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Assessment of Groundwater Dynamics in the Kabul Basin: Implications for Sustainable Management

Nematullah Hasani[1], Farhad Hajian[2], Abbas Ali Ghezelsofloo[3], Ali Haji Elyasi[4], Mobin Eftekhari[5*]

1- Department of Civil Engineering, Water and Hydraulic Structures, Mashhad Branch, Islamic Azad University, Mashhad, Iran.
2- Department of Civil Engineering, Neyshabur Branch, Islamic Azad University, Neyshabur, Iran.
3- Department of Civil Engineering, Mashhad Branch, Islamic Azad University, Mashhad, Iran.
4- Department of Civil Engineering, College of Engineering, University of Tehran, Tehran, Iran.
5- Department of Water Engineering, University of Birjand, Birjand, Iran.
*** corresponding author: mobineftekhari@yahoo.com**

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Abstract

Groundwater, particularly from aquifers in Afghanistan's arid and semi-arid eastern basin, has long served as a primary water source for industry, agriculture, and domestic use. However, population growth and recurrent droughts, along with insufficient planning, have led to a troubling trend of over-extraction in recent decades. Effective groundwater management focusing on controlled extraction that aligns with aquifer capacity, is essential for long-term sustainability. This study employs ArcGIS software to assess quantitative and qualitative shifts in groundwater dynamics within the Kabul Basin. Data from 54 wells, monitored at various intervals from 2005 to 2020, were meticulously analyzed, incorporating geological, climatic, and hydrological parameters. The findings reveal significant fluctuations in groundwater levels, with an average decline of 16.5 meters over the 13-year study period. The groundwater level decreased by 12 meters in some parts of the Kabul aquifers, at a rate of 80 centimeters per year. Particularly in the Paghman-Darulaman and central Kabul aquifers, we observed alterations in flow distribution patterns. Water quality parameters also changed, with 82% of samples collected in November 2020 showing electrical conductivity values greater than 1,000 µS/cm, compared to 73% in 2004, indicating increasing salinity. The total groundwater storage loss in the Kabul aquifer during the study period was estimated at 358 million cubic meters. Groundwater consumption in 2020 was approximately 277 million cubic meters, twice the natural recharge rate. Future projections indicate an accelerated depletion of groundwater reserves, especially in densely populated urban regions like Kabul, necessitating immediate intervention to avert impending water scarcity crises.

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Introduction

Groundwater is a crucial component of the world's dynamic and renewable water resources, playing a vital role in the water cycle and serving as a reliable reserve during critical periods, making it an essential strategic resource (Pereira et al., 2009). Given the constant and renewable nature of groundwater, its preservation is of utmost importance. However, human activities are increasing environmental pollution, exposing groundwater to various contaminants. Understanding the potential impacts of human activities on groundwater quality has become increasingly important for its sustainable use and extraction (Mouser & Rizzo, 2004; Eftekhari et al., 2024). Water scarcity is an escalating global challenge, particularly acute in arid and semi-arid regions where groundwater often serves as the primary water source for urban, agricultural, and industrial needs. The Kabul Basin in Afghanistan exemplifies this critical issue, where rapid urbanization and population growth have placed unprecedented pressure on groundwater resources (Zaryab et al., 2022). As the capital city's population surged from approximately 1 million in 2001 to 5.3 million in 2021, the demand for water has intensified, leading to overexploitation of aquifers and subsequent environmental concerns (Manawi et al., 2020).

The sustainability of groundwater resources is intricately linked to the delicate balance between extraction rates and natural recharge. However, in many urban areas worldwide, this balance has been disrupted by human activities. Kabul, like other rapidly expanding cities in water-stressed regions, faces the dual challenge of meeting increasing water demands while preserving its groundwater resources for future generations. This situation is further complicated by climate change, which alters precipitation patterns and potentially impacts groundwater recharge rates (Hussaini et al., 2021; Khodabandeh Baygi et al., 2023).

