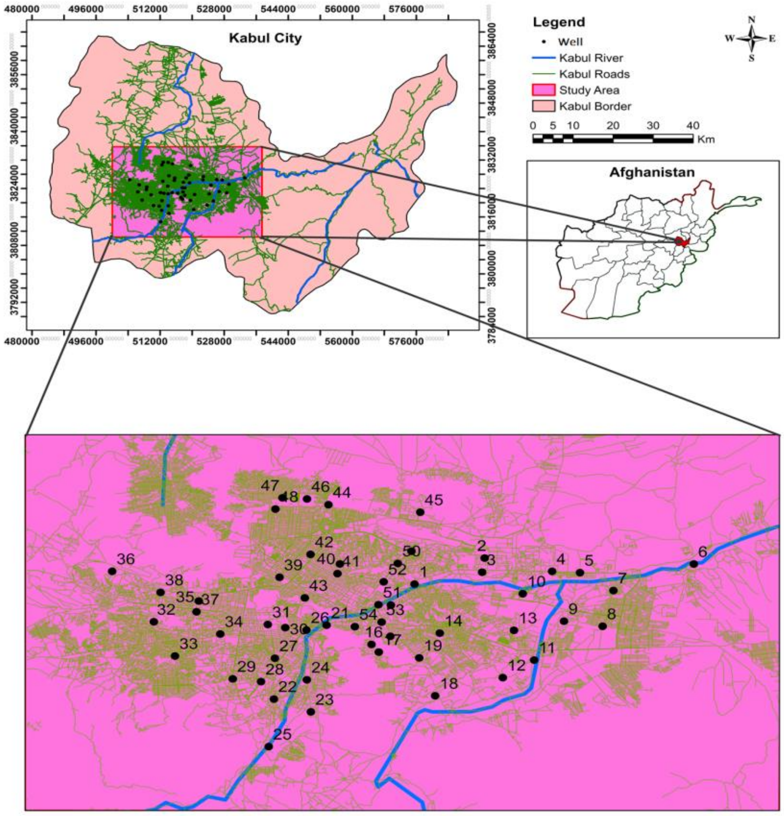

Fig. 1- The study area with 54 bore wells in Kabul, Afghanistan.

Methods for Evaluating the Chemical Quality of Groundwater in Kabul City

To analyze the groundwater quality in Kabul city, a combination of descriptive statistical methods, statistical classification, qualitative indices, and graphical techniques was employed:

1- Descriptive Statistics: A general assessment of groundwater quality was performed by analyzing the descriptive statistics of water samples from 54 bore wells. The average values of groundwater quality components were compared (Yimer & Geberkidan, 2020).

2- Statistical Classification: This method involved calculating the concentration of elements in ppm (parts per million), epm (equivalent per million), and their percentages. The epm is obtained by dividing the ppm value by the element's atomic number, and percentages are calculated to identify the water type if an element exceeds 20% (Elsayed et al. 2020).

3- Qualitative Indices: A numerical index, derived from scaling large datasets of physical, chemical, and biological parameters, provides an overall indicator of water quality, particularly for drinking purposes (Yan et al., 2022).

4- Graphical (Piper, Schoeller, and United States Salinity Laboratory (USSL) diagrams): The Piper diagram is used for quick identification of water types, the Schoeller diagram assesses groundwater quality for drinking, and the USSL diagram evaluates water suitability for agriculture based on the Sodium Adsorption Ratio (SAR) and Electrical Conductivity (EC) (Regional Salinity Laboratory, 1954; Hounslow, 2018; Sadashivaiah et al., 2008).

Investigate the spatial distribution of groundwater quality in the Kabul city

To investigate the spatial distribution of groundwater quality in Kabul city, Ordinary Kriging (OK), Simple Kriging (SK), Indicator Kriging (IK), and Inverse Distance Weighting (IDW) methods, were employed. Among these methods, Inverse Distance Weighting and Indicator Kriging were chosen for further analysis. Subsequently, utilizing a mutual evaluation criterion, the best variogram model was selected to map the estimation, providing insights into the groundwater quality across the study area.

1- IDW: In this estimation method, calculations are based on the values and weights of points close to the point under consideration. In this approach, weighting is solely controlled by the distance between points and the point of interest, such that closer points will have a greater influence on the calculation of the point of interest (Robertson et al., 2000). The estimation value in this method is calculated using the following relationship:

$$Z^{*} = \frac{\sum_{i=1}^{n} {Z_i}/{\left(h_{ij}+s\right)^{p}}}{\sum_{i=1}^{n} {1}/{\left(h_{ij}+s\right)^{p}}} \qquad (1)$$

In the above formula, Z^{*} represents the estimated value at the point of interest, Z_i is the observed value at a point located at a distance h from the point of interest, h_{ij} is the distance between the observed point and the point being estimated, s is a scaling factor, and p is the weight of the point.

2- IK: This method is independent of the distribution of data frequencies. In this approach, the value of the variable at each point, $Z(x)$, is first divided into two codes, 1 and 0, according to the following equation:

$$I(x, z_k) = \begin{cases} 1 & if\ Z(x) \leq z_k \\ 0 & Otherwise \end{cases} \quad k = 1, \ldots, k \qquad (2)$$

In the above equation, $I(\mathrm{x}, z_k)$ represents the indicator variable, z_k is the critical threshold, and k is the total number of thresholds. Subsequently, the cumulative distribution function of Z at the unknown point x_0 is estimated as a linear combination of n known indicator variables $I(x_i, z_k)$ in the vicinity of that point.

$$F^{n}(x_0, z_k) = \sum_{i=1}^{n} \lambda_{ik} I(x_i, z_k) \qquad (3)$$

In the mentioned equation, n refers to the number of observations, λ_{ik} represents the weight assigned to the indicator I at point x_i

based on the critical threshold z_k. Essentially, in this method, indicator variables are estimated instead of the initial continuous variables (Goovaerts, 1997; Farhadian, 2021).

Groundwater quality result of the Kabul city

To assess the chemical quality of groundwater in this city, descriptive statistical tables, statistical classification, and an index table were initially created. Subsequently, Piper, Schoeller, and USSL diagrams were generated to visually represent the groundwater chemistry.

Based on Table (1), it can be concluded that the average value of Electrical Conductivity (EC) is 1877 microsiemens per centimeter, which exceeds the standard (250 microsiemens per centimeter) reported by World Health Organization (WHO). The average Total Hardness (TH) is 773 milligrams of calcium carbonate per liter, which surpasses the standard limit for drinking water (150 to 500 milligrams of calcium carbonate per liter) according to the WHO standard. The average value of Total Dissolved Solids (TDS) in these samples is 1233 milligrams per liter, exceeding the WHO standard of (1000 milligrams per liter). The average magnesium content is 283.4 milligrams per liter, which is higher than the WHO standard of (150 milligrams per liter). Furthermore, the average acidity (pH) is 7.55, indicating an alkaline range. However, according to the WHO standard (6.5 to 8.5), the mentioned value is within the permissible limit. The average bicarbonate content is 389.8 milligrams per liter, which exceeds the WHO standard. Consequently, in terms of bicarbonates, the quality of groundwater is in a highly unfavorable condition, indicating an elevated risk of excess bicarbonate. The average potassium content is 17.48 milligrams per liter, which is higher than the WHO standard. The average sulfate content is 104.9 milligrams per liter, which is below the WHO standard. This level of sulfate is within the permissible limit for drinking water (500 milligrams per liter). The average values of calcium and sodium are 118.8 and 121.6 milligrams per liter, respectively, which are below the permissible limit for drinking water (200 milligrams per liter).

