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REPORT

The effects of urbanization on the groundwater system of the Kabul shallow aquifers, Afghanistan

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Abstract
The capital city of Afghanistan, Kabul, has experienced rapid urbanization since the end of 2001. The aim of this study is to evaluate the impact of rapid urbanization on the Kabul aquifer system, which is the main source of water for domestic, agricultural and industrial use in the area. Satellite imagery, groundwater levels and rainfall historical data were analyzed in conjunction with physico-chemical parameters that were measured at 27 water wells located in the Kabul Plain in 2020. Land-cover maps indicate that the urban surface area increased by 40% between 2000 and 2020, whilst the agricultural surface area simultaneously decreased by 32%. Meanwhile the Kabul Plain has globally experienced a severe decrease in groundwater levels (-0.8 m/year on average, and a fall of 60 m in some places) due to overabstraction, which has also seen changes in groundwater flow directions. Hydrochemistry, on the other hand, reveals that chloride concentrations and salinity increased throughout the aquifer between 2005 and 2020, while the nitrate concentration decreased in most places of the Kabul Plain over the considered period. The results suggest that rapid urbanization has had serious detrimental effects on both groundwater quantity and quality. Without urgent preventive policy and the implementation of effective practices, groundwater resource depletion and groundwater quality deterioration in the Kabul shallow aquifers are likely to continue in the future.

Keywords Urbanization · Groundwater management · Over-abstraction · Land-use changes · Afghanistan

Introduction

Groundwater plays a significant role in terms of the economic and social health of the urban population of developing countries (Rodell et al. 2009; Wakode et al. 2017; Jia et al. 2019; Foster 2020). More than half of the global population lives in cities, a proportion that is expected to increase in the few next decades (Schirmer et al. 2013; McDonald et al. 2014). Many large cities depend mainly on groundwater resources, for instance, Beijing in China (Zhou et al. 2012), Delhi (Dash et al. 2010) and Kolkata (Sahu et al. 2013) in India, Hong Kong in China (Jiao et al. 2008), Seoul in South Korea (Choi et al. 2005), Dhaka in Bangladesh (Morris et al. 2003), and Mexico City (Ramos-Leal et al. 2010), amongst others. Such population growth has resulted in intense abstraction of aquifers and reduction in recharge beneath the cities, bringing significant changes in groundwater quality and quantity.

The rapid urbanization has led to groundwater deterioration in many cities such as Taejon (Jeong 2001) in South Korea, Beijing (Zhou et al. 2012) and Shanghai (Dong et al. 2013) in China, Solapur (Naik et al. 2008) and Shimla (Sahil and Bhardwaj 2020) in India, Nairobi in Kenya (Oiro et al. 2020) and so forth. These cities depend heavily on groundwater as the main water resource. Generally, urbanization has many consequences for the hydrological cycle and water resources, including water shortage due to rising consumption, flooding as a result of increased soil compaction, changes in the river and groundwater regimes and associated water quality deterioration, land subsidence and saltwater intrusion due to overabstraction of groundwater, and increase in groundwater recharge because of leakage from water distribution systems (Rogers 1994; Takizawa 2008;

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Sharp 2010). Urbanization can have a significant effect on the groundwater system (Konikow and Kendy 2005). Both the quantity and quality of groundwater are altered due to urbanization (Khazaei et al. 2004; Jia et al. 2019). Rapid urbanization usually changes the sources and flow directions of groundwater recharge. The estimation of various components of the water balance in an urban area is a very complex process and it is hard to achieve an accurate result due to lack of data and information (Wakode et al. 2017; Minning et al. 2017).

A few studies indicate that groundwater recharge in urban areas increases, mostly due to reduction of evapotranspiration, leakage of water distribution systems, and sewage infiltration (McFarlance 1984; Minning et al. 2017; Malik et al. 2010; Wakode et al. 2017). While some other studies indicate that groundwater recharge decreases in urban areas because of ground surface sealing and increasing surface-water runoff in comparison with natural landscapes (Grischek et al. 1996; Graniel et al. 1999; Hoque et al; 2007; Hardison et al. 2009; Oiro et al. 2020; Mohanavelu et al. 2020).

In general, all studies noted that urbanization has altered natural groundwater systems and the net effect of urbanization on groundwater recharge and quality is difficult to anticipate, as every city has a different socio-economic setting and hydrogeological regime.

Kabul is the capital and the largest city in Afghanistan with a population of about 5.3 million. It has experienced rapid urbanization over the past two decades. It is considered as the fifth fastest-growing city in the world. A relative social, economic, and political stability gradually returned to Afghanistan since the end of 2001. Subsequently, with the establishment of peace and security in the country, people from poor villages and deprived areas of the country migrated to Kabul to benefit from the available facilities there (APPRO 2012; Barbé 2013). In addition, hundreds of thousands of Afghan refugees from neighboring countries returned back to the country and most of them settled in in the city of Kabul. As a result, the population living in Kabul increased from around 1 million in 2001 to 5.3 million people in 2021 (NSIA 2021; UN 2021).

Groundwater is the main source of water for domestic, agricultural, and industrial usage in Kabul (Houben et al. 2009b; Zaryab et al. 2017; Saffi 2011; Brati et al. 2019; Farahmand et al. 2021). The urban areas have expanded mostly through informal settlement construction by refugees and returnees after the establishment of the post-Taliban government at the end of 2001 (Bertaud 2005; Amiri and Lukumwena 2018). A mixture of geogenic and anthropogenic factors have deteriorated the groundwater quality in the Kabul aquifer system and the role of anthropogenic factors in groundwater degradation is more prominent (Houben et al. 2009a; Saffi 2019; Brati et al. 2019; Jawadi et al. 2020; Mahaqi et al. 2021).

Population growth and rapid urbanization in the Kabul Plain has increased the water demand for drinking, agricultural, and industrial usages. The Kabul aquifers are the main source of water supply for Kabul residents and socio-economic development in the city. The groundwater levels have severely declined in some places of the Kabul Plain due to overexploitation (Noori and Singh 2021b). Saffi (2019) claims that the withdrawal of groundwater is six-fold faster than its recharge condition. Currently, the Paghman-Darulaman and Central Kabul aquifers are in crisis due to overexploitation associated with population growth. Furthermore, overabstraction and unsustainable groundwater development have caused groundwater quality deterioration as well. Groundwater depletion due to unsustainable development and management seriously threatens socio-economic and environmental security in the region.

Therefore, it is extremely important to study the qualitative and quantitative changes in the groundwater of Kabul due to the unsustainable development of water resources in the region. This study assesses land-use changes and impacts of population growth on groundwater resources of Kabul, where development and supply of water is 95% reliant on the groundwater. Additionally, the study endeavors to apprise the national authorities and international community about the alarming situation of serious groundwater-level decline in some places of the Kabul aquifers in the upcoming years. This report is of particular importance, being the first study in Afghanistan, to the authors' knowledge, on the effects of rapid unplanned urbanization on the aquifer system.

Study area

The study area, the city of Kabul, is located in the Kabul Plain in the center of the Kabul province in eastern Afghanistan. Kabul is divided into upper and lower parts by the Asmai (TV) and Share Darwaza mountains (Fig. 1). The Kabul district is divided into 22 precincts, with a total area of 1,030 km^2. The northern rims of the plain are dominated by metamorphic rocks such as gneiss and schist of Paleoproterozoic age. The mountains in the southern edges of the plain are mainly made up of Neoproterozoic and Mesozoic metamorphic rocks, and sedimentary rocks, including limestone and dolomite. The plain is surrounded and underlain by mountain ranges composed primarily of various metamorphic rocks, including amphibolite, quartzite, slate, schist and marble (Bohannon 2010a, b).

