



Spatial estimation of groundwater quality, hydrogeochemical investigation, and health impacts of shallow groundwater in Kabul city, Afghanistan

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Received: 20 February 2022 / Accepted: 7 December 2022
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Abstract

The management of groundwater in densely populated areas with no centralized water treatment is critical for the prevention of diseases and maintaining sanitation. Here, we determine the bacteriological and chemical characteristics of groundwater in Kabul city, a resource that 4.1 million individuals rely on. Groundwater samples were analyzed from 41 newly established piezometric wells across Kabul, and data were compared with the last detailed study, undertaken in 2007, to understand contamination trends in an area that has undergone significant development and social changes. Piper diagrams, Gibbs diagrams, correlation analysis, and bivariate plots examine the hydrogeochemical and natural occurring processes of groundwater. The average concentration of cations followed the order $\text{Na}^+ > \text{Mg}^{2+} > \text{Ca}^{2+} > \text{K}^+$, and anions $\text{HCO}_3^- > \text{NO}_3^- > \text{Cl}^- > \text{SO}_4^{2-} > \text{F}$ with Gibbs diagrams indicating mainly rock-weathering influence groundwater chemistry. An increase in nitrate (NO_3^-) and *E. coli* indicates anthropogenic activities impacting the shallow groundwater quality, with significantly elevated nitrate (over 50 mg/L) and *E. coli* (up to 250 CFU/100 mL). The increasing presence of *E. coli* and NO_3^- in the shallow groundwater of Kabul city in turn suggests problematic links to the prevalence of waterborne diseases. Additionally, the water quality index (WQI) was used to assess groundwater quality, and rank its suitability for drinking purposes. The WQI analysis showed that less than 35% of shallow groundwater samples had good water quality. The findings of this study are crucial for the development and sustainable management of groundwater in the city. In short term, we propose interventions such as point-of-use (POU) water purification which may offer temporary respite for waterborne disease prevention. Kabul city requires immediate attention to developing sustainable groundwater management policies, expansion of the water supply network, groundwater quality monitoring, and wastewater management.

Keywords Water quality · Water quality index · WQI · Sustainable groundwater management · Kabul city

Introduction

Water is one of the most valuable natural resources on Earth, yet in many areas is categorized as vulnerable. Water quality is of concern to humanity through its direct relationship to health, development and social prosperity (Milovanovic 2007; Singh et al. 2012). Under the United Nations Sustainable Development Goal (UN SDG) 6, targets 6.1 and 6.3 seek to ensure sustainable access to clean drinking water (UN 2015). Subterranean aquifers are vital bodies of fresh water and, in many urban areas in developing economies, are relatively safe compared to surface watercourses, which are invariably polluted by anthropogenic sewage and other waste sources (Christopher and Mohd 2011). As such, groundwater is widely used for different purposes and is the primary

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source of drinking water in many regions, especially in arid and semi-arid regions (Yu et al. 2014). The determining factor for the safe use of groundwater in different uses, including drinking, agriculture and industry, is the groundwater's chemical and biological composition (Kumar et al. 2010; Davraz and Özdemir 2014; Mallick et al. 2018). The physical and chemical characteristics of groundwater are influenced by natural processes such as climatic conditions, aquifer lithology, and interaction between surface water and aquifer, as well as anthropogenic activities including infiltration of agricultural fertilizers and wastewater, over-exploitation of groundwater, urbanization, industrialization, and population growth (Guo et al. 2017; Abbasnia et al. 2018; Jehan et al. 2019).

The most common method of assessing the suitability of water quality for drinking purposes is using the water quality index (WQI). The WQI is a dimensionless number that expresses water quality in a straightforward manner and is useful for decision-making for sustainable groundwater management when combined with GIS to demonstrate spatial variation in water quality and identification of vulnerable sites (Badeenezhad et al. 2020; Verma et al. 2021). Horton created a WQI in 1965 based on eight water quality parameters. Later, various WQIs have been established, including the National Sanitation Foundation WQI (Wills and Irvine 1996), the Canadian WQI (Davies 2009), and the Oregon WQI (Lumb et al. 2011). WQI is used to demonstrate groundwater suitability for drinking purposes (Ramakrishnaiah et al. 2009; Adimalla et al. 2018; Udeshani et al. 2020; Badeenezhad et al. 2020).

Afghanistan is classified as one of the extremely high water stress countries with a water stress of more than 80% (WRI 2015), based on a baseline water stress measure which is the ratio of total withdrawals to total renewable supply. Afghanistan's capital city, Kabul, is almost entirely reliant on groundwater owing to the seasonality of river water availability and a lack of water storage infrastructure for utilizing surface water supplies. Meldebekova et al. (2020) quantified a mean annual -5.3 cm/year vertical displacement in Kabul city as a result of groundwater over-exploitation. Kabul is one of the fastest-growing cities in the world, the mean annual population growth rate was 2.96% between 2004 and 2020 (UN 2019), during which time the Kabul city population increased from 2.6 million to 4.1 million (CIESIN 2018; NISA 2020). Research suggests that rapid urbanization and population growth have an adverse impact on groundwater quantity and quality (Singh et al. 2012; Badeenezhad et al. 2020). Though groundwater is the main source of drinking water in Kabul, there are significant water quality problems due to the lack of a municipal waste collection network, population growth and the consequence of decades of conflict prevented sustainable management (Broshears et al. 2005; Houben et al. 2009; Saffi and Kohistani 2013; Mack

et al. 2013; Zaryab et al. 2017; Hayat and Baba 2017; Saffi 2019; Brati et al. 2019; Jawadi et al. 2020). Therefore, it is very important to the groundwater water quality in Kabul city. In their study, Jawadi et al. (2020) used WQI to assess the groundwater quality of the Kabul basin in Afghanistan; however, their work has been mostly restricted to limited samples (15 sampling points) located inside Kabul City, the general applicability of the published research is problematic due to diversity in land use, geology, water use practices, and population density.

Nevertheless, little is known about the natural mechanisms that govern the chemical composition of groundwater, bacterial contamination, and the impact of anthropogenic activities on groundwater quality in Kabul city. A network of pre-existing groundwater wells were identified by the United States Geological Survey (USGS) and Japan International Cooperation Agency (JICA) for monitoring groundwater levels and quality in Kabul city (Houben et al. 2009) and was handed over to the Hydrogeology Department of the Ministry of Energy and Water in Kabul in 2011. However, this network was not optimal for monitoring groundwater due to private ownership, limited access and corroded pumps installed in the wells. In addition, there has not been regular monitoring of water level and quality since (KMARP 2018a). In 2018, findings of the Kabul Managed Aquifer Recharge Project (KMARP 2018a) suggested the establishment of a network of piezometers in Kabul dedicated to sustainable water level and quality monitoring which was operationalized in 2019.