As observed in Table (2), the predominant types of groundwater for the collected samples based on International Association of Hydrogeologists (IAH) method are Mg-HCO_3 and Mg-Ca-HCO_3. This is mainly attributed to the high bicarbonate content in all samples and the presence of magnesium in most of them, indicating variations due to the influx of river water into the groundwater. In addition to magnesium-bicarbonate, calcium, sodium, and sulfate are also observed in groundwater samples, with potassium present in one sample.

Additionally, the water quality is assessed using both the Water Quality Index (WQI) and the Average Water Quality Index (AWQI) (Chidiac, 2023). According to Table (3), the average quality index values for well numbers 2, 3, 5, 9, 10, 11, 12, 13, 14, 19, 20, 39, and 53, located in the eastern part of Kabul city, exceed the permissible pollution limit which located in east of Kabul city. The remaining samples are within the acceptable range.

Based on Table (4), there are 23 samples with a negative saturation index, one sample with a zero index, and 30 samples with a positive index. For Ryznar Stability Index (RSI) values Shams et al., (2012), one sample is between 5 and 6, eight samples are between 6 and 6.5, eleven samples are between 6.5 and 7, and 34 samples are above 7. Based on previous studies, out of the 54 bore wells mentioned in the table, for Langelier index values, one sample has neutral characteristics, 30 samples are scale-forming, and 23 samples are inclined to corrosion. Additionally, for RSI values, one sample has relatively scale-forming and slightly corrosive characteristics, eight samples are neutral, 11 samples are corrosive with low scaling, and 34 samples are highly corrosive.

Table 1- Descriptive statistics of groundwater quality parameters in 54 bore wells in Kabul city

	EC	TH	TDS	Mg	Ca	Na	K	HCO_3	SO_4	Cl	F	TA	Mn	pH	SAR
Unit	µs/cm	mg $CaCO_3$/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg $CaCO_3$/l	mg/l	-	-
Min	364	50	242	13.1	16	0	0.9	150	5	0	0	150	0	6.96	0
Max	9600	3580	6354	1977.9	505	1400	146.2	1600	1000	0.05	1.21	1600	11.5	8.21	20
Mean	1877	773	1233	283.4	118.8	121.6	17.48	389.8	104.9	0.011	0.497	389.8	0.718	7.55	1.60
SD	1924	738	1305	357.7	99.2	245.7	28.98	215.4	133	0.014	0.395	215.4	1.54	0.27	2.98
CV	102.5	95.38	105.84	126.21	83.54	202.1	165.7	55.25	126.8	121.97	79.53	55.25	214.54	3.56	186.9
N	54	54	54	54	54	54	54	54	54	54	54	54	54	54	54

Table 2- Classification and typing of water samples collected using the IAH method

Bore Well code	Na%	K%	Mg%	Ca%	Cl	SO_4%	HCO_3%	Type of water
MR6	1.29	1.38	94.48	2.84	0	11.44	88.56	Mg-HCO_3
TW3	0.00	0.82	92.17	7.01	0	8.38	91.62	Mg-HCO_3
51	4.52	0.58	93.46	1.43	0	11.53	88.47	Mg-HCO_3
34	6.78	0.87	82.38	9.96	0	18.99	81.01	Mg-HCO_3
95	86.06	1.21	8.67	4.06	0.005	81.15	18.85	Na-SO_4
41	14.67	2.81	47.69	34.82	0.004	13.30	86.70	Mg-Ca-HCO_3
39	41.75	2.97	34.36	20.92	0.009	14.09	85.91	Na-Mg-Ca-HCO_3
37	24.24	3.48	41.80	30.48	0	15.77	84.23	Na-Mg-Ca-HCO_3
89	9.36	1.18	87.29	2.17	0.009	15.93	84.07	Mg-HCO_3
33	13.56	5.39	78.67	2.39	0	12.60	87.40	Mg-HCO_3
LG1	3.86	0.64	84.25	11.25	0	11.69	88.31	Mg-HCO_3
NP2	3.82	1.11	92.38	2.69	0.020	19.44	80.56	Mg-HCO_3
94	41.41	3.19	53.25	2.15	0.011	11.75	88.25	Na-Mg-HCO_3
73	37.07	1.17	41.57	20.19	0.007	37.19	62.81	Na-Mg-Ca-SO_4-HCO_3
18	10.77	4.89	63.10	21.24	0	15.29	84.71	Mg-Ca-HCO_3
B124	14.58	3.98	59.60	21.84	0	14.69	85.31	Mg-Ca-HCO_3
B125	12.46	1.28	63.13	23.12	0	24.04	75.96	Mg-Ca-SO_4-HCO_3
24	48.12	4.35	30.56	16.97	0.004	13.79	86.21	Na-Mg-HCO_3
74	30.36	0.99	55.29	13.36	0.002	3.95	96.05	Na-Mg-HCO_3
MR2A	36.91	6.36	40.86	15.87	0.004	17.35	82.65	Na-Mg-HCO_3
OY2	7.24	2.75	51.34	38.67	0.004	10.35	89.65	Mg-Ca-HCO_3
75	9.43	3.21	64.04	23.33	0	7.68	92.32	Mg-Ca-HCO_3
10	6.10	1.03	78.30	14.57	0.005	18.00	82.00	Mg-HCO_3
11	12.25	2.98	73.99	10.78	0.005	12.30	87.70	Mg-HCO_3
77	9.36	4.15	65.90	20.59	0.008	6.93	93.07	Mg-Ca-HCO_3
OY3	2.97	0.88	49.68	46.47	0	14.65	85.35	Mg-Ca-HCO_3
57	3.61	0.82	59.84	35.74	0	7.39	92.61	Mg-Ca-HCO_3
61	10.10	0.76	64.29	24.85	0	10.67	89.33	Mg-Ca-HCO_3
5	6.88	1.27	70.65	21.19	0	17.77	82.23	Mg-Ca-HCO_3
63	5.67	0.87	68.52	24.95	0.004	14.06	85.94	Mg-Ca-HCO_3
UY2	0.58	0.28	93.20	5.94	0	10.65	89.35	Mg-HCO_3
AF7	0.00	1.21	37.35	61.44	0	5.49	94.51	Mg-Ca-HCO_3
80	4.13	2.63	68.22	25.01	0.007	7.86	92.14	Mg-Ca-HCO_3
7	9.03	4.84	66.25	19.88	0.010	7.53	92.47	Mg-HCO_3
B23	2.91	0.12	71.01	25.96	0.019	3.40	96.60	Mg-Ca-HCO_3
83	2.43	0.16	71.32	26.10	0.040	1.41	98.59	Mg-Ca-HCO_3
B81	3.88	0.38	70.11	25.63	0.006	3.40	96.60	Mg-Ca-HCO_3
4	2.74	0.16	63.74	33.37	0.021	4.21	95.79	Mg-Ca-HCO_3
15	14.32	1.04	51.51	33.13	0.003	11.33	88.67	Mg-Ca-HCO_3
WA4	59.82	1.15	22.54	16.48	0	6.26	93.74	Na-Mg-HCO_3
TW2	76.58	0.74	6.16	16.52	0.010	18.86	81.14	Na-HCO_3
WA2	69.51	0.46	16.95	13.09	0.014	21.34	78.66	Na-SO_4-HCO_3
14	61.96	2.42	9.22	26.40	0	14.57	85.43	Na-Ca-HCO_3
B114	66.61	1.41	12.40	19.58	0.008	27.54	72.46	Na-SO_4-HCO_3
85	40.42	0.94	32.50	26.14	0	28.59	71.41	Na-Mg-Ca-SO_4-HCO_3
KN6	54.64	1.61	29.29	14.45	0	21.07	78.93	Na-Mg-SO_4-HCO_3
KN4	54.60	1.35	22.17	21.88	0.006	22.90	77.10	Na-Mg-Ca-SO_4-HCO_3
43	35.15	0.36	58.53	5.96	0.007	29.80	70.20	Na-Mg-SO_4-HCO_3
70	5.21	0.93	56.18	37.69	0.007	9.25	90.75	Mg-Ca-HCO_3
B109	43.01	0.51	31.38	25.09	0.003	10.36	89.64	Na-Mg-Ca-HCO_3
19	39.62	9.79	38.06	12.53	0	12.28	87.72	Na-Mg-HCO_3
20	36.41	1.10	40.79	21.70	0	11.24	88.76	Na-Mg-Ca-HCO_3
47	38.30	38.44	8.21	15.05	0.011	0.67	99.33	Na-K-HCO_3
46	37.54	16.42	17.54	28.50	0	13.22	86.78	Na-Ca-HCO_3