The study area is a Neogene to Quaternary sedimentary basin at 1,800 m above sea level (a.s.l.), located within the city of Kabul (Fig. 1), at 69°02′E–69°23'E longitude and 34°25′N–34°36′N latitude, with an area of 271 km^2. Three major seasonal rivers flow through the city: Kabul, Logar and Paghman (Fig. 1). Upper Kabul is drained by the upper

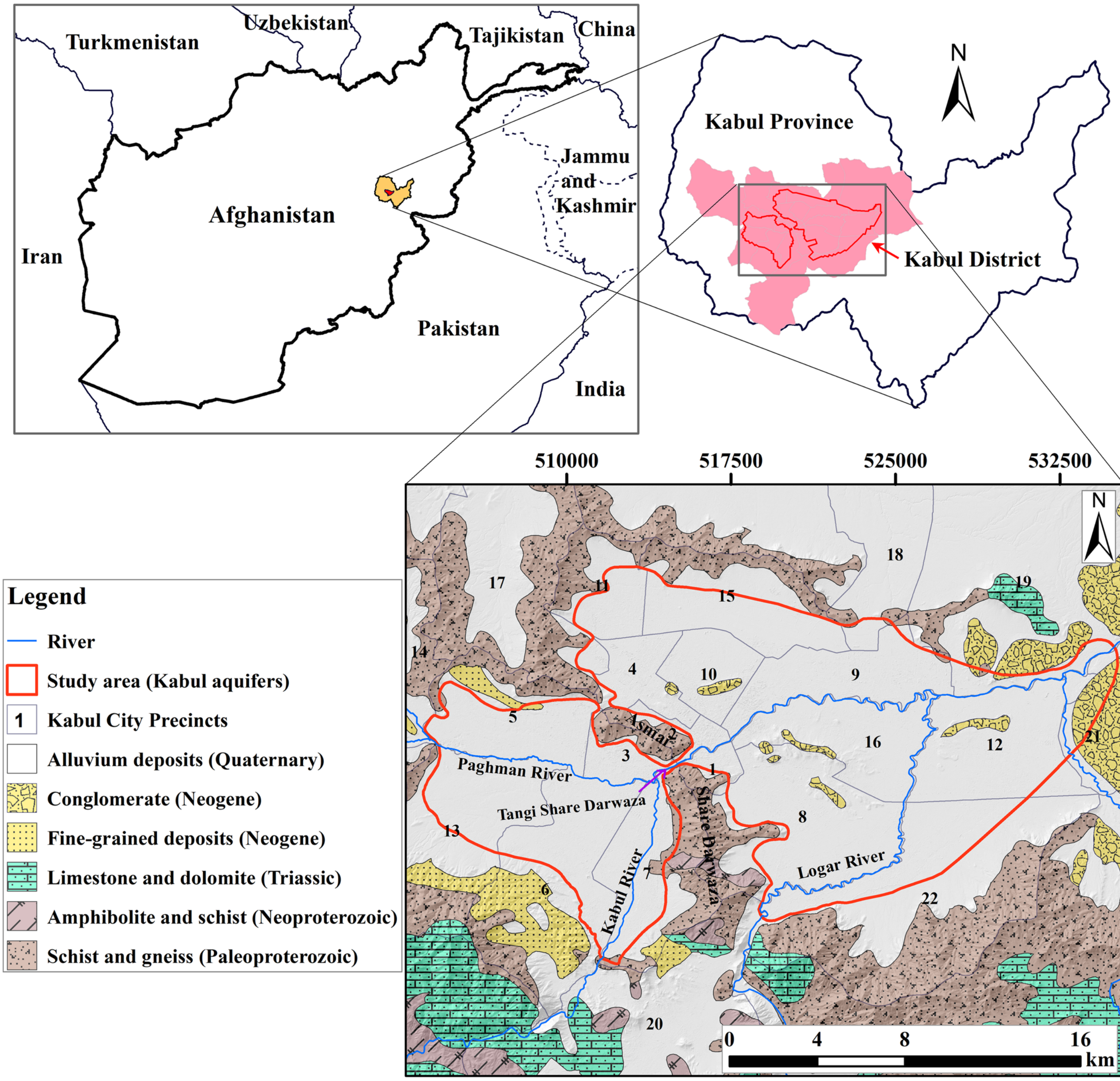

Fig. 1 Geological map and location map of the study area

Kabul and Paghman rivers and Lower Kabul is drained by Kabul and Logar rivers. The Kabul Plain drains to the northeast through the very narrow canyon of Tangi Gharu. The Kabul Plain is characterized by semiarid climate with an average annual precipitation of 315 mm. The air temperature in the Kabul Basin ranges from an average monthly low in January of –7 °C to an average monthly high in July of +32 °C (Zaryab et al. 2017).

From a hydrogeological perspective, the Kabul Plain is divided into Quaternary and Neogene aquifers. The Quaternary aquifer, which was explained in detail by Houben et al. (2009b), is generally considered shallow and divided into three (Paghman-Darulaman, Central Kabul and Logar) interconnected Quaternary unconfined aquifers (Fig. 2). The Paghman-Darulaman aquifer is hydraulically connected with the Central Kabul aquifer through Tangi Share Darwaza (Fig. 1). The Quaternary aquifer consists of gravel, sand and silt, and the thickness of this shallow aquifer can be up to 80 m. The hydraulic conductivity of shallow aquifer ranges from 4 to 112 m day^{-1} (Houben et al. 2009b). The hydraulic conductivities of Logar aquifer are higher than Central Kabul and Paghman-Darulaman aquifers (Houben et al. 2009b). The Neogene aquifer, on the other hand, is deep and semiconfined (N1). Its thickness ranges between 30 and 600 m and it is partly an aquitard (N2) (JICA 2011; Landell Mills 2020a).