Understanding the quantity and quality of groundwater resources is crucial for maintaining and optimally managing water supplies, especially during droughts and periods of water scarcity. Groundwater pollution is of greater concern than surface water pollution because the time between the onset of contamination and the manifestation of its effects can span several years. As a result, identifying and addressing the source of contamination is often costly and time-consuming (Ibrahim et al., 2010; Dehkordi & Pourmoghaddas, 2006). While some pollutants, such as agricultural waste, are biodegradable and can be reduced relatively easily, others, like heavy metals (e.g., cadmium, lead, and arsenic), are non-biodegradable and highly toxic. A critical issue with heavy metals is their inability to be metabolized by the body (Hadizadeh et al., 2009). Once heavy metals enter the body, they are not excreted but accumulate in tissues such as fat, muscles, bones, and joints, leading to various diseases and adverse health effects. Neurological disorders, various cancers, and, in severe cases, death are among the potential outcomes of heavy metal exposure. Moreover, the accumulation of heavy metals in plants and their entry into the food chain exacerbate the associated risks (Karbasi and Bayati, 2001).

The reduction of groundwater levels and the deterioration of water quality due to over-extraction beyond the capacity of aquifers not only have negative environmental impacts but also diminish livelihood opportunities in the region. Additionally, uncontrolled withdrawals can lead to land subsidence, which has garnered the attention of regional officials (Ranjbar & Jafari, 2009). Given that protecting water resources and ensuring their sustainable performance is cost-effective, water resource management and planning should be prioritized in each region (Valayati, 2002). Groundwater recharge and levels are influenced by various factors, including cropping patterns and their intensity, irrigation methods, climatic parameters (such as precipitation frequency and intensity, temperature, evaporation, and transpiration), and soil hydraulic properties, such as hydraulic conductivity (Hajian, 2021). In recent years, several studies have highlighted the growing concerns regarding groundwater depletion and contamination in urban areas. For instance, Manawi et al. (2020) investigated urban flooding in Kabul, emphasizing the interconnection between surface water management and groundwater recharge. Hussaini et al. (2021) focused on site selection for managed aquifer recharge in Kabul, addressing the need for artificial recharge to combat groundwater depletion. (Tani & Tayfur, 2021) evaluated the groundwater potential zones in the Kabul River Basin, Afghanistan, using GIS and AHP. The results show that the very good potential zones are mainly located in the downstream and central parts of the basin, while only 18% of the annual precipitation recharges the groundwater. (Hilal et al., 2024) employed GIS, AHP, and remote sensing to assess groundwater potential in the Moulouya Basin, using seven parameters including drainage density, lithology, and precipitation. The area was classified into five zones of groundwater potential, with 26% very high and 51% high potential. The model's accuracy was validated using 96 well/borehole data points, achieving a high correlation coefficient, with 89.5% of boreholes located in high and very high potential zones.

These studies underscore the urgency of comprehensive groundwater management in rapidly urbanizing regions. However, there remains a significant knowledge gap in understanding the long-term quantitative and qualitative changes in groundwater resources in the Kabul Basin, particularly in relation to rapid urbanization and climate variability. Previous studies have not fully integrated spatial and temporal analyses of groundwater level fluctuations with water quality parameters over an extended period, nor have they comprehensively assessed the impact of land-use changes on groundwater dynamics in this region.

Our study aims to bridge this gap by employing an innovative approach that combines GIS-based spatial analysis with long-term temporal data to provide a holistic assessment of groundwater resources based on quantity and quality of water in the Kabul Basin. Specifically, this research:

- Analyzes groundwater level fluctuations and flow distribution patterns from 2005 to 2020 using data from 54 wells.
- Assesses changes in water quality parameters, focusing on electrical conductivity, nitrates, and other key indicators.
- Quantifies the impact of land-use changes, particularly urbanization, on groundwater recharge and quality.
- Estimates the current groundwater balance and projects future trends under various scenarios.

By integrating these multiple facets, our study provides a more comprehensive understanding of the groundwater system in the Kabul Basin than previous research. This approach allows for a nuanced analysis of the interplay between urbanization, climate variability, and groundwater dynamics, offering valuable insights for sustainable water resource management in rapidly developing urban areas.