Table 3- Quality index values and average water quality index for 54 bore wells

Well Number	Well code	WQI	AWQI	Well Number	Well code	WQI	AWQI
1	MR6	2330.85	93.23	28	61	1860.25	74.41
2	TW3	2989.04	**119.56**	29	5	1568.02	62.72
3	51	2987.24	**119.49**	30	63	1814.46	72.58
4	34	2195.72	87.83	31	UY2	1859.67	74.39
5	95	5095.01	**203.80**	32	AF7	1153.13	46.13
6	41	2193.46	87.74	33	80	1292.69	51.71
7	39	2062.12	82.48	34	7	1571.85	62.87
8	37	1812.13	72.49	35	B23	2198.41	87.94
9	89	2958.82	**118.35**	36	83	1316.43	52.66
10	33	3046.56	**121.86**	37	B81	1558.44	62.34
11	LG1	2631.43	**105.26**	38	4	1643.91	65.76
12	NP2	5068.52	**202.74**	39	15	2526.61	**101.06**
13	94	7744.46	**309.78**	40	WA4	1889.59	75.58
14	73	4150.20	**166.01**	41	TW2	1471.16	58.85
15	18	2394.83	95.79	42	WA2	1659.13	66.37
16	B124	1849.98	74.00	43	14	1583.76	63.35
17	B125	1820.52	72.82	44	B114	1305.20	52.21
18	24	2177.45	87.10	45	85	2052.49	82.10
19	74	3897.98	**155.92**	46	KN6	1845.49	73.82
20	MR2A	2671.65	**106.87**	47	KN4	1933.68	77.35
21	OY2	1746.52	69.86	48	43	2059.88	82.40
22	75	1739.75	69.59	49	70	1731.60	69.26
23	10	1670.98	66.84	50	B109	1930.69	77.23
24	11	1666.82	66.67	51	19	2481.92	99.28
25	77	1474.00	58.96	52	20	2286.72	91.47
26	OY3	1824.46	72.98	53	47	2714.29	**108.57**
27	57	2289.87	91.59	54	46	2165.23	86.61

Table 4- Calculated Langelier and RSI indices for the 54 investigated samples

Well Samber	Well code	Langelier	RSI	Well Sample	Well code	Langelier	RSI
1	MR6	-0.6	8.39	28	61	-0.05	7.46
2	TW3	0.16	7.04	29	5	-0.07	7.69
3	51	-0.09	8.07	30	63	-0.05	7.42
4	34	0.7	6.81	31	UY2	0.06	7.53
5	95	0.25	7.68	32	AF7	-0.09	7.68
6	41	0	7.51	33	80	-0.14	7.87
7	39	-0.04	7.68	34	7	-0.71	8.8
8	37	0.12	7.49	35	B23	0.62	6.22
9	89	-0.15	7.95	36	83	0.59	6.71
10	33	0.17	7.58	37	B81	0.41	6.71
11	LG1	0.36	6.83	38	4	0.67	6.22
12	NP2	-0.38	8.14	39	15	0.26	6.44
13	94	-0.21	7.71	40	WA4	0.14	7.48
14	73	0.36	6.56	41	TW2	-0.08	7.69
15	18	0.34	6.57	42	WA2	0.78	6.54
16	B124	-0.12	7.56	43	14	0.33	6.98
17	B125	-0.08	7.33	44	B114	0.08	7.59
18	24	0.14	7.18	45	85	0.8	6.38
19	74	1.19	5.36	46	KN6	0.23	7.44
20	MR2A	0.12	7.02	47	KN4	0.43	6.98
21	OY2	-0.01	7.5	48	43	-0.05	7.94
22	75	-0.26	7.93	49	70	0.72	6.24
23	10	-0.29	7.98	50	B109	0.28	6.67
24	11	-0.68	8.83	51	19	0.18	6.97
25	77	-0.33	8.16	52	20	0.57	6.39
26	OY3	0.52	6.4	53	47	-0.03	7.49
27	57	0.59	6.18	54	46	-0.26	7.71

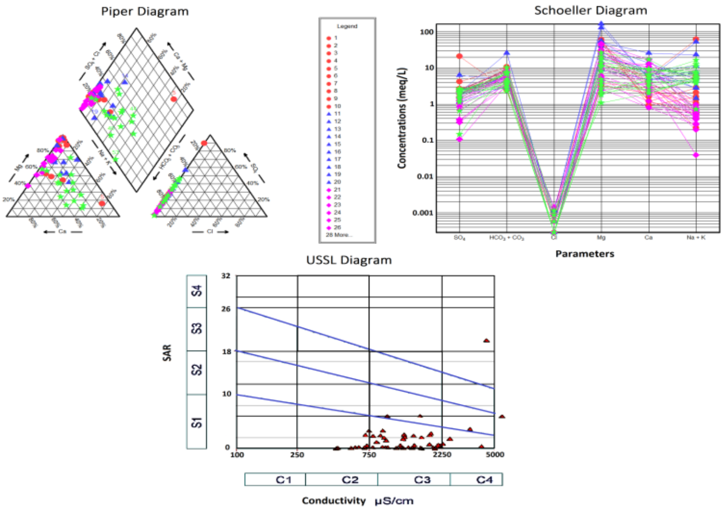

Fig. 2- Piper, Schoeller, and USSL Diagrams for the Aggregate of Groundwater Samples in Kabul City