The present study is the first of its kind in 14 years aimed at a detailed assessment of groundwater in Kabul city, relying on the analysis of groundwater samples from the recently established network of piezometric wells. The objectives of this study include (a) a detailed assessment of shallow groundwater suitability for drinking purposes in Kabul city using WQI and GIS, (b) evaluate the shallow groundwater characteristics, water type, and the mechanisms controlling groundwater hydrogeochemistry in the study area, (c) explore the current trend of bacteriological contamination in groundwater and its health risk across Kabul city, and (d) investigate the potential impact of anthropogenic activities on groundwater pollution. The findings of this study are crucial for the development and sustainable management of groundwater in Kabul city including the Kabul Managed Aquifer Recharge pilot project and follow-up schemes.

Materials and methods

Study area and data sources

The study covers 450 km² of the Kabul urban and peri-urban area with a population of 4.1 million, excluding internally

displaced people and nomads (NISA 2020). The elevation of the city is 1800 m above mean sea level (Leslie 2019). The climate of Kabul is defined as a continental, cold semi-arid climate according to Peel et al. (2007) with approximately 300 mm average annual rainfall and evapotranspiration at 1600 mm, annually. Low rainfall, combined with a high evaporation rate, has a significant impact on groundwater storage and water quality, as well as community health (Sheikhi et al. 2020). Furthermore, multi-model ensemble precipitation projections for Kabul province by World Bank (2021) suggest little to no increase in the near future and an increase in the far future under Shared Socioeconomic Pathways (SPP) 2–4.5, relative to the baseline period 1995–2014. The precipitation projections under different scenarios by World Bank (2021) as in (Fig. A1) and Sidiqi et al. (2018) predict an increase. This indicates that climate change is intensifying the existing obstacles to sustainable access to groundwater in Kabul city.

Kabul city is divided into east and west sub-basins by mountains. The city lies at the intersection of the Kabul River, Logar River, and Paghman River (Fig. 1). In the west of the city, the Paghman river joins the Kabul River near Deh Mazang area and then flows east toward its confluence with the Logar River (Saffi 2019). In the alluvial Kabul, the seasonal river beds are connected by loess and sandy soils that are responsible for a significant amount of discharge to the shallow aquifer (Broshears et al. 2005; Hossaini 2019; Zaryab et al. 2022).

The historic data consisted of 75 groundwater sampling points located in the study area, which were collected from May 2006 through to June 2007 as described by Mack et al. (2010). As part of the present study, groundwater samples for chemical analyses were collected in January 2020 from 41 piezometric wells in the study area (Fig. 1). From each sampling point, two samples were collected: 50 mL (0.20 µm

filtered onsite) in sterile Falcon tubes and 500 mL in polythene containers. The pH and electrical conductivity were measured onsite by CHECKER1 pH Meter. The 500 mL sample was autoclaved (121 °C for 20 min) at the Central Veterinary Diagnostic and Research Laboratory of the Ministry of Agriculture, Irrigation and Livestock in Kabul. The collected and pretreated samples were transported in a cool box by air to Durham University, UK. Samples for major cation analyses were delivered to Durham Geochemistry Centre. Water samples for major anion analysis were sent to the High-performance Analytical Hub at the Centre for Agroecology, Water and Resilience (CAWR) at Coventry University, UK. The water samples for dissolved inorganic carbon (DIC) analysis were sent to the James Hutton Institute, Aberdeen, UK.

Analytical methods

The groundwater samples were analyzed for *E. coli* counts at the Central Veterinary Diagnostic and Research Laboratory of the Ministry of Agriculture, Irrigation and Livestock in Kabul. The APHA (2017, pt. 9216) standard for the direct total microbial count was used to analyze water samples. All groundwater samples were analyzed for major cations (Na^+ , Mg^{2+} , Ca^{2+} and K^+) according to the United States Environmental Protection Agency (EPA) (1994) using inductively coupled plasma-optical emission spectrometry (ICP-OES ThermoScientific ICAP 6000). The analysis of major anions (NO_3^- , SO_4^{2-} , Cl^- , Br^- and F^-) was delivered using ion chromatography on a Thermo Scientific™ Integriion™ system. The total hardness (TH) was calculated and expressed as an equivalent of calcium carbonate using Eq. 1, as described by the American Public Health Association (APHA) (2017, sec. 2340: Hardness) and the total dissolved solids (TDS) was calculated using Eq. 2, as described by APHA (2017, sec. 1030 E.):

$$\begin{aligned} \text{Total Hardness, mg equivalent CaCO}_3/\text{L} \\ = 2.497[\text{Ca, mg/L}] + 4.118[\text{Mg, mg/L}], \end{aligned} \quad (1)$$

$$\begin{aligned} \text{Total Dissolved Solids} \\ = 0.6(\text{alkalinity as CaCO}_3) + \text{Na}^+ \\ + \text{K}^+ + \text{Ca}^{2+} + \text{Mg}^{2+} + \text{Cl}^- \\ + \text{SO}_4^{2-} + \text{SiO}_3^{2-} + \text{NO}_3^- + \text{F}^-. \end{aligned} \quad (2)$$

We relied on dissolved inorganic carbon (DIC) analysis for calculating the bicarbonate and carbonate concentrations in groundwater samples. The DIC was measured by pipetting 0.5 mL of water into a 12 mL Exetainer® vial and capped. The vials were flushed with N_2 gas using a Gas-bench II (Thermo Finnigan, Bremen, Germany). 0.1 mL of

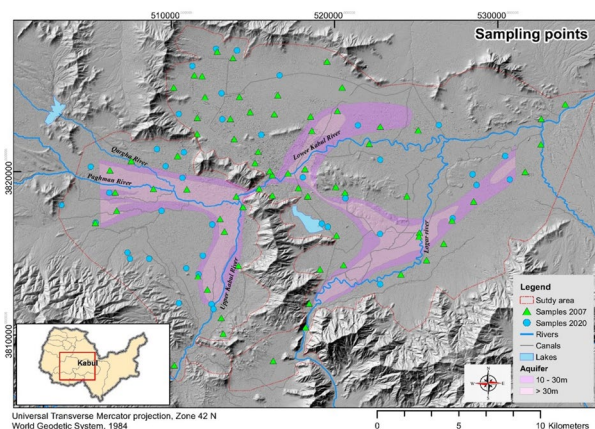


Fig. 1 Groundwater sampling points in 2007 and 2020, the water flows from west to east; the city is divided into east and west catchments by the mountains