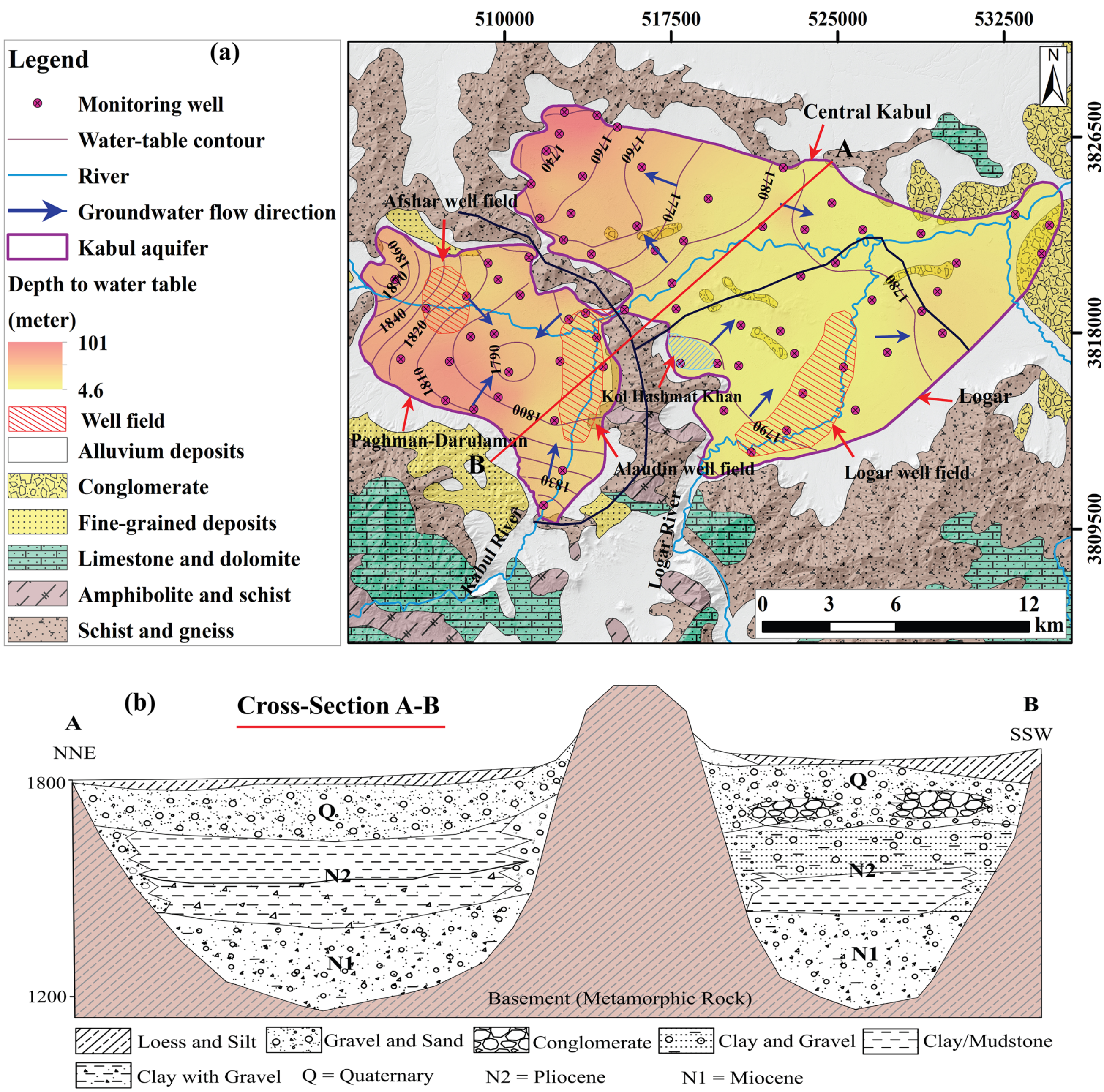

Fig. 2 **a** Hydrogeological map of the Kabul Plain. **b** Conceptualized geological cross section of the study area. Water-table elevation contours (m) are shown for the Kabul aquifer system

The Neogene deep aquifer is composed of hard clay with unconsolidated sand, gravel and conglomerates with transmissivity ranging from 2 to 27 m^2/day. Therefore, the deep aquifer productivity is significantly lower in comparison to the shallow aquifer due to low transmissivity. It is worth mentioning that the hydraulic characteristics of the deep aquifer have not yet been fully studied. In recent years, due to drying out of shallow wells, many deep water wells have been drilled in the deep aquifer; however, JICA (2013) pointed out that the deep aquifer contains fossil water which is outside of the natural water circulation system and without any recharge (JICA 2013). The groundwater is extensively exploited from the shallow and deep aquifers of Kabul Basin to supply domestic consumption, irrigation, and industrial applications. Figure 2 shows the water-table contour lines in December 2020. According to Fig. 2, depth to water level ranges from 4.6 m in the south-east to 101 m in the north-west of the Kabul Plain. In Paghman-Darulaman aquifer, flow direction is from the plain margin toward the central parts of the western plain. The general flow direction in the eastern plain is from the south-western part of the aquifer toward the north-eastern plain margin, and from the central part of the plain toward the north-western plain margin (Fig. 2).

Materials and methods

The monthly groundwater level measurements of 79 observation wells for the period of 2004 to 2020 were gathered from the National Water Affairs Regulation Authority (NWARA) of Afghanistan and the rainfall data were obtained from Afghanistan Civil Aviation Authority (ACAA). The groundwater hydrograph of the Kabul aquifers prepared using observation well data and by splitting the study area into polygons through the Thiessen method. Moreover, a map of groundwater-level changes between 2005 and 2020 was prepared using the kriging interpolation method.

Regarding physiochemical data, the US Geological Survey (USGS) and Afghan Geological Survey (AGS) carried out a detailed groundwater investigation in the Kabul Basin in 2004 and provided very accurate and useful data. The current work only focused on shallow aquifers of the Kabul Plain; thus, the physiochemical results of 48 groundwater samples collected from Kabul Plain were selected for assessing groundwater quality. Detailed information regarding sampling techniques and the results of analyzed samples are given in Broshears et al. (2005) and Mack et al. (2010); furthermore, after consideration of the different hydrogeological conditions and land use information, 27 shallow wells were selected for groundwater sampling (Fig. 2). Before collecting the samples, each water well was purged for up 10 min, until all the in-situ water quality parameters had stabilized. Water samples were collected by the authors during November 2020. A hand-held meter was used to measure water temperature, pH, and electrical conductivity (EC) in the field. Two samples were collected from each sampling point in 1.5-L polyethylene bottles for analyzing the nitrate and major ion concentrations. Nitrate concentrations were measured with a spectrophotometer (DR 5000, Hach, USA) on sample collection day at the Green Tech Laboratory in Kabul. The major ions were analyzed at the laboratory of Tehran Regional Water Authority (TRWA). The measurement of major ions (except HCO_3^-) was carried out by ion chromatography (S 151 IC, Sykam, Germany) per APHA/AWWA/WEF (2017). HCO_3^- concentrations were determined using the titration method outlined by Stumm and Morgan (2012). The accuracy of the chemical analyses was checked by calculating the ionic charge balance error (CBE). The CBE of all water samples was within $\pm 5\%$. The aforementioned physio–chemical data were used to assess the temporal variations in chloride and nitrate concentrations and EC values in the Kabul aquifers from 2004 to 2020 using kriging interpolation method. The AqQA software was used for the characterization of hydrogeochemical facies. ArcGIS tools and Surfer 17 were employed to represent groundwater-level contour lines and changes in spatio-temporal distribution of chloride and nitrate concentrations and EC values.

Landsat images for 2000 and 2020 were downloaded from the EarthExplorer website (https://earthexplorer.usgs.gov/) for land-use classification. Using ArcGIS tools, the images were firstly merged and then clipped for the area of the city of Kabul. These were then classified using a conversion of categorized classes of land cover to assess temporal changes between 2000 and 2020 in Kabul. In the GIS environment, polygons were drawn for classes derived from raster input data. Drawn signature polygons were grouped into built-up area, green area, bare land and water bodies. The resulting classified image maps were then employed, and the surface areas of the different land-use categories were calculated to quantify land-cover changes over the considered period.

Results and discussion

Water-table fluctuations

Figure 3 illustrates the groundwater hydrograph along with the changes of precipitation in the Kabul Plain during the period of 2005–2020. The hydrograph indicates that the groundwater levels have continuously decreased in the plain. In general, the evolution in groundwater level can be divided into two time periods, 2005–2011 and 2011–2020. In the time period 2005–2011, the downward trends in groundwater levels were slow, while the downward trends in groundwater levels dramatically increased from 2011 to 2020. Figure 3 shows that groundwater levels have dramatically declined in most parts of the plain, particularly in the north-west part of Central Kabul aquifer and in the south-east Paghman-Darulaman aquifer.