Inference from Fig (2) suggests that, according to the Piper diagram, the overall status and type of water samples, influenced by river water, fall within the magnesium-bicarbonate and brackish water categories. Sodium has also increased in seven samples. Anionic-wise, the water samples are within the bicarbonate-sulfate range, and cationic-wise, they are within the magnesium-sodium range, as depicted in the Piper diagram. In the Schoeller diagram, the excessive reduction in chloride ions has occurred due to the influence of river water, leading to an increase in magnesium and bicarbonate ions. This increase has, in fact, resulted in water salinization in terms of drinking suitability. Additionally, the elevated level of calcium ions indicates the groundwater's tendency towards hardness.

The USSL diagram delineates the suitability of water in the studied area for agricultural purposes. According to this diagram, all samples fall within the electrical conductivity (EC) range exceeding 250 microsiemens per centimeter, predominantly within the range of 750 to 2250 microsiemens per centimeter. Therefore, the majority of the variation in Sodium Absorption Ratio (SAR) values falls within the C_3S_1 range, with a small portion of samples falling within the C_4S_4 range. In other words, the groundwater quality in Kabul city is predominantly in the C_3S_1 class, relatively in C_2S_1, and to a lesser extent in C_3S_2, C_4S_2, C_4S_4, and C_4S_1 classes.

Secondly, to investigate the spatial variations of physicochemical parameters, including electrical conductivity (EC), total hardness (TH), total dissolved solids (TDS), magnesium (Mg^{+2}), calcium (Ca^{+2}), sodium (Na^{+1}), potassium (K^{+1}), bicarbonate (${HCO_3}^{-1}$), and sulfate (${SO_4}^{-2}$) in the aquifers of Kabul city, data from 54 bore wells were analyzed using geostatistical techniques. To assess the normality of physicochemical parameters of groundwater in Kabul city, the Kolmogorov-Smirnov test and histogram plots were employed. The investigation revealed that, with the exception of bicarbonate, the research data were not normally distributed. Consequently, for the remaining data, log transformation and Box-Cox transformation were applied to achieve normality. Table (5) presents the results of the Kolmogorov-Smirnov (K-S) test for non-normally distributed data. As observed in the above table, the significant level (Sig.) for the bicarbonate parameter is greater than 0.05, indicating the normality of bicarbonate data. Additionally, Table (6) displays the results of the Kolmogorov-Smirnov test for normalized data.

According to Table (6), the Sig. value is greater than 0.05, indicating that physicochemical parameters are statistically significant at a 95% confidence level. Therefore, the assumption of normality has been confirmed. Despite the confirmation of the normality assumption, there might still be skewness and kurtosis in the distribution of data. This was further examined by plotting histograms, revealing skewness and kurtosis in the data. Consequently, by taking the logarithm of the data and applying the Box-Cox transformation, the skewness and kurtosis of the data were reduced, bringing them closer to a normal distribution. It is worth mentioning that, for normalizing the parameters EC, TH, TDS, Mg^{+2}, Na^{+1}, and Ca^{+2} in the research data, the log transformation method was used. However, in the bicarbonate ($\mathrm{HCO_3}^{-1}$) data, there was an outlier that was removed. Additionally, the data for potassium (K^{+1}) and sulfate ($\mathrm{SO_4}^{-2}$) did not become normal with logarithmic transformation; therefore, the Box-Cox method was applied for normalizing them. In the sulfate data, there was also an outlier that was removed, and after that, the data became almost normal. After examining the normality of the data, the semi-variograms of the physicochemical parameters were interpreted. In order to illustrate the spatial continuity of the variables, the semi-variograms of the data were separately plotted in the ArcGIS 10.8 software environment. Then, an appropriate interpolation method was employed for modeling and generating maps to classify the spatial variations of physicochemical parameters. The cross-validation criterion was used to assess the effectiveness of the interpolation method for each parameter individually, and zoning maps were drawn accordingly.

In Table (7), it can be observed that considering the values of RMSE and spatial autocorrelation ($\mathrm{C_0}/\sigma^2$), the best method for estimating electrical conductivity (EC), total hardness (TH), total dissolved solids (TDS), magnesium (Mg^{+2}), calcium (Ca^{+2}), and sulfate ($\mathrm{SO_4}^{-2}$) is the inverse distance weighting method. For sodium (Na^{+1}), potassium (K^{+1}), and bicarbonate ($\mathrm{HCO_3}^{-1}$), the indicator kriging method is the most suitable. Fig. (3) presents the variograms of sodium, potassium, and bicarbonate parameters along with the best-fitted models. Fig. (4) also illustrates the spatial distribution map of physicochemical parameters, cations, and anions of groundwater in Kabul city.

From Table (8), it can be concluded that the general type of groundwater in Kabul for industrial use is highly corrosive, inclined to corrosion with low scaling, and sometimes neutral. This indicates the unsuitability of this water for transportation through pipelines. Therefore, the best condition is when the water does not cause corrosion or scaling in the distribution network pipes because both conditions lead to a reduction in the lifespan of the pipes, increasing costs. Hence, the water should ideally be neutral (stable).Based on the hydrochemical diagrams, it can be stated that the groundwater in Kabul falls into the category of brackish waters, mainly characterized by the general type of Mg-$\mathrm{HCO_3}$ and, in some cases, Na-$\mathrm{HCO_3}$. Additionally, the water in the study area tends to hardness due to increased levels of magnesium and calcium. Bicarbonate is the predominant anion, exceeding the permissible limit, and among the cations, magnesium, calcium, and sodium contribute the most. Among these cations, magnesium has the highest concentration. However, the presence of sulfate is noticeable in some water types. According to the USSL diagram, the groundwater in the study area, intended for agricultural purposes, is evaluated as relatively good to moderate in some cases and slightly unsuitable in others. Additionally, based on the Schuler diagram, the groundwater in the region is categorized as brackish for drinking purposes, with moderate conditions in some areas. The main reasons for these conditions include the inflow of river water, excessive concentration of certain parameters due to overexploitation, infiltration of sewage, and contaminated water through non-standard wells. In some instances, the use of chemical fertilizers can also contribute to these conditions.