1.3 M H_3PO_4 was injected through the septa of the cap into the sample and left overnight. The concentration released into the headspace of the Exetainers[®] was analyzed using a Gas-bench II connected to a DeltaPlus Advantage isotope ratio mass spectrometer (both Thermo Finnigan, Bremen, Germany). Through the use of the Valco valve and a sample loop within the gas bench and the instrument Isodat NT software version 2.0, each Exetainer[®] was sampled eight times of which the last four values were averaged to give a single sample value. Concentration values were based on the “area all” of the m/z (mass to charge ratios) 44, 45 and 46 of the samples compared with similarly treated DIC standards of 0, 25, 50 and 100 ppm. Bicarbonate and carbonate concentrations were calculated from DIC and pH using Eqs. 3 and 4 as described by Clark (2015):

$$m_{\text{HCO}_3^-} = \frac{K_1 \times m_{\text{DIC}}}{a_{\text{H}^+} \times \gamma_{\text{HCO}_3^-} + K_1}, \quad (3)$$

$$m_{\text{CO}_3^{2-}} = \frac{K_2 \times m_{\text{DIC}} \times \gamma_{\text{HCO}_3^-}}{a_{\text{H}^+} \times \gamma_{\text{CO}_3^{2-}} + K_2 \times \gamma_{\text{HCO}_3^-}}, \quad (4)$$

where K_1 and K_2 are the first and second dissociation constants for H_2CO_3 and HCO_3^- with values $10^{-6.38}$ and $10^{-10.38}$, respectively, considering the temperature of the water as 20 °C; m_{DIC} is the concentration of dissolved inorganic carbon. $\gamma_{\text{HCO}_3^-}$ and $\gamma_{\text{CO}_3^{2-}}$ are 0.89 and 0.63, respectively; and, a_{H^+} is $10^{-\text{pH}}$ as described by Clark (2015). We used the Piper diagram, developed by Piper (1944), to investigate the types of water, the chemical analysis was plotted on a Piper diagram, using AquaChem software (Waterloo 2021). To differentiate the mechanisms governing the hydrogeochemical compositions of groundwater in the study area, we relied on Gibbs diagrams, proposed by Gibbs (1970). Gibbs diagram is primarily used for surface water. However, researchers applied it in alluvial regions where rivers and aquifers are well connected (Chintalapudi et al. 2017; Singh et al. 2018).

Water quality index

There are three steps in calculating the WQI (Ramakrishnaiah et al. 2009). Considering the relative significance of the groundwater quality for drinking purposes and health impact in the study area, 12 parameters were selected and a weight (w_i) scale of 1–5 was assigned (Table 1). TDS and nitrate are having the highest influence on the groundwater quality of Kabul city, with a maximum weighting of 5 and the lowest weighting of 1 was assigned to F^- . The relative weight was calculated using Eq. 5:

Table 1 Relative weight of each parameter considering WHO and ANDWQS guidelines

| Parameter | WHO/ANDWQS guideline | Weight (w_i) | Relative weight (W_i) |
|--------------------|----------------------|-------------------|---------------------------|
| TDS | 1000 mg/L | 5 | 0.128 |
| NO_3^- | 45 mg/L | 5 | 0.128 |
| Total hardness | 500 mg/L | 4 | 0.103 |
| pH | 6.5–8.5 | 4 | 0.103 |
| SO_4^{2-} | 250 mg/L | 4 | 0.103 |
| Ca^{2+} | 200 mg/L | 3 | 0.077 |
| Mg^{2+} | 150 mg/L | 3 | 0.077 |
| Na^+ | 200 mg/L | 3 | 0.077 |
| Cl^- | 250 mg/L | 3 | 0.077 |
| K^+ | 12 mg/L | 2 | 0.051 |
| HCO_3^- | 500 mg/L | 2 | 0.051 |
| F^- | 1.5 mg/L | 1 | 0.026 |
| | | $\Sigma w_i = 39$ | $\Sigma W_i = 1.00$ |

$$W_i = w_i / \sum_{i=1}^n W_i, \quad (5)$$

W_i represents the relative weight, w_i is the weight assigned and n is the number of parameters (Vasanthavignar et al. 2010).

A relative quality rating (qi) was assigned for each measured parameter in each sample using Eq. 6:

$$qi = \frac{Ci}{Si} \times 100, \quad (6)$$

where Ci is the amount of measured parameter in a sample and Si is the respective standard value based on World Health Organization (WHO 2017) and Afghanistan National Drinking Water Quality Standard (ANDWQS 2012).

A sub-index (Sli) is determined for each chemical parameter using Eq. 7; and, the sum of Sli is the value of WQI for each sample, as given in Eq. 8:

$$Sli = W_i \times qi, \quad (7)$$

$$\text{WQI} = \sum Sli, \quad (8)$$

where W_i is the relative weight; qi is the relative quality rate of the parameter and WQI is the water quality index. In this study, the WQI is calculated for 2007 and 2020 for each sampling point. Interpolation and maps were created using inverse distance weighting (IDW) in ArcGIS software (Esri 2019), as described by Sardoo and Azareh (2017).

Table 2 Summary statistics of measured parameters of Kabul city shallow groundwater samples from 2020

| Parameters | Excluding two hotspots | | | | Including two hotspots | | | |
|---|------------------------|------|------|--------------------|------------------------|--------|------|--------------------|
| | Min | Max | Mean | Standard deviation | Min | Max | Mean | Standard deviation |
| pH | 7.04 | 8.22 | 7.58 | 0.32 | 7.04 | 8.22 | 7.58 | 0.34 |
| TDS (mg/L) | 173 | 1430 | 611 | 341 | 173 | 11,800 | 1151 | 2430 |
| TH (mg of CaCO ₃ /L) | 93.3 | 828 | 345 | 183 | 93.3 | 5630 | 554 | 976 |
| Ca ²⁺ (mg/L) | 4.45 | 174 | 30 | 38.9 | 4.45 | 626 | 50 | 106 |
| Mg ²⁺ (mg/L) | 19.9 | 151 | 66 | 40.0 | 19.9 | 986 | 104 | 178 |
| Na ⁺ (mg/L) | 15.3 | 452 | 106 | 89.2 | 15.3 | 2970 | 219 | 525 |
| K ⁺ (mg/L) | 1.53 | 17.8 | 6 | 3.42 | 1.53 | 22.8 | 7 | 4.78 |
| HCO ₃ ⁻ (mg/L) | 43.5 | 527 | 208 | 122 | 43.5 | 2200 | 253 | 334 |
| SO ₄ ²⁻ (mg/L) | 5.93 | 380 | 54 | 74.9 | 5.93 | 380 | 54 | 74.9 |
| NO ₃ ⁻ (as NO ₃ ⁻ mg/L) | 19.5 | 494 | 125 | 107 | 19.5 | 5630 | 363 | 1080 |
| Cl ⁻ (mg/L) | 9.97 | 308 | 102 | 82.8 | 9.97 | 2410 | 207 | 478 |
| F ⁻ (mg/L) | 0.01 | 0.26 | 0.09 | 0.08 | 0.01 | 0.26 | 0.07 | 0.08 |