The groundwater hydrograph shows that groundwater levels declined 12 m over 15 years (from 2005 to 2020) at a rate of 80 cm/year in some parts of the Kabul aquifers. The hydrograph indicates that the decline in groundwater level has rapidly increased since 2011. It is most likely to be due to population growth, change in precipitation type, and increasing urban areas. The city of Kabul has witnessed rapid population growth since the end of 2001. As a result, the population living in Kabul has increased from around 1 million in 2001 to 5.3 million in 2021 (APPRO 2012; NSIA 2021; UN 2021). Currently, over 70% of the population is estimated to live in informal settlements (Barbé 2013). During the considered period, Kole Hashmat Khan (the only remained wetland in the Kabul Plain) and a significant number of shallow wells dried up due to overexploitation

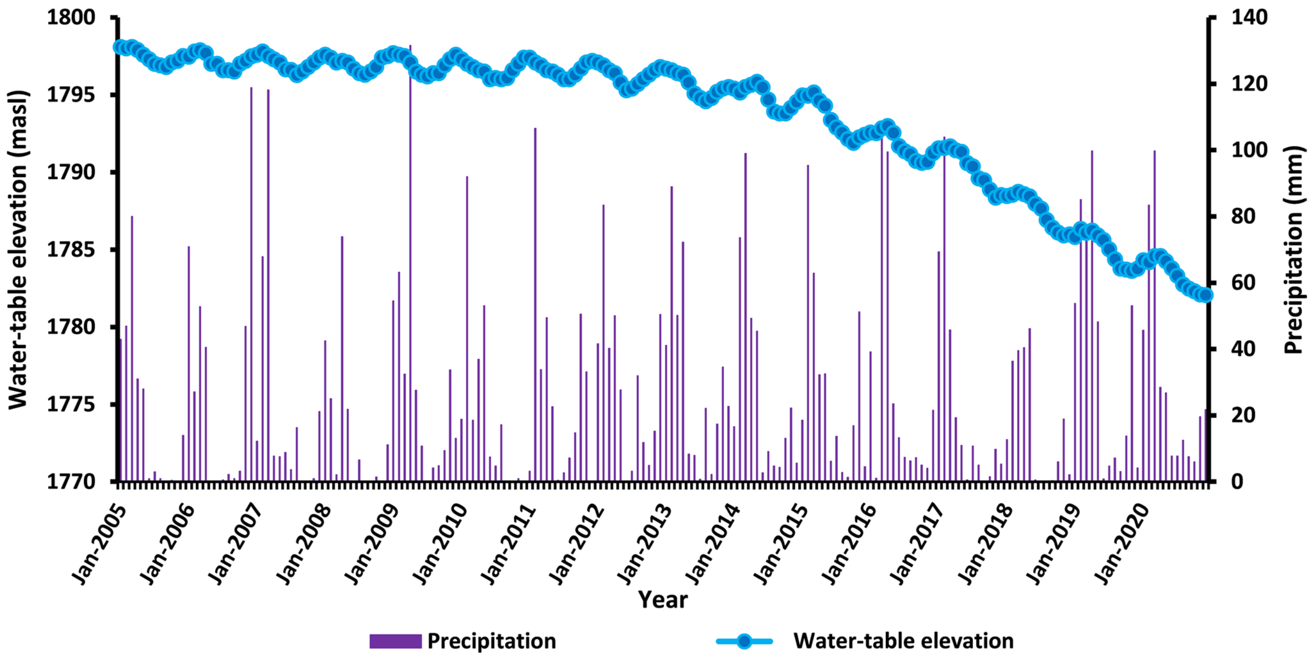

Fig. 3 Decline of water table in the Kabul Plain (2005–2020)

(Fig. 2). The response of the groundwater levels is sensitive to rainfall in parts of the aquifers where the groundwater levels are at shallow depth. When precipitation occurs, the water level rises after a few weeks. The groundwater level commonly dips during the dry period (May–December) and peaks during the wet period (January–April) of every year.

Overall, four land-use types were identified in the study area (Fig. 4a,b). Figure 4a,b shows that the areas under different land use and land cover (LULC) classes have changed in various localities over time. The agricultural area decreased significantly (from 106.5 km^2 in 2000 to 72.5 km^2 in 2020), whereas the urban area increased considerably from 160.9 km^2 in 2000 to 410.2 km^2 in 2020. The area covered by bare land in the study area declined from about 762.6 km^2 in 2000 to 546.3 km^2 in 2020. The analysis of LULC shows that the built-up areas significantly increased in the Kabul Plain during 2000–2020. The results also indicate that a new urban region has grown largely towards the plain margins (Fig. 4b). Overall, natural groundwater recharge within the Kabul Plain has been altered as a consequence of rapid

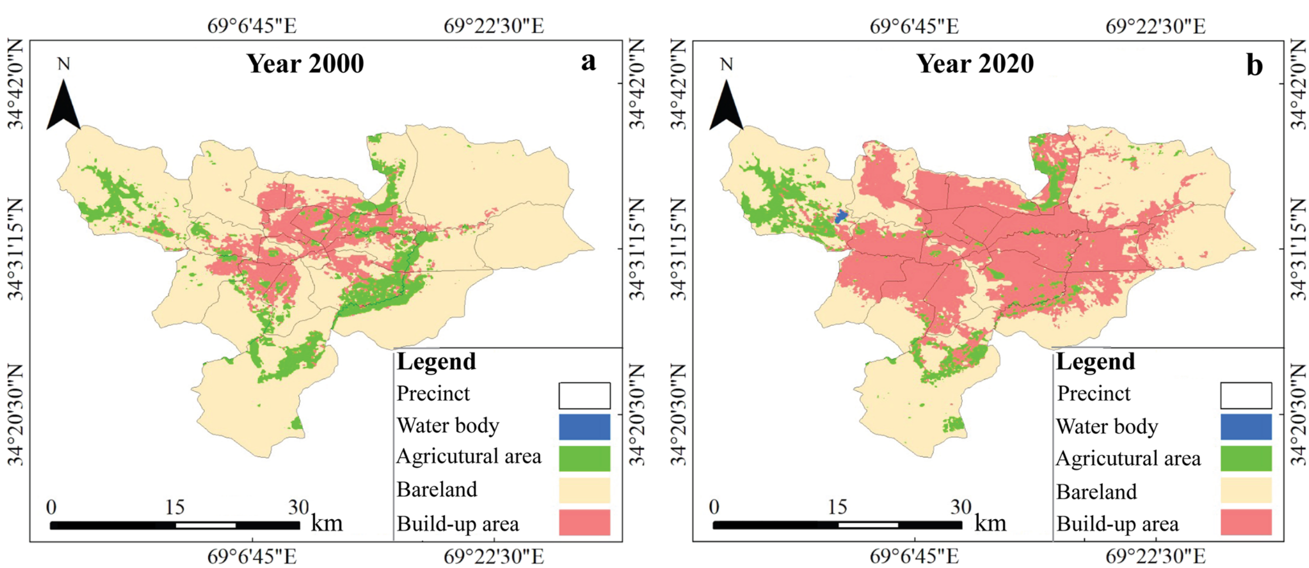

Fig. 4 **a** Map of Kabul city land use in **a** 2000 and **b** 2020 urbanization, and natural recharge within the urban area has decreased due to the construction of buildings and roads.

Figure 5 shows the groundwater-level contour lines and flow directions in December 2004 and December 2020 for the shallow aquifer system. The water-table elevation contours and flows directions in 2004 and 2020 are shown in blue and magenta/purple colors, respectively (Fig. 5). Figure 5 indicates that groundwater flow directions have significantly changed over the study period. In 2004, the groundwater flow path was from west and south-west to the east along the rivers in the western plain, and from south and south-west towards the plain center, then to the north and east in the eastern plain (Broshears et al. 2005; Houben et al. 2009b). According to Fig. 5, groundwater discharged from the Paghman-Darulaman aquifer through Tangi Share Darwaza to the Central Kabul aquifer. The groundwater flow direction in the western plain changed by 2020, and flow is now towards the central part of the plain (Fig. 5). The groundwater flow direction in the eastern plain in 2020 is similar to the one in 2004; however, the figure illustrates, that by 2020, the groundwater flow path in the central and north-west part of the plain changed and the flow is now concentrated to the north-west. Changes in groundwater flow direction in the Kabul Plain are most likely due to overexploitation and unplanned rapid urbanization.

Figure 6 shows changes in groundwater levels in the Kabul aquifer from 2007 to 2020. According to Fig. 6, the maximum decline in groundwater level is observed in the south-western part of Paghman-Darulaman aquifer and north-western part of Central Kabul aquifer (>60 m). The sharp drop of groundwater level in the aforementioned areas is most likely due to the lower storativity of the aquifer (Landell Mills 2020a; Meldebekova et al. 2020). Figure 6 shows that during 13 years, groundwater levels declined all across the Kabul Plain, except in a small area in Bagrami district, where the water table rose about 2 m over the considered period. Rising groundwater level in Bagrami (Fig. 6) district is most likely to be as a result of recharge from the river and irrigation return-flows. Groundwater-level decline in the Kabul Plain has caused most shallow wells in the north-western and south-western parts of the study area to become dry (Zaryab et al. 2017; Saffi 2019).