Table 5- Results of the Kolmogorov-Smirnov (K-S) test for non-normally distributed data of physicochemical parameters of groundwater in Kabul city

		EC	TDS	TH	Mg^{+2}	Ca^{+2}	Na^{+1}	K^{+1}	HCO_3^{-1}	SO_4^{-2}
N		54	54	54	54	54	54	54	54	54
Normal Parameters[a,b]	Mean	1876.85	1232.865	773.37	283.405	118.793	121.59	17.484	360.19	86.348
	Std. Deviation	1923.880	1304.894	737.610	357.678	99.241	245.732	28.977	143.986	49.216
Most Extreme Differences	Absolute	0.277	0.287	0.163	0.225	0.157	0.310	0.347	0.069	0.167
	Positive	0.277	0.287	0.157	0.186	0.157	0.292	0.347	0.069	0.167
	Negative	-0.224	-0.232	-0.163	-0.225	-0.150	-0.310	-0.284	-0.054	-0.120
Test Statistic		0.277	0.287	0.163	0.225	0.157	0.310	0.347	0.069	0.167
Asymp. Sig. (2-tailed)		0	0	0.001	0	0.002	0	0	0.2	0.001

Table 6- Results of the Kolmogorov-Smirnov (K-S) test for normalized data of physicochemical parameters of groundwater in Kabul city

		EC	TDS	TH	Mg^{+2}	Ca^{+2}	Na^{+1}	K^{+1}	SO_4^{-2}
N		54	54	54	54	54	52	54	54
Normal Parameters[a,b]	Mean	3.154	2.966	2.708	2.180	1.936	1.634	0	0
	Std. Deviation	0.291	0.297	0.425	0.512	0.361	0.646	1	1
Most Extreme Differences	Absolute	0.109	0.111	0.111	0.083	0.056	0.099	0.105	0.148
	Positive	0.109	0.111	0.058	0.083	0.050	0.099	0.085	0.116
	Negative	-0.068	-0.064	-0.111	-0.069	-0.056	-0.070	-0.105	-0.148
Test Statistic		0.109	0.111	0.111	0.083	0.056	0.099	0.105	0.148
Asymp. Sig. (2-tailed)		0.157	0.093	0.095	0.2	0.2	0.2	0.2	0.005

Table 7- Selected methods for zoning the investigated parameters of groundwater in Kabul city

Parameters	EC	TH	TDS	Mg^{+2}	Ca^{+2}	Na^{+1}	K^{+1}	HCO_3^{-1}	SO_4^{-2}
Method	IDW	IDW	IDW	IDW	IDW	IK	IK	IK	IDW
Model	-	-	-	-	-	Gossin	Exponential	Exponential	-
Nugget	-	-	-	-	-	0.061	0	0	-
Sill	-	-	-	-	-	0.246	0.242	0.265	-
Range	-	-	-	-	-	8416.029	9501.364	4590.276	-
Spatial Correlation	-	-	-	-	-	0.248	0	0	-
Power	2	3	2	3	2	-	-	-	2
RMSE	0.199	0.354	0.205	0.430	0.335	0.345	0.320	0.441	0.844
Trend	-	-	-	-	-	3	3	3	-

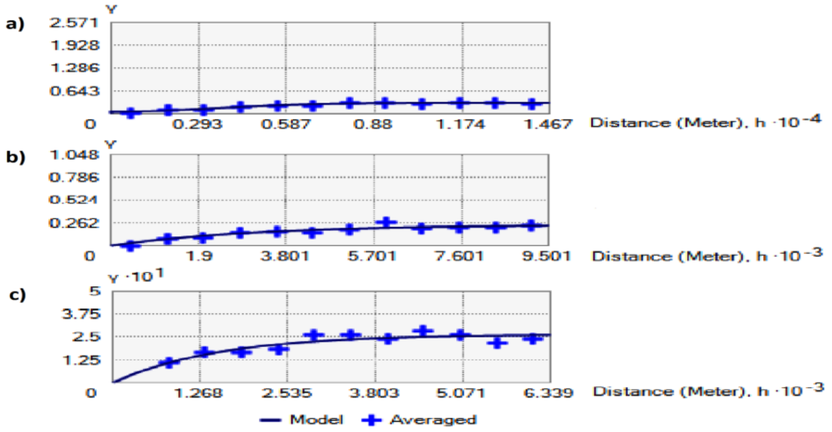

Fig. 3- Experimental semivariogram and the best-fitted model in the indicator kriging method: a) Gaussian model for parameter Na^{+1}, b) Exponential model for parameter K^{+1} and c) Exponential model for parameter HCO_3^{-1}