Results and discussion

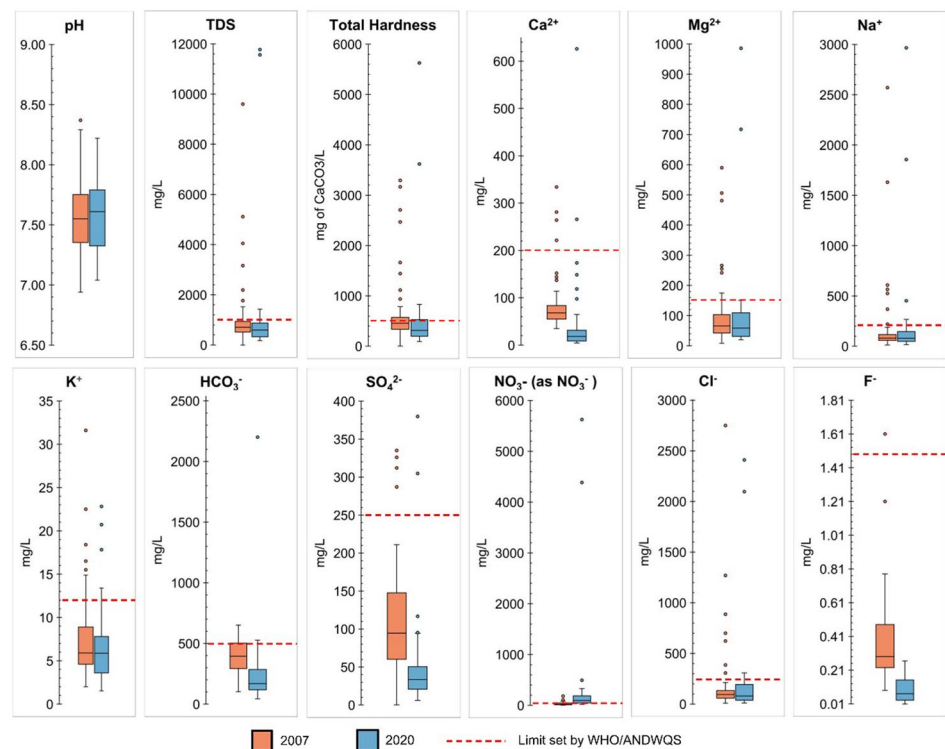
Statistical results of hydrochemical parameters

The statistical analysis results of measured parameters for 41 groundwater samples are presented in Table 2, with and without two identified locations as hotspots. The two hotspots were located in areas where all the measured parameters were anomalously high both in 2007 and 2020 (see

Sect. 3.2). The statistical analysis results are illustrated with the corresponding box and whisker plots in Fig. 2.

The measured pH varied from 7.04 to 8.22 suggesting a weakly alkaline association. TDS concentrations varied from 173 to 1430 mg/L. This indicates distributed water quality in the basin and could be due to a variety of factors (e.g., aquifer heterogeneity and anthropogenic activities). The TDS value in several cases in the northeast and southeast of Kabul city is higher than the permissible level for drinking (1000 mg/L) set by WHO (2017) and ANDWQS (2012). The

Fig. 2 Box and whisker plots of measured parameters of groundwater samples for 2007 (*n* = 75) and the new piezometer wells in 2020 (*n* = 41)



results also indicate that the total hardness (TH) values vary between 93 and 828, which also confirms that the distribution of water quality is varied in Kabul City.

Nitrate (as NO_3^-) concentration ranges between 17.6 and 494 mg/L. The maximum allowable limit for NO_3^- in drinking water is 50 mg/L (as NO_3^-), set by WHO (2003) and ANDWQS (2012). Due to the lack of nitrate in most geologic formations, elevated NO_3^- concentrations are commonly representative of water pollution by anthropogenic sources such as animal waste, and fertilizer (Adimalla and Qian 2019). Over 86% of the households in Kabul dispose of sewage via a simple pit latrine or cesspit without any further wastewater treatment (Houben et al. 2009).

Water quality index

The WQI was used to assess the trend and suitability of shallow groundwater quality for drinking purposes in the study area, Kabul city. The classification of the type of water according to the WQI is presented in Table 3, following the work of Sheikhi et al. (2020) and Vasanthavigar et al. (2010). The quality of water in shallow aquifers of Kabul city has significantly deteriorated between 2007 and 2020, as illustrated in Fig. 3a, b, respectively. In the east of the city, it is illustrated that in 2007 the quality of shallow

groundwater was excellent to good water except in two spots (Fig. 3a). While in 2020, the quality of shallow groundwater is poor to unsuitable for drinking purposes except for the very few wells with good quality (Fig. 3b). In the west of the city, the water quality has also deteriorated from most of the area having excellent water in 2007 to good water in 2020. Because of their sandy to gravel composition and related high permeabilities, the aquifers in the Kabul Basin provide a little barrier to the spread of pollutants (Houben et al. 2009).

The two hotspots illustrated in Fig. 4a, b highlight high WQI values for drinking water quality. In both locations, the water quality ranked as unsuitable for drinking purposes. The two hotspots are located in the vicinity of surface wastewater collection and inundation control canals. In both areas, the WQI was classified as very poor water quality in 2007, while contamination has spread in the area and the quality index increased to unsuitable for drinking purposes by 2020. As illustrated in Fig. 4a, the area is densely populated besides industrial activities taking place. The sampled piezometer well (Fig. 4a) is located near a perennial canal that takes surface and wastewater to the Logar River. Similarly, a sampled piezometer well located 3.5 km downstream of the canal also indicates WQI over 100, poor water quality. The second hotspot illustrated in Fig. 4b shows the sampled piezometer well located in an area near a perennial and an intermittent canal used for surface wastewater collection and inundation control.

Table 3 WQI based classification of water type (Vasanthavigar et al. 2010; Sheikhi et al. 2020)

| Range | Type of water |
|---------|----------------------------------|
| < 50 | Excellent water |
| 50–100 | Good water |
| 100–200 | Poor water |
| 200–300 | Very poor water |
| > 300 | Unsuitable for drinking purposes |

Groundwater hydrochemical type

To observe changes and to classify the groundwater type or hydrochemical facies of shallow groundwater in Kabul city, the cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+}) and anions (Cl^- , HCO_3^- , SO_4^{2-}) composition were plotted on Piper trilinear diagrams for 2007 (Fig. 5a) and 2020 (Fig. 5b).