The findings of this study have significant implications for water resource management policies in Kabul and similar urban areas in arid and semi-arid regions. By identifying critical areas of groundwater depletion and quality degradation, this research can inform targeted interventions and sustainable management strategies, contributing to long-term water security in the region.

Materials and Methods

As previously mentioned, this research aims to monitor the spatial quantitative and qualitative changes in groundwater within the Kabul basin, investigating the impact of excessive exploitation and groundwater level decline on its quality, particularly focusing on salinization, nitrate levels, and heavy metal contamination. To gather the necessary data for assessing groundwater level decline and its effects on quality, information on the average groundwater depth is first collected. Groundwater depth measurements are then taken from selected observation wells within the aquifer zone to create a long-term variation graph of the groundwater table and absolute groundwater levels. Additionally, the electrical conductivity of the groundwater is measured over a specific period to prepare a hydrograph.

Sampling is conducted using standard methods, and laboratory analysis is performed to evaluate the data. The data collected includes various groundwater quality parameters, such as calcium, electrical conductivity, salinity, pH, magnesium, dissolved salt concentrations, water hardness, sodium, nitrate, potassium, sulfate, fluoride, chloride, total dissolved solids, iron, manganese, copper, aluminum, cyanide, alumina, and dissolved oxygen levels in the wells. Finally, the aquifer is simulated in both quantitative and qualitative aspects, with the input and output balances of surface and groundwater in the Kabul basin plotted. Management solutions are then proposed to address and control critical conditions.

Study Area

Kabul, the capital of Afghanistan, is situated in the central part of the Kabul River basin, which forms a smooth alluvial plain dating from the Neogene to the Quaternary periods. This area is commonly referred to as the “Kabul Basin.” Located in eastern Afghanistan, the Kabul River basin lies between approximately 34°31’ north latitude and 69°12’ east longitude, with a total drainage area of 375 square kilometers (Hussaini et al., 2021). The basin’s average elevation is about 1,800 meters above sea level, with prominent mountain ranges including Paghman, Qurugh, Shir Darwaza, Wais-e-Qarni, and Safi. The Kabul River and its tributaries flow through this region. Kabul is characterized by a continental climate. Although recent weather data are scarce, historical data recorded by the World Meteorological Organization from 1956 to 1983 indicate that the average temperature in January was as low as -7.1°C, while the average temperature in July exceeded 32.1°C, with an annual rainfall of less than 500 millimeters (Zaryab et al., 2022). Geological structures in this region include anticlines, synclines, hills, and faults. As the most populous city in Afghanistan, Kabul’s population growth may necessitate increased water resources for drinking and food production.

The Kabul basin consists of three interconnected aquifers with thicknesses ranging from 20 to 70 meters. The study area extends from a Neogene alluvial basin to the Quaternary period. Groundwater in the basin is replenished by three main rivers. The aquifer’s raw materials have high permeability and infiltration capacity. In the deeper parts of the aquifer, semi-diagenetic conglomerate rocks have formed due to the high density of space, reducing the voids and internal connections, which in turn decreases well water production. The primary groundwater recharge occurs after snowmelt, primarily through direct absorption from the rivers (Hussaini et al., 2021). The geological map and geographical location of the study area are shown in Fig 1.

The northern margin of the Kabul basin consists of Paleoproterozoic metamorphic rocks such as gneiss and schist. The mountains on the southern edges are mainly composed of Neoproterozoic and Mesozoic metamorphic rocks, along with sedimentary rocks like limestone and dolomite. The basin is surrounded by mountain ranges, with its lower part consisting of various metamorphic rocks such as amphibolite, quartzite, slate, and marble (Zaryab et al., 2022). A digital elevation model (DEM) map showing the elevation of the study area is provided in Figure 1. The DEM map, with a resolution of 30 meters, was downloaded from the USGS public geospatial data portal and clipped using ArcGIS.