Given the current situation, groundwater depletion will likely continue to grow in Paghman-Darulaman and Central Kabul aquifers. As shown in Fig. 2, Afshar and Alaudin well fields are located in Paghman-Darulaman aquifer and significant amounts of groundwater are annually discharged through Afshar and Alaudin public water supply wells (Landell Mills 2020a); besides, the western plain has witnessed a rapid and unplanned urbanization and a large number of private wells and private company water supply wells have been drilled in the Paghman-Darulaman aquifer in the recent years (Noori and Singh 2021a, b; Saffi 2019). It is worth noting that almost all deep wells (>150 m) in the Kabul Plain have been drilled in the Paghman-Darulaman and Central Kabul aquifers during the last decade. Overall, increasing water demands associated with rapid urbanization has led to overabstraction of groundwater, particularly in south-west Paghman-Darulaman and the north-western Central Kabul aquifers. Thus, withdrawals from Afshar and Alaudin well fields must be reduced and abstraction from Logar well field can be increased.

The most direct way to estimate the volume of water depletion from an aquifer is to integrate maps of water-level

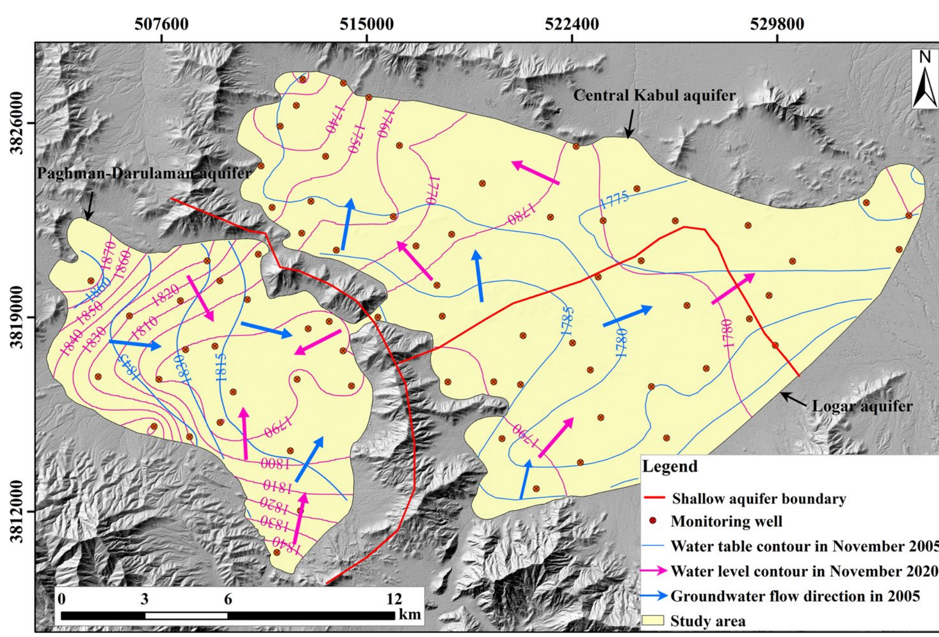

Fig. 5 Horizontal distribution of hydraulic head (meters below sea level) and groundwater flow directions in December 2004 and December 2020

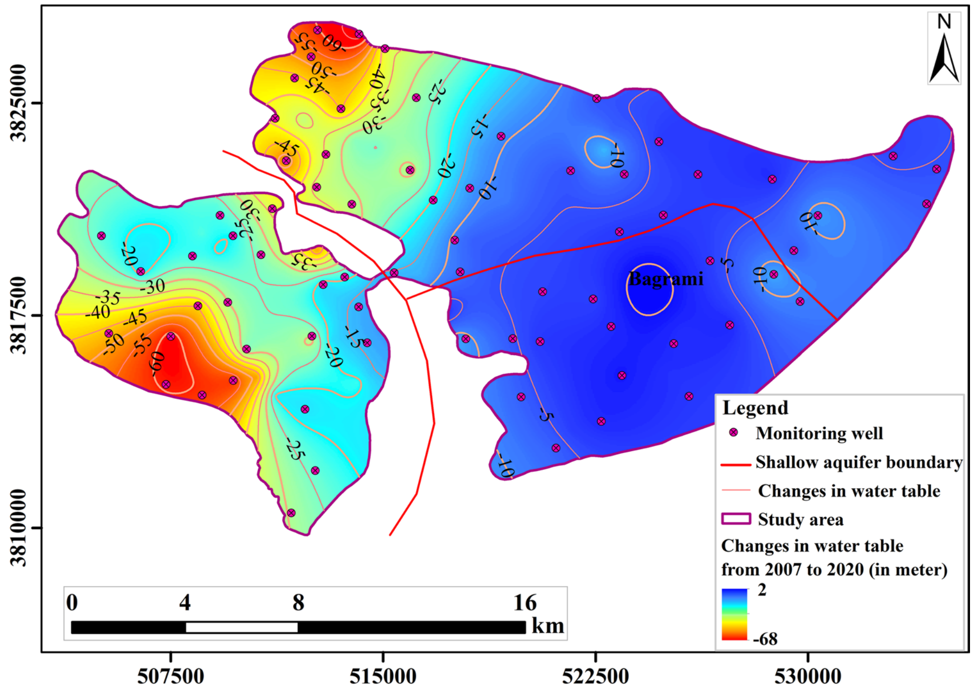

Fig. 6 Changes in groundwater level from November 2007 to November 2020

changes over the aquifer. The resulting aquifer volume is multiplied by the storage coefficient to compute the corresponding volume of water (Konikow and Kendy 2005). According to Fig. 5, the mean decline in groundwater level from 2007 to 2020 is around 16.5 m, the total area of the aquifer is 271 km^2 and the average specific yield of the aquifers is estimated to be 0.08. Thus, 358,000 million m^3 of water was lost from the Kabul aquifer over the considered period. Reducing groundwater reserves in the Kabul aquifers is directly associated with rapid urbanization in the Kabul Plain.

Rapid urbanization and overexploitation of groundwater in the Kabul Plain have adversely affected terrestrial and aquatic ecosystems. Kole Hashmat Khan wetland (Fig. 2) completely dried up as a consequence of extensive groundwater abstraction (Shroder and Ahmadzai 2016). Meldebekova et al. (2020) studied subsidence in the Kabul Plain and the results of their study indicate that the maximum vertical subsidence (–5.3 cm/year) has occurred in the south-western part of the western plain, where the groundwater level has rapidly decreased due to overexploitation. As mentioned earlier, rapid urbanization has altered the groundwater flow directions in Paghman-Darulaman and Central Kabul aquifers.

The components of natural groundwater recharge to the Kabul aquifers are presented in Table 1. The natural recharge was estimated using river discharge data, rainfall data and hydrogeological characteristics of the aquifers. According to the river discharge data, 587×10^6 m^3 water entered the Kabul Plain through Paghman, Kabul and Logar rivers during 2020. The infiltration from the river beds was roughly estimated at about 9% of the total amount of water entering the plain during 2020 (Houben et al. 2009b; Landell Mills 2020a).