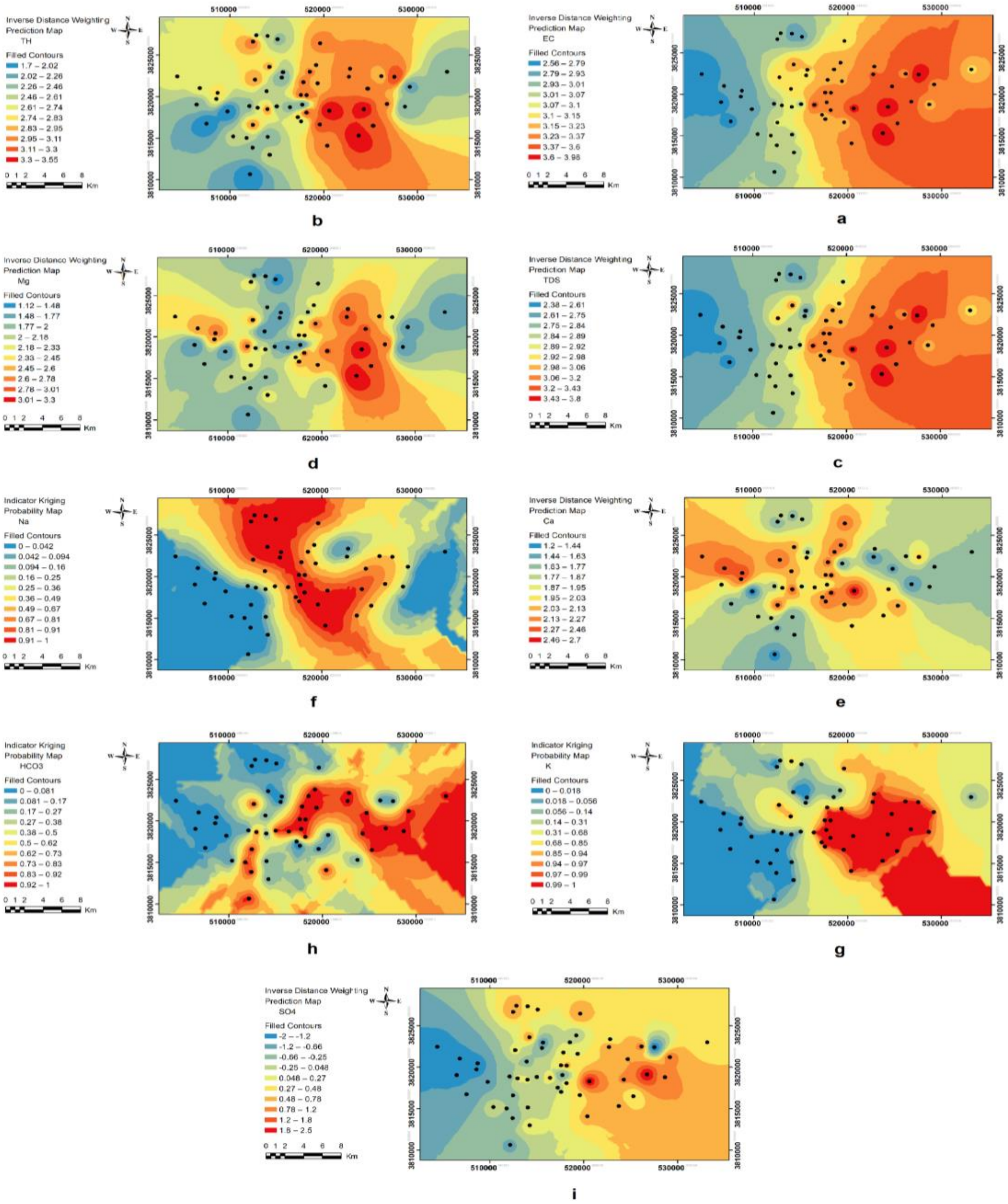

Fig. 4- Map of estimated physicochemical parameters of groundwater in Kabul city: a) EC, b) TH, c) TDS, d) Mg^{+2}, e) Ca^{+2}, f) Na^{+1}, g) K^{+1}, h) HCO_3^{-1} and i) SO_4^{-2}

Table 8- Determination of the overall status of 10 water samples for industrial purposes

Well Number	Langelier	RSI
1	Prone to corrosion	Severe corrosion
2	Sedimentation	Severe corrosion
3	Prone to corrosion	Severe corrosion
4	Sedimentation	Corrosive with low deposition
5	Sedimentation	Severe corrosion
6	Neutral	Severe corrosion
7	Prone to corrosion	Severe corrosion
8	Sedimentation	Severe corrosion
9	Prone to corrosion	Severe corrosion
10	Sedimentation	Severe corrosion

Summary of the key findings of the spatial distribution of groundwater quality in Kabul:

The physicochemical parameters investigated in the groundwater of Kabul city include EC, TH, TDS, Mg^{+2}, ca^{+2}, Na^{+1}, K^{+1}, $\mathrm{HCO_3}^{-1}$ and $\mathrm{SO_4}^{-2}$. The normality of these parameters was assessed using the Kolmogorov-Smirnov test, indicating that all parameters, except $\mathrm{HCO_3}^{-1}$, did not follow a normal distribution. Therefore, logarithmic and Box-Cox transformations were applied to normalize the data, resulting in a suitable spatial structure. It is noteworthy that parameters such as EC, TH, TDS, Mg^{+2}, Ca^{+2} and Na^{+1} were normalized using logarithmic transformation, while K^{+1} and $\mathrm{SO_4}^{-2}$ were normalized using the Box-Cox method. After plotting the histograms of the data, it became evident that there is an outlier data point for bicarbonate related to well number 19 and an outlier data point for sulfate related to well number 5. For a precise geostatistical analysis, these two data points were excluded. In this study, the results of zoning each of the examined parameters were evaluated using the spatial correlation criterion ($\mathrm{C_0}/\sigma^2$) and cross-validation method with the RMSE index. Subsequently, for zoning and mapping the estimates, the analyzed parameters (electrical conductivity, total hardness, total dissolved solids, magnesium, calcium, sodium, potassium, bicarbonate, and sulfate) were used to geostatistical methods, including indicator kriging and inverse distance weighting. The table of selected methods, fitting variogram plots, and estimation maps for each of the examined parameters in the previous section is presented. According to Table (7), it can be stated that the best method for zoning EC, TH, TDS, Mg^{+2}, Ca^{+2} and $\mathrm{SO_4}^{-2}$ is the inverse distance weighting method with powers of 2, 3, 2, 3, 2, 2, respectively. For Na^{+1}, K^{+1} and $\mathrm{HCO_3}^{-1}$, the indicator kriging method with Gaussian, exponential, and exponential variogram models, respectively, is the best approach. These methods exhibit high accuracy for the mentioned parameters, with spatial correlation criteria less than 0.5 and RMSE values lower as well. In general, the quality of groundwater in Kabul city decreases towards the east, northeast, and southeast. This means that as one moves towards the east, northeast, and southeast, the quality of groundwater decreases. Additionally, the quality of groundwater in Kabul city is moderate and suitable towards the west. This implies that as one moves towards the west, the quality of groundwater becomes more suitable. Major reasons for this trend include the absence of an integrated sewage system, the presence of non-standard sewage well rings, excessive population density, the presence of industrial estates and factories on the eastern side of the city, and the use of chemical fertilizers. In recent years, Kabul city has experienced an excessive population influx, particularly due to migration, leading to an overwhelming population density. This surge in population density has not only resulted in the deterioration of groundwater quality but has also contributed to a reduction in agricultural lands. Zaryab et al (2022) in the year 2022, conducted a study on nitrate pollution in the Kabul city region. They examined various areas of the city in terms of population density, agriculture, transportation, commercial (Fig. 5a). As depicted in this Fig., considering the conducted studies and comparing it with the zoning map of the average physicochemical parameters (EC, TH, TDS, Mg^{+2}, Ca^{+2}, Na^{+1}, K^{+1}, $\mathrm{HCO_3}^{-1}$ and $\mathrm{SO_4}^{-2}$ under investigation, it can be concluded that, in addition to the inflow of river water into groundwater, geological characteristics of the region, the concentration of agricultural areas towards the east of the city, high population density, and consequently the concentration of urban sewage, can play a significant role in groundwater pollution (Fig. 5b).