Two important rivers enter the study area, playing a critical role in the water balance. The Kabul River flows from west to east, joining various tributaries before eventually reaching the Indus River in Pakistan. One of its main tributaries, the Logar River, drains the Logar Valley watershed in the south, covering about 10,000 square kilometers. The confluence of these two rivers occurs in the center of the Kabul Basin, within the city of Kabul.

Study Procedure

In general, this study is divided into three parts, in each part steps have been taken to reach the main goal. These three steps include the following:

a) Preparation of Base Maps:

Initially, base maps of the Kabul basin were created, covering aspects such as geology, topography, slope, surface runoff, thickness of the unsaturated zone, permeability, soil type, land use, waterways, residential areas, contour lines, and quality parameters. These maps were developed using geographic information systems (ArcGIS) by inputting the necessary data into the software.

b) Collection of Well Data:

At this stage, data from piezometer wells and water observations in the Kabul basin, provided by the Ministry of Energy and Water, were collected. To assess changes in groundwater levels and elevations in the study area, 54 selected piezometer wells from the groundwater monitoring network were used. Recorded values and groundwater elevations were collected for each well.

c) Data Analysis for Plotting Relevant Graphs and Maps

Quantitative geophysical maps, including contour lines of the groundwater table in the basin, were prepared and compared with well depths and aquifer capacity, which are represented as points with

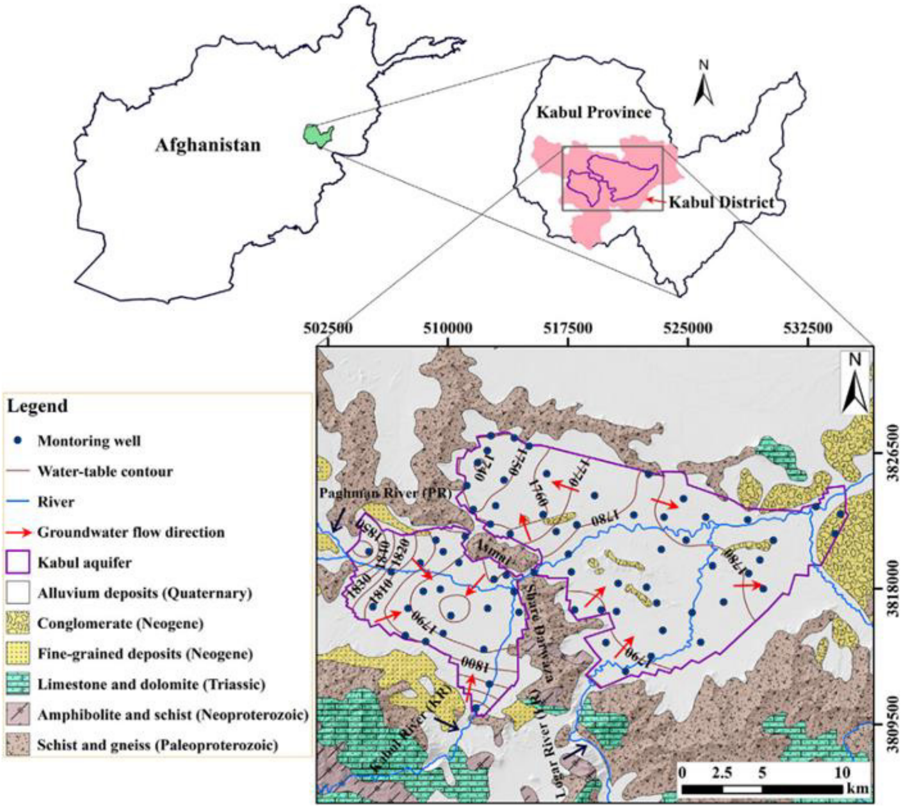


Fig 1. Geological map and location of the study area (Zaryab et al., 2022)

the same groundwater level. Qualitative isochemical maps were generated based on 2020 statistics for water quality parameters in the Kabul basin's groundwater table, provided by the Ministry of Energy and Water. These were compared with research results obtained in 2004. The framework for conducting the research is illustrated in the following figure (Fig 2).