Table 1 Components of estimated natural recharge to Kabul aquifer in 2020

Source of groundwater recharge	Volume (MCM/year[a])	Percentage of total natural recharge
Inflow from other basins	29.2	26.6
Recharge from precipitation	28.1	25.7
Infiltration from rivers	52.2	47.7
Total natural recharge (MCM/year)	109.5	100

[a]Million cubic meters

Rainfall data from six hydrometeorological stations that are located in the Kabul Basin were employed to establish a relationship between precipitation and elevation. Then groundwater recharge from precipitation was estimated through the relationship between precipitation and elevation considering the catchment area and soil characteristics. Inflow from other basins was calculated by employing a water-table map and Darcy's equation ($Q = TILt$). Where Q is the rate of flow through a cross-section of aquifer (L^3T^{-1}); T is the transmissivity (L^2T^{-1}); I is the hydraulic gradient (LL^{-1}); L is the length of flow path (L); and t time (T). According to Table 1, the main contribution to groundwater regeneration in the Kabul Plain comes from river-bed infiltration. Groundwater recharge rates from precipitation and inflow from other basins are relatively the same (Table 1).

Landell Mills (2020a) estimated that the annual average net abstraction from Kabul aquifers was 277 million m^3 in 2020. Therefore, the rate of groundwater abstraction is thus twofold higher than the rate of natural recharge; however, Saffi (2019) claims that withdrawals of groundwater from Kabul aquifers is six-fold faster than its recharge. Given the current situation, there is a significant imbalance between groundwater recharge and discharge in the Paghman and Central Kabul aquifers; thus, Paghman-Darulaman and Central Kabul aquifers are in crisis due to overexploitation associated with population growth and groundwater depletion, which will likely continue to grow in the future. Immediate actions are required to reverse the further depletion of groundwater resources and deterioration of groundwater quality in the plain; therefore, effective measures and integrated approaches for safeguarding the water supply should be implemented to decrease groundwater deterioration and increase groundwater recharge. Moreover, increasing groundwater recharge by using artificial recharge should be seriously taken into consideration.

To prevent further groundwater depletion in the Kabul aquifers, the quantity of groundwater exploitation should be limited to the amount of groundwater recharge. A comprehensive policy is required to be prepared and passed by national authorities for water allocation in the city of Kabul. The water user should pay a penalty price which may be threefold higher than the usual price for withdrawals above the prescribed norm. Moreover, some adjustments in industrial structures must be carried out to stop conflicts between water supply and demand—for instance, industries that consume large amounts of water such as mineral water factories, swimming pools, carpet washing and so forth, should be moved away from areas that suffer high aquifer depletion. Moreover, pipelines could be constructed to transfer water from water-rich areas to water-poor areas; thus, as mentioned earlier, supplying drinking water from Afshar and Alaudin well fields must be reduced and abstraction from Logar well field can be increased. Groundwater should be used only for drinking and domestic applications in higher-depletion areas. All high water-consuming crops such as potato and cucumber can be imported from other places and the cultivation of these products should be stopped in the Kabul Plain. Mineral water factories should be moved away from the Kabul Plain and other large water-consuming factories such as swimming pools, and carpet and car washing facilities should be moved away from high-aquifer-depletion areas. Moreover, irrigation water-use efficiency measures should be improved in the region. In addition, there are some potential water resources within the Kabul Basin that could be used (JICA 2011; Zaryab et al. 2017; Saffi 2019; Noori and Singh 2021a) such as the Maidan River (Shatood Dam), Panjshir River, Salang River and the Panjshir fan aquifer. Supplying water from these resources may reduce the stress on the Kabul aquifers.

Managed aquifer recharge (MAR) can be employed as an adaptation method to meet the increasing future water demands and retrieve the groundwater level. A pilot MAR project was carried out in the city of Kabul by Landell Mills and DACAAR between 2017 to 2020 (Landell Mills 2020b). The outcomes of this pilot MAR project indicate that groundwater levels have been raised locally in the Kabul aquifer. Thus, implementing such projects may reduce stress on the Kabul aquifer. Since the recharge water is not accessible in all four seasons in the region, the MAR project could be efficient in rainy seasons at least.

Additionally, rainwater and runoff harvesting through recharge pits, recharge trenches and recharge wells can be used for groundwater recharge of Kabul aquifer during rainy seasons (Hussain et al. 2019; Noori and Singh 2021a). It should be noted that harvested rainwater should firstly be used to alleviate water shortages in the households and only secondly to recharge the aquifer. The responsible organizations must apprise the importance of rainwater harvesting for Kabul's inhabitants.

Hydrochemical evolution

The statistical parameters of the groundwater samples collected in the Kabul aquifers between July and November 2004 and in November 2020 are shown in Table 2. The pH of groundwater in the Kabul aquifers in both sampling periods was in the neutral range. The average temperature of the groundwater samples was the same in both sampling periods. The results for dissolved oxygen (DO) show that groundwater was predominantly oxic in both sampling periods. The electrical conductivity (EC) ranged from 497 to 15,290 $\mu S\ cm^{-1}$ and from 618 to 61,400 $\mu S\ cm^{-1}$ in 2004 and 2020, respectively. The highest EC values (12,000 $\mu S\ cm^{-1}$ and 16,400 $\mu S\ cm^{-1}$) were observed at sampling points 166.2 in 2004 and W15 in 2020, respectively. About 73% of groundwater samples gathered during 2004 had EC above 1,000 $\mu S\ cm^{-1}$, whereas 82% of the water samples collected in November 2020 have EC above 1,000 $\mu S\ cm^{-1}$. This could mean that groundwater salinity has steadily increased over time, and it might be a consequence of population growth and overabstraction. The majority of groundwater samples from Central Kabul and Logar aquifers exhibited brackish to moderately saline-water facies, while almost all groundwater samples from Paghman-Darulaman aquifer displayed freshwater facies. Table 2 indicates wide range of EC values, which could be due to the presence of evaporitic lacustrine deposits in the Central Kabul aquifer (Zaryab et al. 2021). The common dominance of cations was $Mg^{2+} > Ca^{2+} > Na^+ > K^+$, while the dominance of

Table 2 Statistical summary of the physical and chemical results for sampling points in the Kabul aquifers. *SD* standard deviation

Parameter	Unit	July–November 2004				November 2020			
		Min	Mean	Max	SD	Min	Mean	Max	SD
pH	-	6.94	7.50	8.37	0.3	7.00	7.60	8.10	0.23
T	ºC	10.90	15.50	21.60	1.90	6.00	15.40	17.80	2.10
DO	mg/L	0.4	7.10	14.90	3.40	2.10	5.25	9.60	1.88
EC	µS/cm	497	1760.7	12,000	8.37	618.0	1640.0	16,400	3149.1
Ca^{2+}	mg/L	35.00	81.50	334	51.80	20.50	76.65	362.7	63.70
Mg^{2+}	mg/L	6.60	92.0	590.0	104.80	12.30	82.40	684.00	139.4
Na^{+}	mg/L	14.60	145.40	1630.0	244.30	20.50	94.15	3014.0	567.8
K^{+}	mg/L	2.00	8.30	31.60	5.50	2.16	7.05	74.00	14.0
HCO_3^-	mg/L	102.5	402.2	651.10	141.60	183.0	429.9	840.0	173.4
Cl^-	mg/L	8.20	208.9	2750	3030.0	7.30	135	3997	838.6
SO_4^{2+}	mg/L	16.1	233.8	3030	492.00	19.80	114	4573	988.4
NO_3^-	mg/L	1.0	31.0	182	33.20	3.98	13.72	120.41	21.0

anions was $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$ in both sampling periods.

The major ion contents of groundwater samples collected between July and November 2004 and in November 2020 are illustrated on a Piper diagram (Fig. 7). Ca–HCO_3 was the dominant water type, followed by Ca–(Mg, Na)–HCO_3–(Cl) in the Paghman-Darulaman aquifer. Mg–(Ca, Na)–HCO_3 was the major water type in the Central Kabul and Logar aquifers, followed by Mg–(Na)–Cl–(SO_4), Na–(Mg)–SO_4–(Cl), Na–Cl, and Mg–Cl water types.