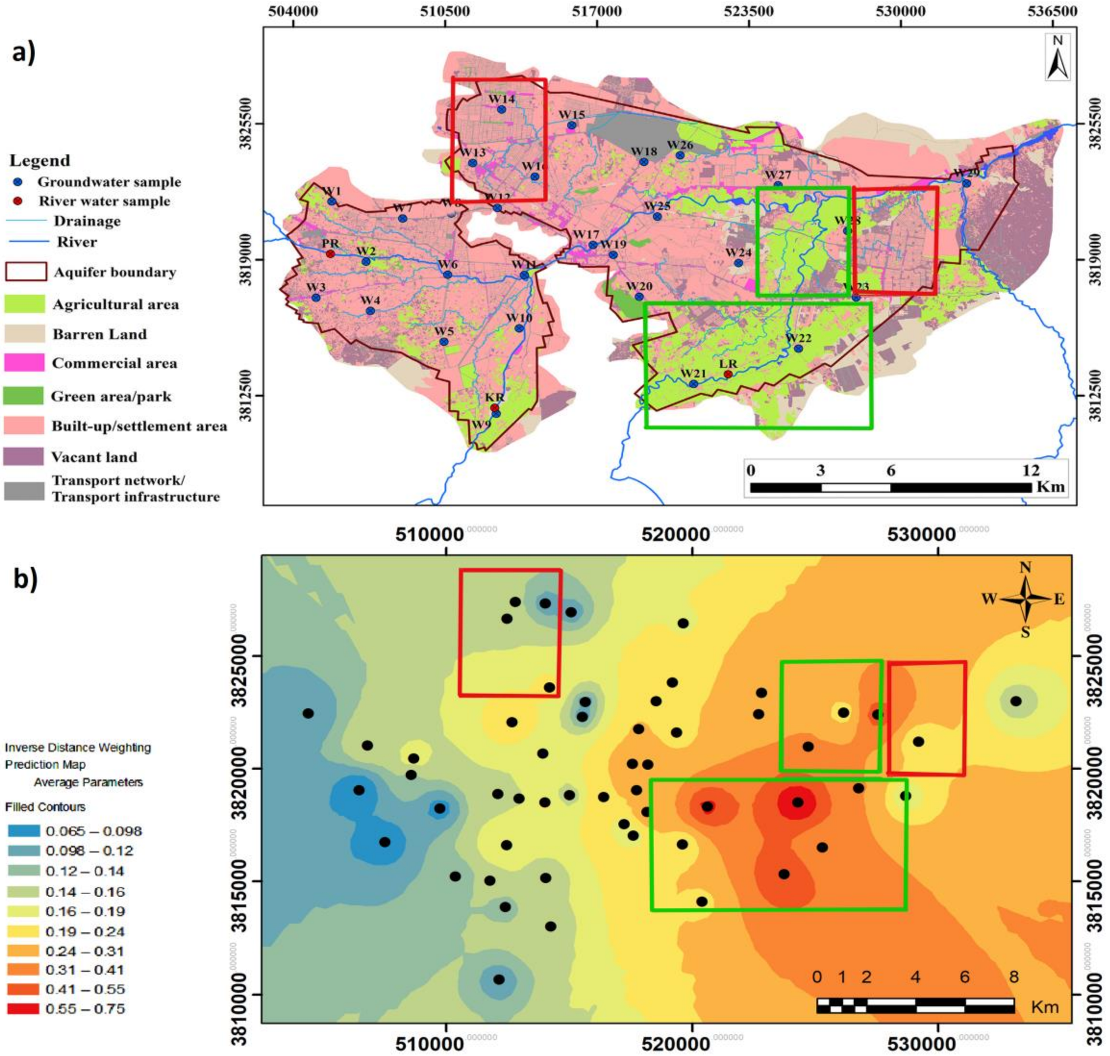

Fig. 5- a) The map illustrates the distribution of agricultural land and population density in Kabul city in the year 2022 (Zaryab et al., 2022). b) The map depicts the zoning of the average physicochemical parameters studied in the groundwater of Kabul city

Conclusion

The groundwater, suitable and sanitary for drinking, agriculture, and industrial purposes, is regarded as a critical factor in the sustainable development of Kabul city. The necessity to study water in this city, particularly concerning the chemical quality and spatial variations of groundwater parameters, has been emphasized. The selection and accuracy of appropriate interpolation methods and the preparation of maps for classifying the variations in groundwater quality attributes depend on the regional conditions and the availability of sufficient statistics and data. In general, the correct selection of geostatistical methods and the assessment of chemical quality are fundamental and crucial steps in the management of water resources in a region. In the present study, groundwater in Kabul city was chosen as the study area due to its significance for drinking, agriculture, and industrial purposes. According to the obtained results, it can be stated that the chemical quality of groundwater in Kabul city is mostly unsuitable for drinking purposes. In other words, most bore wells exhibit higher salinity levels than acceptable, with exceptions noted for 8 bore wells (numbers: 32, 33, 34, 35, 36, 37, 38, and 46), which have moderate to moderate-low salinity. The groundwater in this city has been assessed as moderate for agricultural purposes and, in some cases, is considered good or unsuitable. The highest concentration of the examined parameters in the groundwater quality of Kabul city is observed from the city center towards the east, northeast, and southeast. Consequently, the groundwater quality decreases from the center towards the east, indicating excessive pollution. Conversely, the groundwater quality becomes suitable as one moves from the city center towards the west. This suggests that the flow direction of groundwater from the west to the east is a key factor in these variations. Groundwater the aquifers of Kabul city is primarily replenished from the west, generally exhibiting good quality. However, as it moves towards the east, in addition to the influence of river water, which predominantly feeds the aquifers of Kabul city, the groundwater quality deteriorates due to factors such as population density, the presence of non-standard sewage well rings, excessive extraction, some geological conditions, and the existence of industrial estates and factories.

It should be noted that out of the 54 sampled wells, as observed in the zoning map, 15 bore wells exhibited very poor water quality. The remaining bore wells had relatively suitable water quality compared to the previous ones, and the quality improves as one moves westward. Therefore, it can be concluded that due to the lower population density in the outskirts compared to the city center, pollution decreases, and groundwater quality becomes more suitable. It is worth mentioning that excessive extraction has led to a decline in the groundwater level in Kabul city, causing some bore wells to dry up and resulting in water shortages. The declining trend is ongoing, and if necessary measures are not taken, it may lead to serious crises in the near future.

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References

1- Ahmadi, S.H. and Sedghamiz, A., 2008. Application and evaluation of kriging and cokriging methods on groundwater depth mapping. *Environmental monitoring and assessment*, *138,* pp.357-368. https://doi.org/10.1007/s10661-007-9803-2.

2- Akbari, M., Jarge, M.R. and MADANI, S.H., 2009. Assessment of decreasing of groundwater-table using geographic information system (GIS)(case study: Mashhad plain aquifer).

3- Askari, M., Mosaedi, A., Dehghani, A.A. and MeftahHalghi, M., 2009. Application of Geostatistics and GIS analysis, in study of groundwater quality spatial variability, Case study: Qazvin aquifer, Iran. In *International Conference Water Recourses. Summer*. (In Persian).

4- Broshears, R.E., Chornack, M.P., Mueller, D.K. and Ruddy, B.C., 2005. *Inventory of ground-water resources in the Kabul Basin, Afghanistan* (No. 2005-5090). US Geological Survey.

5- Chidiac, S., El Najjar, P., Ouaini, N., El Rayess, Y. and El Azzi, D., 2023. A comprehensive review of water quality indices (WQIs): history, models, attempts and perspectives. *Reviews in Environmental Science and Bio/Technology*, *22*(2), pp.349-395. https://doi.org/10.1007/s11157-023-09650-7.

6- Dehshibi, R., Karami, S., Maleki, Z. and Farhadian, H., 2022. A comparative study on evaluation of steady-state groundwater quality in Sirjan’s Golgohar mineral zone. *Arabian Journal of Geosciences*, *15*(9), p.842. https://doi.org/10.1007/s12517-022-10074-w.