Effective Criteria in Groundwater Recharge

In this study, four criteria were considered that these effect on groundwater recharge. These criteria are the data used in this study. Each of them is described below. It should be noted that these data are obtained from reports or through GIS software. The spatial distribution of these criteria is illustrated in Figure 3, which includes maps of slope, surface infiltration rate, drainage density, and the thickness of the unsaturated zone. These maps provide a comprehensive overview of the study area's suitability for groundwater recharge.

Slope

Slope is a critical factor in classifying potential groundwater recharge areas. Higher slopes lead to faster water flow and increased erosion, reducing the potential for groundwater recharge (Hussaini et al.,

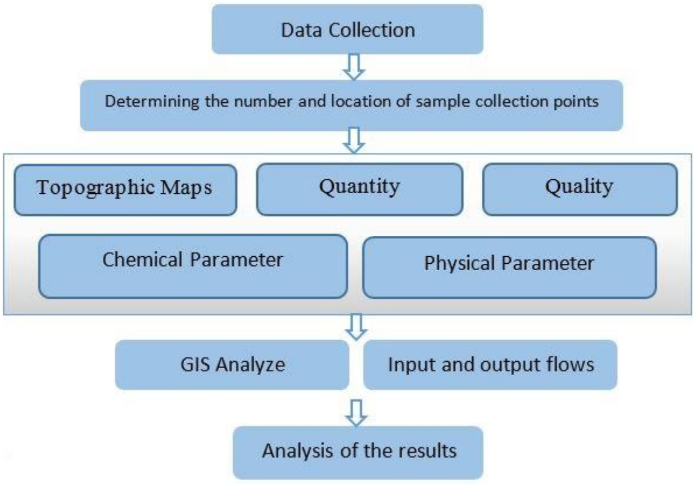


Fig 2. Proposed flow diagram of the modeling procedure and steps in the current steps

2021). In contrast, sedimentary basins, floodplains, and low-lying flat areas are more conducive to groundwater recharge due to the longer travel time of water to downstream locations, allowing sufficient time for infiltration into the soil.

A slope map for the study area was generated using spatial analysis tools in ArcMap software, utilizing DEM data with a cell size of 30 meters and a pixel depth of 16 bits. Based on previous studies, areas with slopes greater than 10% are considered unsuitable for groundwater recharge. Consequently, the slope map was categorized into two main classes: 0-10% (suitable area) and greater than 10% (unsuitable area). The suitable range (0-10%) was further divided into three subcategories. In the study area, the slope ranges from 0% to 31%, and the complete slope map was classified into four classes: 0-2%, 2-5%, 5-10%, and greater than 10%. The majority of the study area falls within the 0-2% and 2-5% subcategories, with some areas of higher slopes around the hills within the study area.

Surface Infiltration Rate

The surface infiltration rate is crucial for groundwater recharge, as it determines the extent to which rainfall and surface water contribute to replenishing groundwater. Areas with high surface infiltration rates are considered suitable for groundwater recharge. In this study, no field measurements were available for this criterion. Consequently, the surface infiltration rate for the study area was derived using the relationship between soil texture and water infiltration rate as proposed by the Food and Agriculture Organization (FAO, 1979; Ghayomian et al., 2007). A soil surface infiltration rate map was produced and classified using ArcGIS software. The map was divided into four classes to assess the suitability of areas for groundwater recharge: unsuitable (less than 15 mm/hr), moderate (15-25 mm/hr), suitable (25-45 mm/hr), and very suitable (greater than 45 mm/hr).

Drainage Density

Drainage density is a measure of the total length of stream channels per unit area within a watershed (Shroder & Ahmadzai, 2016). It is typically calculated by dividing the total length of the channels by the area of the watershed, yielding a value for drainage density. Drainage density is inversely proportional to permeability (Carlston, 1963). High drainage density suggests favorable conditions for surface water flow, but it also indicates a lower potential for groundwater recharge. The drainage density (in kilometers per square kilometer) was calculated using the following equation:

$$DD = (\sum Li)/A \qquad (1)$$

Where (Li) represents the total length of all stream channels in kilometers, and (A) is the area of the study region in square kilometers (Hussaini et al., 2021)

A drainage density map for the area was created using spatial analysis tools in ArcGIS, based on the digital elevation model (DEM) of the region. This map was classified into four categories for groundwater recharge assessment: 0-0.5 (very suitable), 0.5-1.5 (suitable), 1.5-2 (moderate), and greater than 2 (unsuitable). The drainage density in the area ranges from 0 to 4.6 kilometers per square kilometer.