In order to evaluate the effects of urbanization on groundwater quality in the Kabul aquifer, the results of EC, chloride and nitrate analyses from 2004 and 2020 were considered. The maps of changes in EC values, and chloride concentrations from November 2004 to November 2020, are illustrated in Fig. 8a,b. The locations of the sampling points are not the same in both sampling periods, although the authors believed that the maps can fairly well illustrate the real hydrochemical conditions from local hydrogeological prospects.

The comparisons between groundwater-level fluctuations and overall changes in electrical conductivity and chloride concentrations indicate that EC and chloride concentrations have progressively increased across the plain over the considered period, except for sampling point 166.2. Considerable increase in EC values and chloride concentrations in groundwater may be due to rapid urbanization, because chloride is added to groundwater resources through domestic and industrial wastes as well as agricultural activities. The increase in salinity in the Kabul aquifers is due to overexploitation and unsustainable groundwater resources management in the Kabul Plain.

Figure 9 shows the changes in nitrate concentrations from 2004 to 2020. According to Fig. 9, nitrate concentrations have remarkably decreased over the considered time in most places of the Kabul Plain, particularly in heavily populated areas. Figures 6 and 9 show a positive correlation between groundwater-level decline and decreasing nitrate concentrations over time, indicting the natural attenuation of nitrate pollution as water moves through the aquifers (Kendall et al. 2007). Nitrate concentrations have slightly increased in small areas of the Central Kabul and Logar aquifers. The land use maps (Fig. 4a,b) show that the greater part of the plain is made up of urban area, and point sources of nitrate pollution such as pit latrines, septic systems and wastewater storage facilities, were dominant as compared to nonpoint sources of nitrate in the plain; however, evaluating the point sources of nitrate pollution in an aquifer is difficult and requires more detailed study.

Higher NO_3^- concentrations are often the result of anthropogenic activities associated with excessive use of chemical fertilizers and manure by agriculture, sewage waste and urban solid waste landfills (Kendall 1998; Ogrinc et al. 2019; Nejatijahromi et al. 2019). About 83% of the groundwater samples taken in 2004 and 70% groundwater samples in 2020 showed nitrate concentrations exceeding 2.5 mg L^{-1} as NO_3^-–N, the threshold considered as a result of human activities (Panno et al. 2006). On the other hand, about 15% of groundwater samples taken in 2004 and 6% of the groundwater samples in 2020 showed nitrate concentrations above the threshold value (50 mg L^{-1}) as determined by the World Health Organisation (WHO 2017). This highlighted the considerable influence of anthropogenic NO_3^- inputs on groundwater quality in the Kabul aquifers. Houben et al. (2009a) claim that high infant mortality in heavily populated areas of Kabul is most likely partially due to the contaminated groundwater. High levels of NO_3^-–N (>10 mg L^{-1}) in drinking water can cause 'blue baby syndrome' in infants (methemoglobinemia; Fan and Steinberg 1996; Gulis et al. 2002; Fewtrell 2004).

The city of Kabul has no centralized sewerage system and suffers from an ineffective sewage network (Wafa

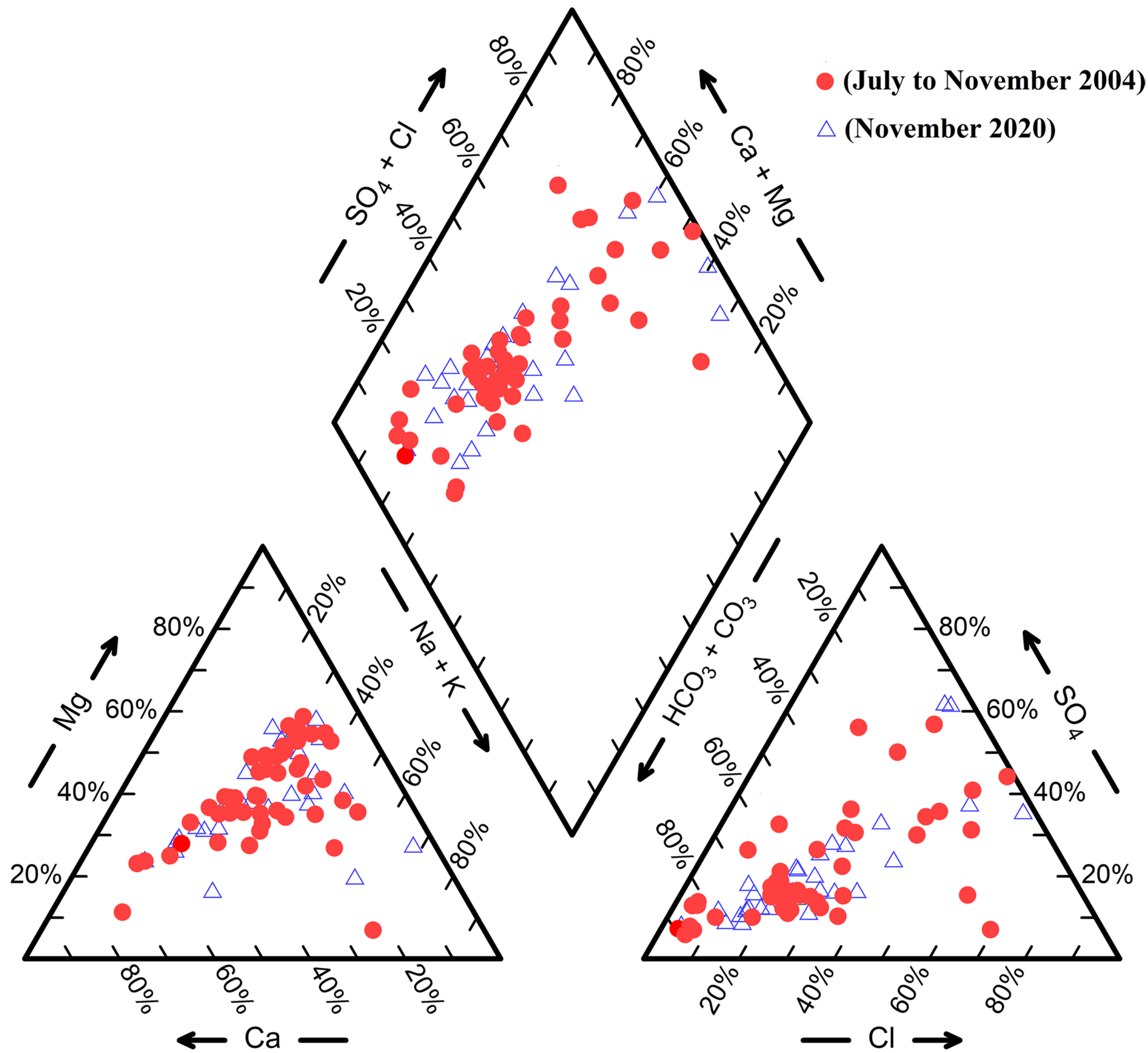

Fig. 7 Piper diagram of groundwater samples from the Kabul aquifers collected during July and November 2004 and November 2020

et al. 2020; Mahaqi et al. 2021). Sewage collection and wastewater treatment plants operate only at small scale (Paiman and Noori 2019; Noori and Singh 2021a); thus, sewage waste might be the main source of nitrate in groundwater of the Kabul aquifers. Land-use information and field observations also confirm that sewage is the dominant source of nitrate in the aquifers. Overall, rapid urbanization has caused groundwater resource degradation in the Kabul Plain in terms of both quantity and quality.