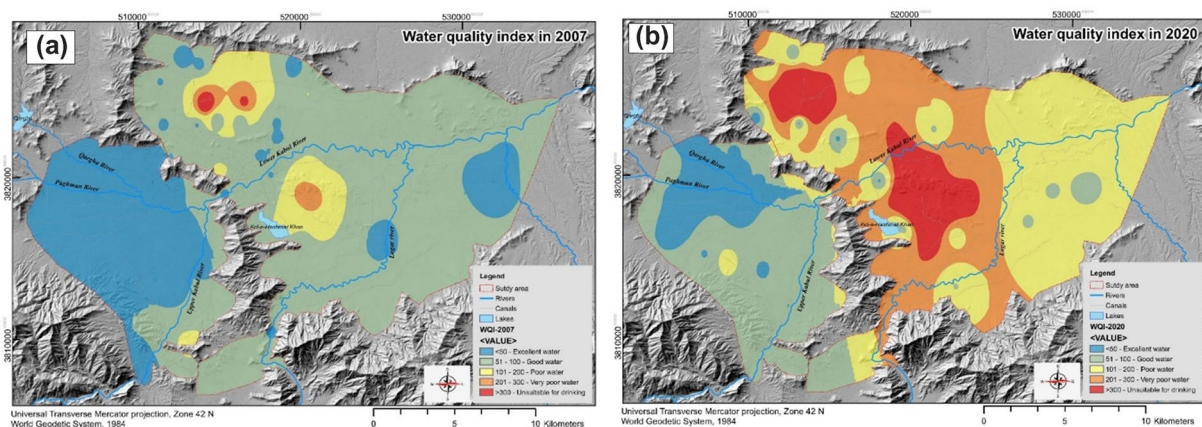


Fig. 3 Spatial distribution of water quality index in Kabul city **a** 2007, and **b** 2020

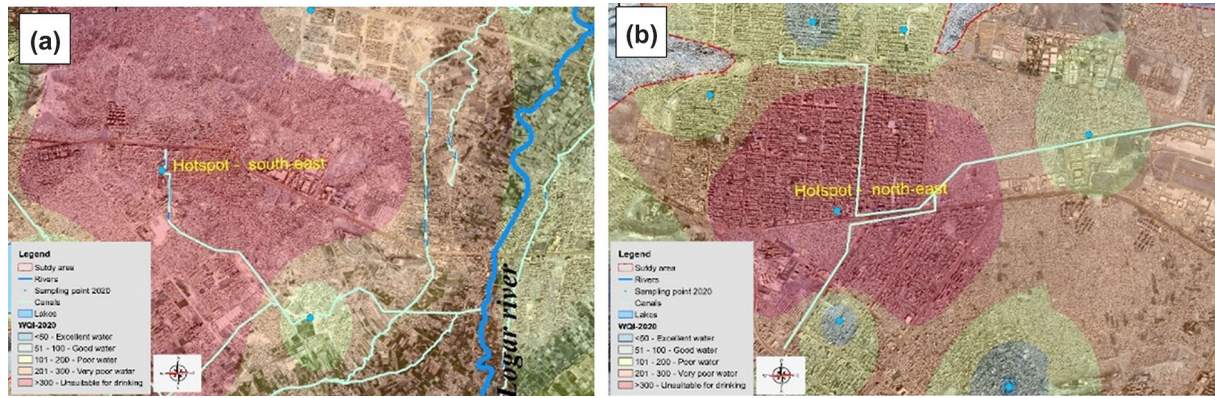


Fig. 4 The two hotspots with high WQI, unsuitable for drinking water **a** southeast of Kabul city, and **b** northeast of Kabul city

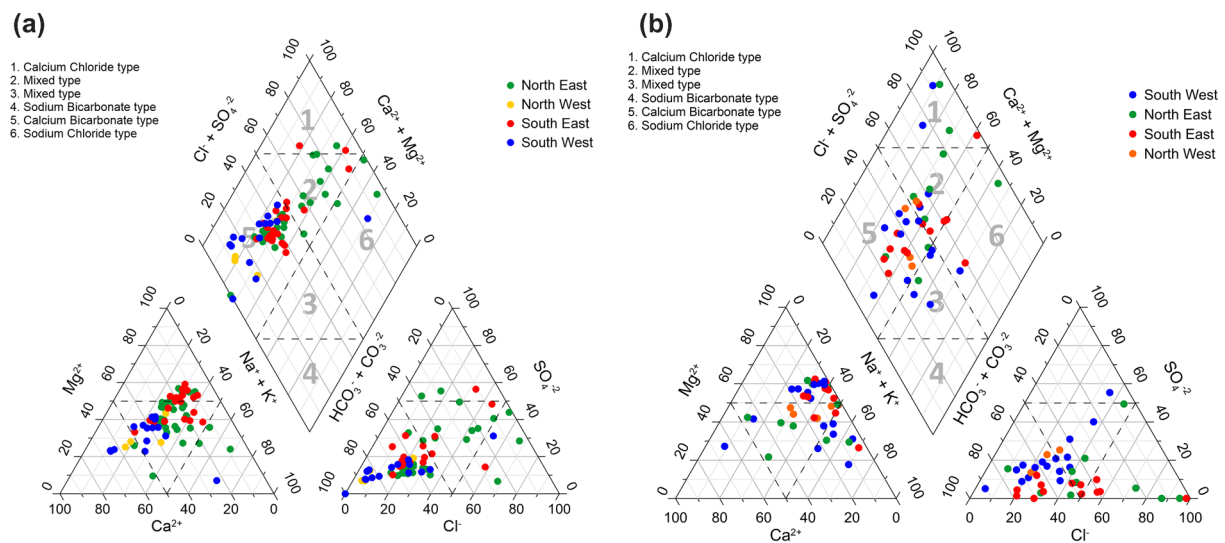


Fig. 5 Piper diagrams for **a** 2007, and **b** 2020—an increase in Na^+ , Cl^- and Mg^{2+} is observed between 2007 and 2020

The water types for the study area are presented in four groups based on the geographic location of sampled wells. The group of samples located in the northeast were mainly Ca-HCO_3 and mixed water type (Ca-Mg-Cl) in 2007 (Fig. 5a). Other groups of samples located in the southeast, northwest, and southwest were mainly Ca-HCO_3 water type in 2007 (Fig. 5a). However, our analysis of sampled piezometric wells in 2020 highlighted some changes in water type compared to 2007. For instance, in the northeast of the city, more samples were Ca-Na-HCO_3 besides other water types including Ca-HCO_3 and mixed water type (Ca-Mg-Cl). In the southeast of the city, more samples illustrated mixed water type (Ca-Mg-Cl) beside the Ca-HCO_3 water type. The northwest of the city is the only region where the groundwater has not observed a significant change in water type, Ca-HCO_3 water type remains unchanged (Fig. 5b). However, in the southwest

of Kabul city, the sampled piezometric wells in 2020 illustrated samples with mixed type water (Ca-Na-HCO_3), Ca-HCO_3 , and few samples were Na-Cl water type. The emergence of Na-Cl water type in the southwest of Kabul city could be due to cation exchange and evaporation. The hydrochemical analysis demonstrated an increase of Na^+ , Cl^- and Mg^{2+} in the groundwater of Kabul city between 2007 and 2020. The enrichment of alkali (Na^+) and strong acid anions (Cl^- and SO_4^{2-}) could be a result of pit latrine leachate infiltration (Rao et al. 2013).