It’s important to note that while drainage density was considered in the analysis, its impact on selecting suitable groundwater recharge sites is limited. This is because the study area is urbanized, and urbanization has altered the natural drainage network, reducing the relevance of this criterion. Therefore, it was assigned a low level of importance.

Urban flooding is a significant challenge in the northern part of Kabul city. In recent years, heavy rainfall has led to frequent urban flooding, primarily due to excessive rainfall combined with inadequate drainage systems. This problem is further exacerbated by unsustainable urban expansion, changes in the catchment area, and an increase in impermeable surfaces. Over the decades, Kabul’s drainage infrastructure has not kept pace with population growth, leading to a higher frequency of urban flooding (Manawi et al., 2020).

Thickness Of Unsaturated Zone

In areas where the water table is near the surface and groundwater is not being extracted, recharge can cause the water table to rise, potentially resulting in marshland formation. In other words, if the natural underground reservoir has limited storage capacity, successful recharge is less certain (Mahdavi et al., 2010). Therefore, the thickness of the unsaturated zone—the distance from the ground surface to the water table—is a critical factor in identifying suitable sites for groundwater recharge.

In this study, water-table depth measurements were collected from 100 observation wells. An interpolated map of the unsaturated zone thickness was then created using the inverse distance weighting (IDW) method. This map illustrates the variation in unsaturated zone thickness across the study area. According to previous research, groundwater recharge is unlikely to be successful if the thickness of the unsaturated zone is less than 10 meters. However, sites with an unsaturated zone thickness greater than 10 meters are considered suitable for recharge. The map was classified into four categories based on suitability for groundwater recharge: very suitable (>30 m), suitable (20–30 m), moderate (10–20 m), and unsuitable (0–10 m).