7- Dhanasekarapandian, M., Chandran, S., Devi, D.S. and Kumar, V., 2016. Spatial and temporal variation of groundwater quality and its suitability for irrigation and drinking purpose using GIS and WQI in an urban fringe. *Journal of African Earth Sciences*, *124,* pp.270-288. https://doi.org/10.1016/j.jafrearsci.2016.08.015.

8- Elsayed, S., Hussein, H., Moghanm, F.S., Khedher, K.M., Eid, E.M. and Gad, M., 2020. Application of irrigation water quality indices and multivariate statistical techniques for surface water quality assessments in the Northern Nile Delta, Egypt. *Water*, *12*(12), p.3300. https://doi.org/10.3390/w12123300.

9- Farhadian, H. and Nikvar-Hassani, A., 2020. Development of a new empirical method for Tunnel Squeezing Classification (TSC). *Quarterly Journal of Engineering Geology and Hydrogeology*, *53*(4), pp.655-660. https://doi.org/10.1144/qjegh2019-10.

10- Farhadian, H., 2021. A new empirical chart for rockburst analysis in tunnelling: Tunnel rockburst classification (TRC). *International Journal of Mining Science and Technology*, *31*(4), pp.603-610. https://doi.org/10.1016/j.ijmst.2021.03.010.

11- Farhadian, H. and Maleki, Z., 2023. Groutability classification of granular soils with cement grouts. *Journal of Rock Mechanics and Geotechnical Engineering*, *15*(6), pp.1580-1590. https://doi.org/10.1016/j.jrmge.2022.09.007.

12- Ghasemi Ziarani, E. and Faryadi, S., 2009. Zoning of Karaj Dam Watershed's PollutingPotentials using Integrated Means of Ecological Land Use Evaluation, Water Quality and SWOT Analysis. *Environmental Sciences*, *7*(2). (In Persian)

13- Goovaerts, P., 1997. *Geostatistics for natural resources evaluation* (Vol. 483). Oxford University Press.

14- Hounslow, A., 2018. *Water quality data: analysis and interpretation*. CRC press.

15- Jawadi, H.A., Sagin, J. and Snow, D.D., 2020. A detailed assessment of groundwater quality in the Kabul Basin, Afghanistan, and suitability for future development. *Water*, *12*(10), p.2890. https://doi.org/10.3390/w12102890.

16- Kamoun, M., Langer, M. R., Zaibi, C., Tlili, A., Mokni, A., Armstrong-Altrin, J. S., & Youssef, M. B. (2022). Geochemical and sedimentological constraints on paleoclimate and paleoenvironment over the past 4000 years in the Thapsus coast, Tunisia. *Arabian Journal of Geosciences*, *15*(17), 1434.

17- Kresic, N., 2006. *Hydrogeology and groundwater modeling*. CRC press. https://doi.org/10.1201/9781420004991.

18- Mack, T.J., Akbari, M., Ashoor, M., Chornack, M.P., Coplen, T.B., Emerson, D.G., Hubbard, B.E., Litke, D.W., Michel, R.L., Plummer, L. and Rezai, M., 2010. *Conceptual model of water resources in the Kabul Basin, Afghanistan*.

19- Mehrjardi, R.T., Jahromi, M.Z., Mahmodi, S. and Heidari, A., 2008. Spatial distribution of groundwater quality with geostatistics (case study: Yazd-Ardakan plain). *World Applied Sciences Journal*, *4*(1), pp.9-17.

20- Mohammadi, Kh. & Jafarbeglou, M. (2016). Flood Risk and Urban Development in Kabul City. The 4th National Geomorphology and Land Survey Conference, University of Tehran, Tehran, Iran. (In Persian)

21- Noori, A.R. and Singh, S.K., 2021. Status of groundwater resource potential and its quality at Kabul, Afghanistan: a review. *Environmental Earth Sciences*, *80*(18), p.654. https://doi.org/10.1007/s12665-021-09954-3.

22- Pande, C.B. and Moharir, K., 2018. Spatial analysis of groundwater quality mapping in hard rock area in the Akola and Buldhana districts of Maharashtra, India. *Applied Water Science*, *8*, pp.1-17. https://doi.org/10.1007/s13201-018-0754-2.

23- Pond, K., 2005. Water recreation and disease: plausibility of associated infections: acute effects, sequelae and mortality. World Health Organization.

24- Regional Salinity Laboratory (US), 1954. *Diagnosis and improvement of saline and alkali soils* (No. 60). US Department of Agriculture.

25- Robertson, W.D., Blowes, D.W., Ptacek, C.J. and Cherry, J.A., 2000. Long-term performance of in situ reactive barriers for nitrate remediation. *Groundwater*, *38*(5), pp.689-695. https://doi.org/10.1111/j.1745-6584.2000.tb02704.x.

26- Sadashivaiah, C.R.R.C., Ramakrishnaiah, C.R. and Ranganna, G., 2008. Hydrochemical analysis and evaluation of groundwater quality in Tumkur Taluk, Karnataka State, India. *International journal of environmental research and public health*, *5*(3), pp.158-164. https://doi.org/10.3390/ijerph5030158.

27- Shams, M., Mohamadi, A. and Sajadi, S.A., 2012. Evaluation of corrosion and scaling potential of water in rural water supply distribution networks of Tabas, Iran. *World Appl Sci J*, *17*(11), pp.1484-89.

28- Tünnermeier, T., Houben, G. and Himmelsbach, T., 2005. Hydrogeology of the Kabul Basin Part I: Geology, aquifer characteristics, climate and hydrography. *BGR Record*, *10277*(05).

29- Xiao, D., Li, X., Song, D. and Yang, G., 2007. Temporal and spatial dynamical simulation of groundwater characteristics in Minqin Oasis. *Science in China Series D: Earth Sciences*, *50*(2), pp.261-273. https://doi.org/10.1007/s11430-007-2001-9.

30- Yan, T., Shen, S.L. and Zhou, A., 2022. Indices and models of surface water quality assessment: Review and perspectives. *Environmental Pollution*, *308*, p.119611. https://doi.org/10.1016/j.envpol.2022.119611.

31- Yimer, Y.A. and Geberkidan, A., 2020. The pollution status of Awash River Basin (Ethiopia) using descriptive statistical techniques. *American Journal of Water Resources*, *8*(2), pp.56-68. DOI:10.12691/ajwr-8-2-2.

32- Zaryab, A., Nassery, H.R., Knoeller, K., Alijani, F. and Minet, E., 2022. Determining nitrate pollution sources in the Kabul Plain aquifer (Afghanistan) using stable isotopes and Bayesian stable isotope mixing model. *Science of the Total Environment*, *823*, p.153749. https://doi.org/10.1016/j.scitotenv.2022.153749.

33- Zhou, Y., Zeng, Y., Zhou, J., Guo, H., Li, Q., Jia, R., Chen, Y. and Zhao, J., 2017. Distribution of groundwater arsenic in Xinjiang, PR China. *Applied geochemistry*, *77*, pp.116-125. https://doi.org/10.1016/j.apgeochem.2016.09.005.