Mechanisms controlling groundwater hydrogeochemistry

The groundwater samples fall mainly in the rock-weathering dominance zone with few samples in the evaporation zone (Fig. 6), indicating that both rock-weathering

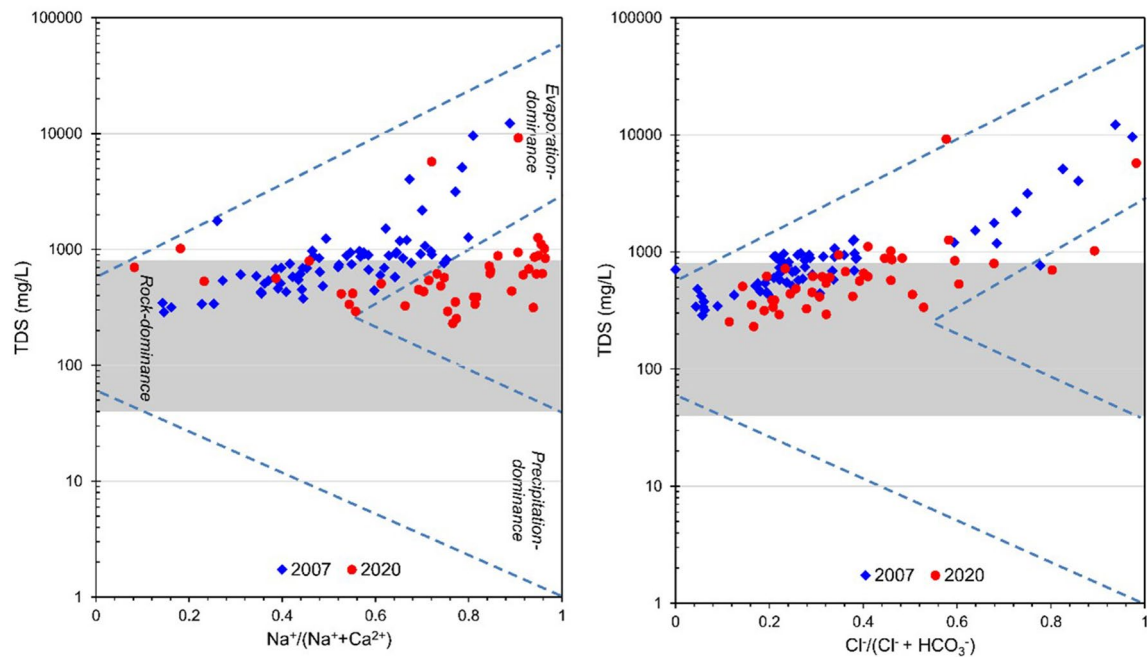


Fig. 6 Gibbs diagrams of the groundwater samples for 2007 and 2020

and evaporation crystallization influence groundwater chemical evolution. As illustrated in Fig. 6, Na^+ is the major cation in groundwater and a major contributor to high groundwater salinity because the values of $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$ for the majority of the samples exceed 0.6. Moreover, the variation of $\text{Na}^+ / (\text{Na}^+ + \text{Ca}^{2+})$ between 0.08 and 0.96 suggest a strong cation exchange in the groundwater. Cation exchange and interactions with silicates are likely to cause the $\text{Na}^+\text{HCO}_3^-$ water type (Toran and Saunders 2002; Su et al. 2017; Gao et al. 2019). The ratio of $\text{Cl}^- / (\text{Cl}^- + \text{HCO}_3^-)$ in the majority of the groundwater

samples is below 0.6 (Fig. 6), with an influence of rock-weathering except for some samples spread in evaporation dominance. The rock-weathering processes could be influenced by anthropogenic activities (Marghade et al. 2012; Pradhan et al. 2022). As illustrated in Fig. 6, none of the groundwater samples falls in the precipitation dominance zone indicating the limited impact of atmospheric participation on the chemical composition of groundwater of Kabul city. In the semi-arid regions, owing to the semi-arid climate conditions, atmospheric precipitation has a

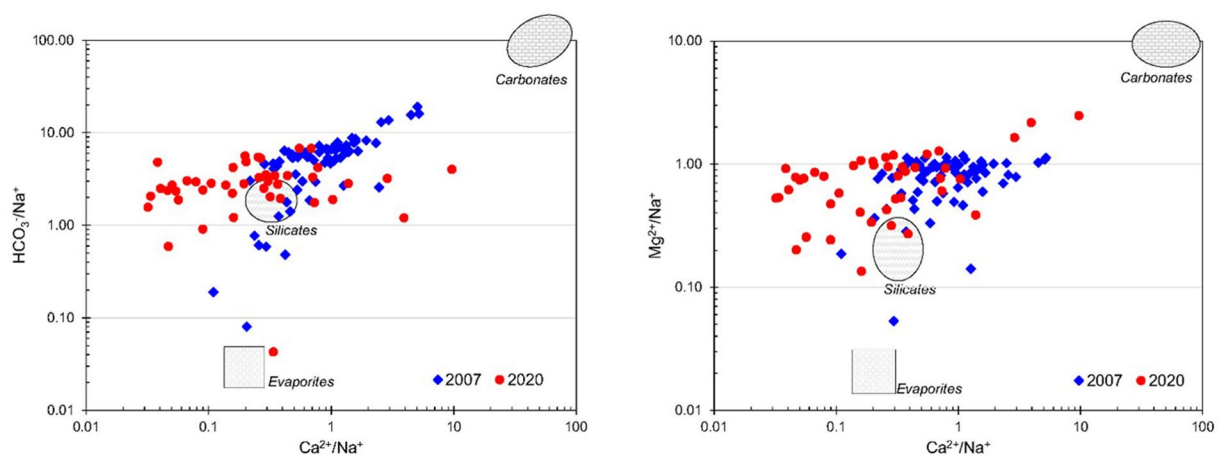


Fig. 7 End-member diagrams of the groundwater samples for 2007 and 2020

limited impact on the chemical composition of groundwater (Feng et al. 2020).