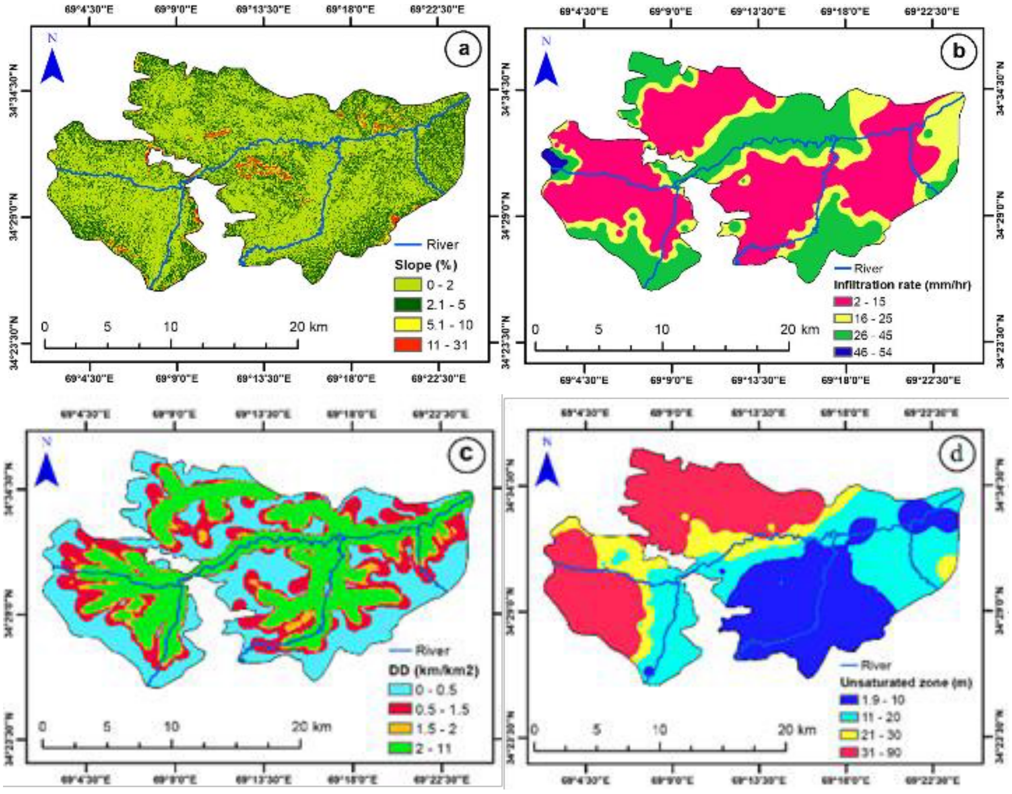


Fig 3. Maps of effective groundwater criteria: a) Slope, b) Surface infiltration rate, c) Drainage density, d) Unsaturated zone.

Results and Discussion

This section presents the results of our comprehensive analysis of groundwater dynamics in the Kabul Basin from 2005 to 2020. The analysis includes quantitative changes in groundwater levels, alterations in flow patterns, shifts in water quality parameters, and the impacts of land use changes on the basin’s hydrology. We utilized data from 54 wells, monitored at various intervals, and integrated geological, climatic, and hydrological parameters to provide a comprehensive overview of the groundwater system’s evolution over the study period. The findings are detailed through statistical analyses, spatial mapping, and temporal trend assessments, offering insights into the complex interactions between natural processes and anthropogenic influences on the basin’s groundwater resources.

Changes in Groundwater Level

The hydrograph indicates a continuous decline in groundwater levels within the basin (Figure 4). This decline can be divided into two distinct periods: 2005-2011 and 2011-2020. During 2005-2011, the groundwater level decreased slowly, but this decline accelerated significantly from 2011 to 2020. Figure 4 illustrates that the groundwater level has notably dropped across most of the basin, particularly in the northwestern part of the Central Kabul aquifer and in the Paghman-Darulaman aquifer in the southeast.

The hydrograph reveals that, in some areas of the Kabul aquifers, the groundwater level has decreased by up to 12 meters (at a rate of 80 centimeters per year) over the past 15 years (2005-2020). The rate of decline has markedly increased since 2011, likely due to factors such as population growth, changes in precipitation patterns, and urban expansion. Since late 2001, Kabul city has experienced rapid population growth, with the population rising from approximately 1 million in 2001 to 5.3 million in 2021 (Afghanistan Public Policy Research Organization, 2012; National Statistics and Information Authority, 2021). Currently, more than 70% of the population resides in unplanned settlements (Barbe, 2013). During the study period, the Heshmat Khan wetland—the last remaining marsh in the Kabul basin—and a significant number of shallow wells have dried up due to overexploitation.