Conclusions

Kabul Plain witnessed rapid urbanization since the end of 2001. Groundwater is the primary source for domestic, agricultural, and industrial usages in the region. The findings indicate that Kabul's groundwater resources have declined much faster than they have recovered over the considered period. The analyses show that the Kabul Plain has experienced rapid changes in LULC, particularly in

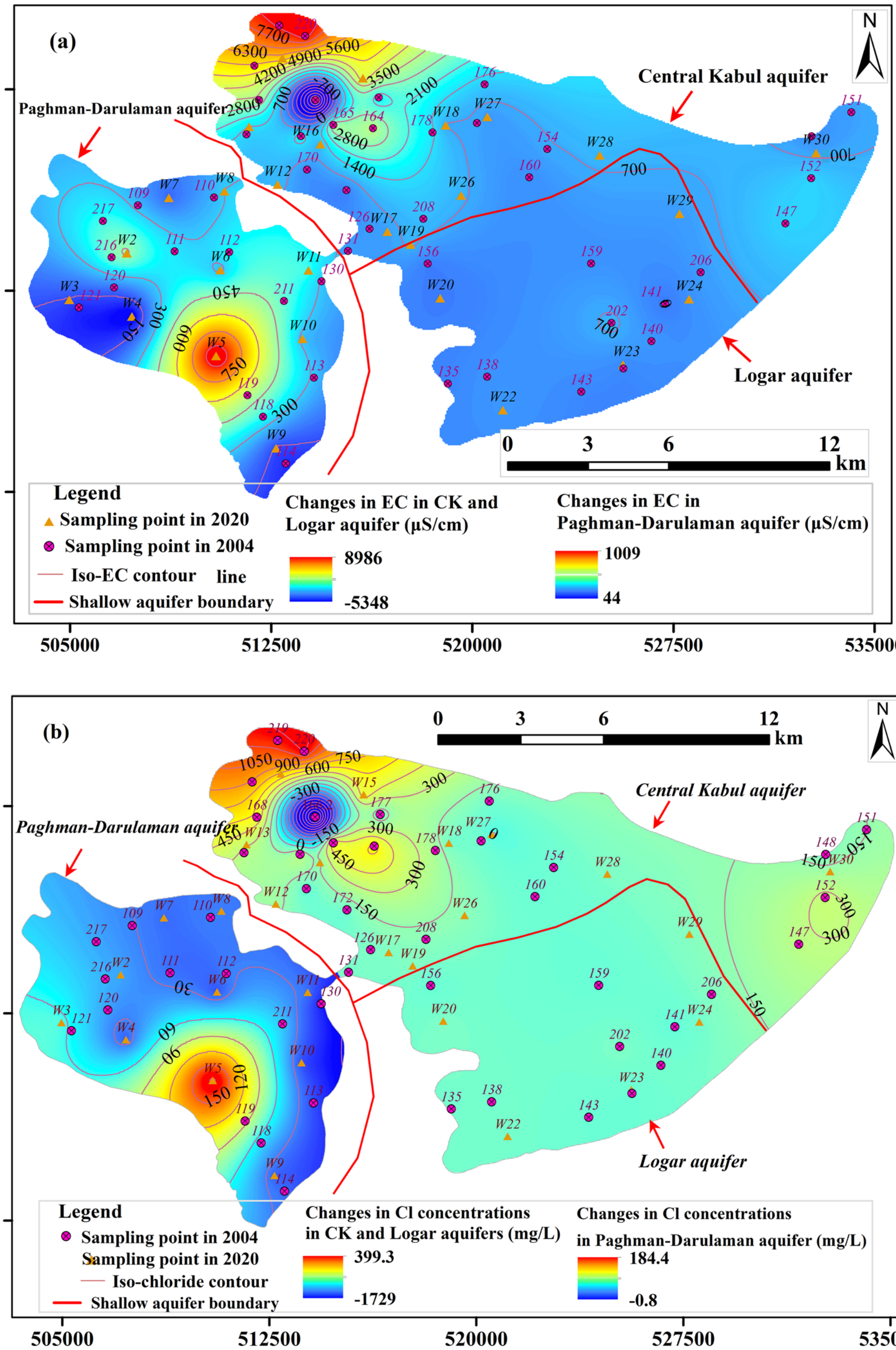

Fig. 8 **a** Changes in electrical conductivity (EC) from November 2004 to November 2020, **b** changes in chloride concentrations from November 2004 to November 2020

respect to built-up areas. Increased abstraction of groundwater in the Kabul Plain has been a direct consequence of increased water demand associated with population growth, as well as significant land-use change. Since 2005, most parts of the Kabul shallow aquifers have experienced an average water-table decline of –0.8 m/year due to overexploitation associated with rapid urbanization. Additionally, groundwater flow directions have also locally changed in the Paghman-Darulaman and Central Kabul aquifers. On the other hand, the results of hydrochemical analyses reveal that chloride concentrations and salinity have been elevated in almost all places of the Kabul aquifers, while nitrate concentrations have considerably decreased over the 15-year study period. There was an overall positive correlation between decreasing nitrate concentrations and the declining water table, indicating that the natural attenuation of nitrate was occurring in most parts of the aquifer system. The study indicates that the groundwater abstraction is more than twofold higher than the rate of natural recharge across the aquifers over the 15-year study

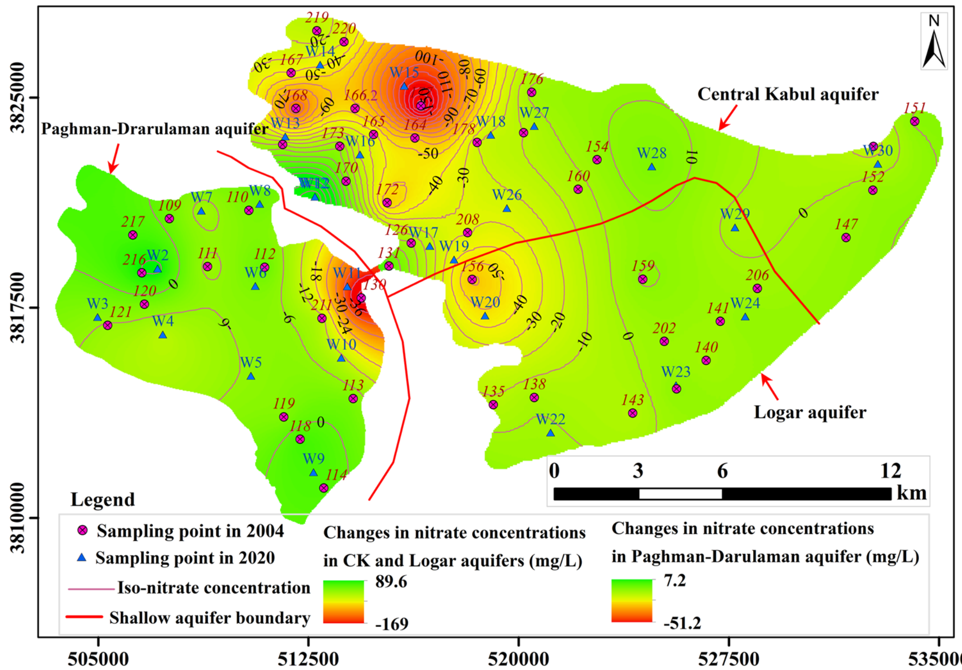

Fig. 9 Changes in nitrate concentrations in groundwater of the Kabul aquifers from 2004 to 2020

period. However, nitrate concentration decreased where the maximum groundwater level declines, which has led to remarkable groundwater resource depletion, manifested by dried-up wells in most parts of the plain as well as dried wetland. The findings clearly reveal that extensive groundwater depletion in Kabul Plain is largely due to anthropogenic factors. Given the current situation, groundwater depletion is likely to rapidly continue in the future, particularly in densely populated areas of the city. Finally, the Kabul residents are faced with serious water shortages in the near future if suitable actions are not initiated at this stage. Overall, this study highlights the urgent need for sustainable development and management of groundwater resources by ensuring sufficient recharge of the aquifer to accommodate the sharp decline in groundwater levels due to rapid urbanization and potential impacts of changes in rainfall patterns. This report apprises the decision-makers and stakeholders of the effect of rapid unplanned urbanization on the groundwater quality and quantity of the Kabul aquifer. This article is of particular importance being the first study in Afghanistan (to the authors' knowledge) to study the impacts of rapid urbanization on the aquifer system.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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