To investigate and identify the sources of rock-weathering in relation to the hydrochemical properties of groundwater in the study area, following Pradhan et al. (2022) and Roy et al. (2020), we used end-member diagrams as suggested by Gaillardet et al. (1999). As illustrated in Fig. 7, the chemical composition of groundwater in the study area is primarily between carbonate and silicate, indicating that groundwater chemical composition originates from carbonate and silicate mineral weathering.

Nitrate contamination

Long-term nitrate exposure could result in a lack of oxygen delivery to numerous bodily tissues and organs, causing brain damage and, finally, death in infants (Ahada and Suthar 2018). As presented in Sect. 3.1, nitrate in Kabul city groundwater wells exceeds the WHO guidelines for safe drinking water. The maximum level of nitrate (NO_3^-) contamination recommended by the WHO is 50 mg/L. The results show that 76% of the analyzed groundwater samples from Kabul city in 2020 exceeded the limit of 50 mg/L up to tenfold. Spatially distributed maps of nitrate contamination (as NO_3^-) for Kabul city in 2007 and 2020 are provided as supplementary material (Figs. A2 and A3). The present study evaluated NO_3^- connections with physiochemical indices to assess the consequences of anthropogenic activities on groundwater quality in Kabul city. The relationship between NO_3^- and Cl^- , as illustrated in Fig. 8, shows that the two ions originate from the same source. Because wastewater has a substantial impact on Cl^- , it is plausible to assume that wastewater has a similar impact on NO_3^- (Li et al. 2016). Thus, as illustrated in Fig. 8, the strong correlation between Cl^- and NO_3^- ($R^2=0.98$ including the two hotspots, $R^2=0.5$

and excluding the two hotspots) suggests a similar source, mainly through anthropogenic activities, happened in Kabul city over time. We also noted a statistically significant positive relationship between TDS and $(\text{NO}_3^- + \text{Cl}^-)/\text{HCO}_3^-$ ($R=0.19$). A positive correlation between TDS and ions indicates that human activities influence groundwater chemistry (Jalali 2009).

Nitrate pollution in groundwater and surface water results from solid waste, leaching from agricultural land, disposal sites, human excreta, or ammonia oxidation (WHO 2003; Rahman et al. 2021). The redox potential in Kabul city measured by Houben et al. (2009) suggested that ammonium nitrification is most likely occurring in the pit latrines and unsaturated zone and nitrification occurs to a lesser extent in shallow groundwater. Houben et al. (2009) found that despite its near-surface location, the groundwater in Kabul city exhibits strong signs of oxygen depletion due to the oxygen-consuming processes of nitrification and oxygenation of dissolved organic matter from sewage. However, there are many variables and uncertainties. Nitrate is well known as a pollutant from anthropogenic activities such as fertilizer application and domestic wastes (Li et al. 2016). A substantial increase in urban built-up areas is observed in Kabul between 2007 and 2020 (Noori and Singh 2021). Besides agriculture activities in parts of the city, Kabul is populated with high density, experienced rapid growth of non-standard urbanization, lacks wastewater collection systems, and most houses are accommodated with a pit latrine or cesspit. As a consequence, NO_3^- pollution may regularly occur in the study area and increase over time due to geogenic and anthropogenic activities. In their study, Borchardt et al. (2021), showed that total coliforms at well sites and nitrate were strongly linked to depth-to-bedrock and neighboring agricultural land use.

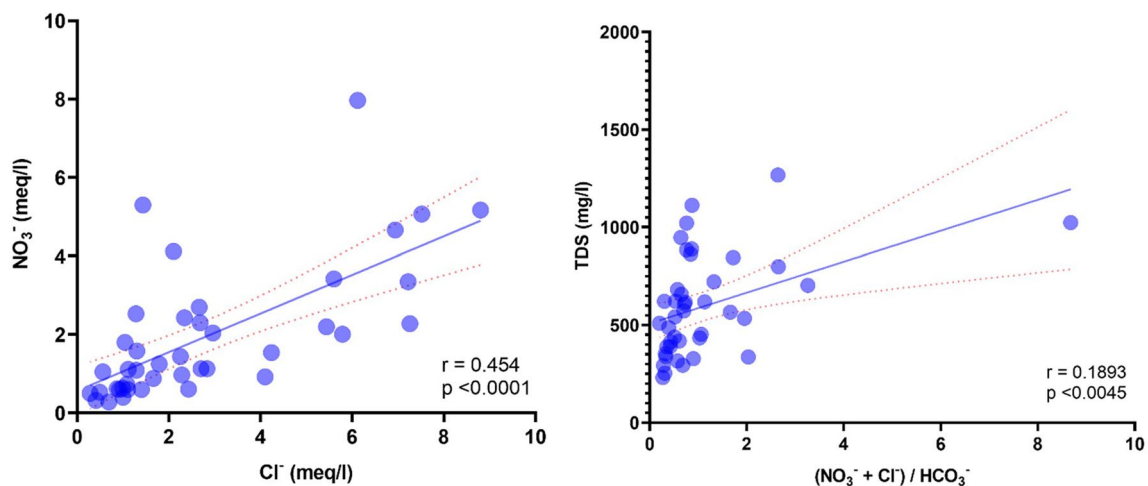


Fig. 8 Signification correlation of NO_3^- with Cl^- suggesting a similar source

Bacteriological contamination

Escherichia coli (*E. coli*) found in drinking water indicates water pollution with feces which might contain different disease-causing microorganisms including certain types of bacteria, viruses and protozoa, WHO set a limit of zero colony-forming units per 100 milliliters (0 CFU/100 mL) (WHO 2017; Ibrahim 2019). The groundwater biological contamination in Kabul city was investigated by WHO and confirmed the presence of coliform bacteria as reported by Proctor & Redfern International Limited (1972). As reported by Banks and Soldal (2002), the bacteriological study of Kabul city groundwater in 1996 by Timmins, based on 1400 samples of drinking water sources, confirmed the presence of *E. coli* > 100 CFU/100 mL in wells with hand pumps (11.1%), open wells (31.9%) and distribution networks (15.7%).

The sampling campaign from 2004 to 2007 reported by Mack et al. (2010) found that *E. coli* was present in 97% of the groundwater samples (Fig. A4); however, *E. coli* concentrations appeared to be spread randomly throughout the city. The range of *E. coli* presence in groundwater in the southwest of Kabul city was reported between 1 and 8 CFU/100 mL in 2007 (Fig. A4) but the results of this study found an unexpected increase to an average of 110 CFU/100 mL in 2020 (Fig. 9). The increase of *E. coli* prevalence in the southwest of Kabul is potentially related to an increase of inhabitants between 2007 and 2020 (Noori and Singh 2021; Zaryab et al. 2022), the common use of pit latrines in local houses, and the use of human excreta in nearby agricultural land as fertilizer. In light of these conditions, a determining factor for the widespread and increasing *E. coli* contamination in the area could be the shallow depth of groundwater (2–25 m) beside the existence of three

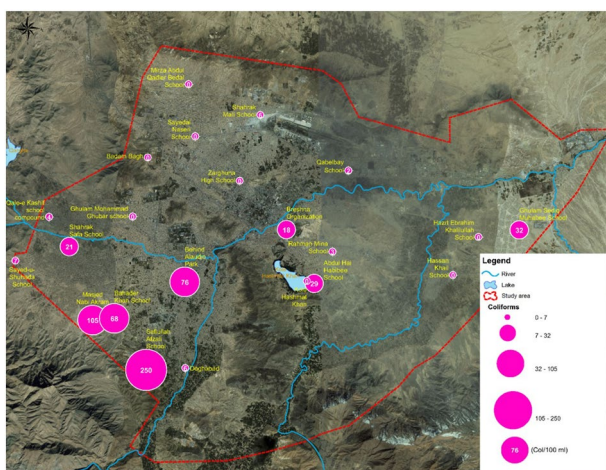


Fig. 9 *E. coli* count in groundwater samples of Kabul city in 2020

surface canals transporting water from the river to irrigate the land.

The increase of *E. coli* in groundwater between 2007 and 2020 is also consistent with an increase of NO_3^- in the southwest of Kabul city (which was also observed in the southeast of the city). The presence of *E. coli* in the northeast of Kabul city remains unchanged (0–6 CFU/100 mL), while an evident increase of NO_3^- might have been an effect of the depth of the water table with an average depth of 80 m.

Health risks of shallow groundwater consumption for drinking purposes

For every 1000 children born in Afghanistan, 97 children die before the age of five, and waterborne illnesses are a major contributor to this high level of child mortality (Rasooly et al. 2014). A survey of 71 health centers around Kabul city by KMARP (2018b) found that reported waterborne diseases include amoebic dysentery, hepatitis A, typhoid and paratyphoid, shigellosis, salmonellosis (Fig. 10).

Our study suggests that the extensive and growing chemical and biological contamination of the groundwater in Kabul city risks aggravating this critical public health concern. Section 3.5 thereby demonstrated that the nitrate contamination (as NO_3^-) of groundwater in Kabul city is worryingly high, and Sect. 3.6 showed that the biological contamination is beyond the limit set by WHO. In the southwest of the city, groundwater biological contamination is high.

Taken together, our findings, therefore, establish that the prevalence of waterborne disease in Kabul city is spatially distributed, and the majority are linked to biological

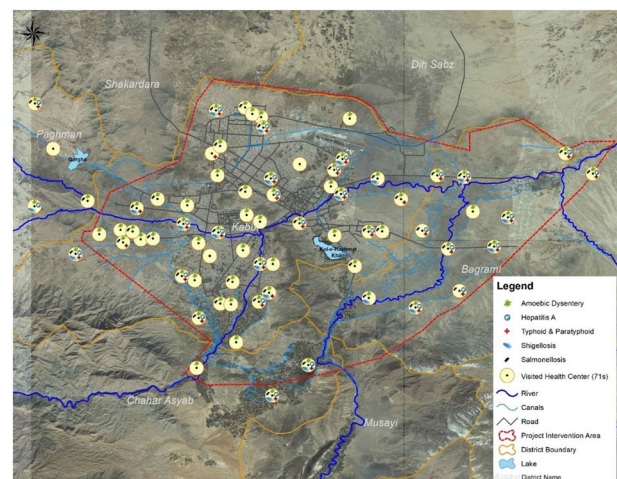


Fig. 10 Waterborne disease prevalence in Kabul city (KMARP 2018b)

contamination with *E. coli*. Although the presence of *E. coli* is a proxy for broader bacterial, viral and protozoal contamination, the available data indicate the widespread and increasing fecal contamination of groundwater in Kabul city (see Sect. 3.6) that is particularly concerning in light of the high burden of waterborne disease, especially among children.

Conclusions

Kabul city is heavily reliant on groundwater for drinking and other purposes. The primary findings of this research, using data from groundwater samples from 41 new piezometric wells to those used in 2007 (75 sampling points), revealed a significant decline in water quality from 2007 to 2020, and the key findings are outlined as follows:

- (a) The prevalent groundwater hydrochemical type in Kabul city is the Ca–HCO₃ water type. The chemical composition of groundwater in the study area is primarily influenced by water–rock interaction.
- (b) The hydrochemical analysis demonstrated an increase of Na⁺, Cl[−] and Mg²⁺ in the groundwater of Kabul city between 2007 and 2020.
- (c) The results of our study suggest an increasing impact of anthropogenic activities on groundwater in Kabul city, which has led to an increase and the spread of chemical contamination, as illustrated using WQI. The increase of WQI in the southwest and southeast of Kabul city is potentially related to agricultural activities and growing population pressure between 2007 and 2020.
- (d) An increase of NO₃[−] and *E. coli* is observed indicating more intensive fecal contamination in areas that had already struggled with a high prevalence of waterborne diseases.
- (e) Sustainable access to clean water in the densely populated city of Kabul requires urgent attention as it threatens public health and the socio-economic recovery of a post-conflict environment. Although the government is constructing two dams for providing piped drinking water to residents, water quality and the distribution network expansion remain major concerns due to the timescale and limited financial resources for major infrastructural developments. Considering the health risks of water contamination, sustainable groundwater management in Kabul requires establishing water distribution systems, wastewater treatment and long-term quality and water level monitoring. This requires long-term planning and extensive financial resources, which are further complicated by the events in August 2020 that left Afghanistan not only in a complex post-conflict context but indeed no longer recognized by the international community.
- (f) Groundwater is frequently utilized without any form of treatment or even purification at the household level. As an interim, inexpensive, and sustainable solution for residents of Kabul city, we propose interventions such as point-of-use (POU) water purification which may offer temporary respite for waterborne disease prevention.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s40899-022-00808-9>.

Acknowledgements The authors would like to acknowledge and are thankful to Landill-Mills for facilitating and financing the transport of water samples from Afghanistan with the cooperation of the National Water Affairs Regulation Authority (NWARA) under the Kabul Managed Aquifer Recharge (KMAR) project financed by the Asian Development Bank (ADB) and the United States Agency for International Development (USAID). We are also very grateful to the anonymous reviewers and the editor for their constructive comments.

Author contributions The author's contribution to this work is original. The final manuscript was read and approved by the authors.

Funding MDH and CG were supported by a Royal Academy of Engineering Frontiers of Engineering for Development seed fund award (Ref. FoE2122\10\10). The funders had no influence on the design, implementation, and reporting of the research project.

Availability of data and materials The data used in this study will be available upon request.

Declarations

Conflict of interest The authors declare no conflict of interest.

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