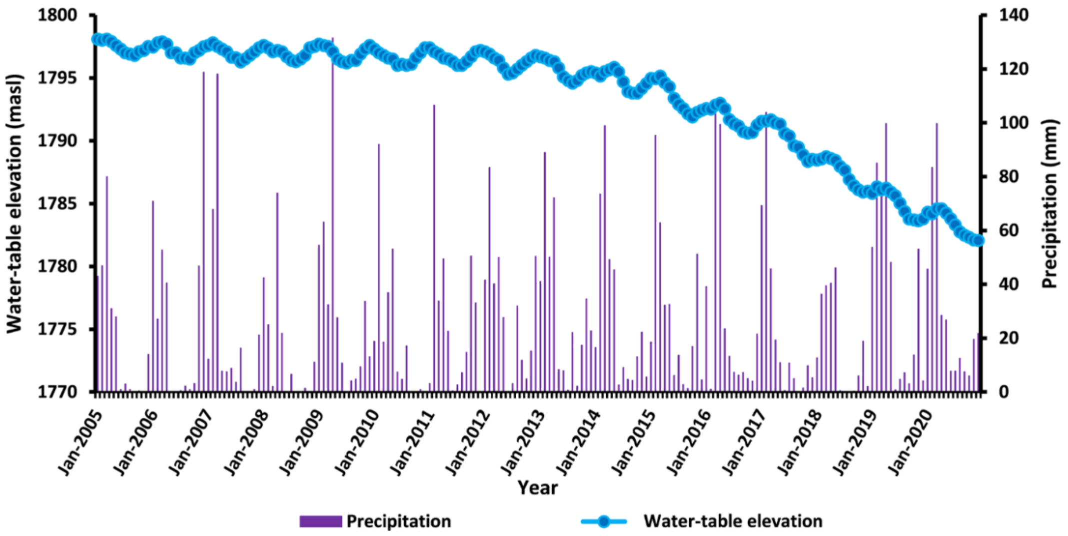


Fig 4. Changes in Groundwater Level in the Kabul Basin (2005-2020)

In areas of the aquifers where the water table is shallow, groundwater levels are sensitive to seasonal changes. During the rainy season, the water table rises after a few weeks of precipitation. Generally, groundwater levels decrease during the dry period (May to December) and increase during the rainy season (January to April) each year.

Impact of land use/land Cover on Groundwater

In the study area, four types of land use have been identified (Figure 5). The land use map illustrates how different land use and land cover (LULC) classes have shifted over time across various regions. Notably, agricultural land has significantly decreased, from 106.5 square kilometers in 2000 to 72.5 square kilometers in 2020. Conversely, urban areas have expanded substantially, increasing from 160.9 square kilometers in 2000 to 410.2 square kilometers in 2020. Additionally, barren lands have reduced from approximately 762.6 square kilometers in 2000 to 546.3 square kilometers in 2020. The LULC analysis indicates a significant increase in built-up areas in Kabul city between 2000 and 2020, with a notable expansion of new urban areas towards the city's outskirts.

Groundwater Flow Directions

Natural groundwater recharge in the Kabul Basin has been impacted by rapid urbanization, leading to a decrease in recharge in urban areas due to the construction of buildings and roads. Figure 6 depicts groundwater level contours and flow directions for the aquifer system in December 2004 and December 2020. The contour lines for groundwater levels in 2004 and 2020 are shown in blue and purple/dark purple, respectively.

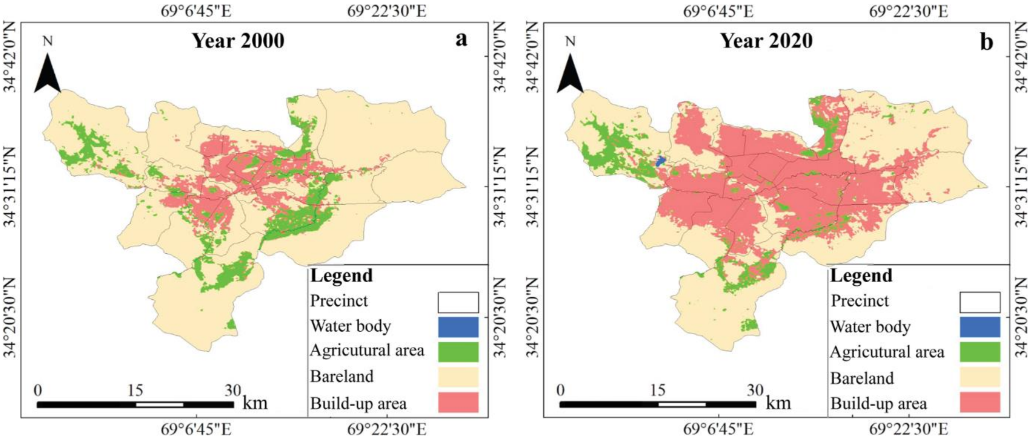


Fig 5. Groundwater Contour Lines and Flow Directions in December 2004 and December 2020 for the Aquifer System

Figure 7 illustrates significant changes in groundwater flow direction over the study period. In 2004, groundwater flow moved from the west and southwest towards the east along the rivers in the western basin and from the south and southwest towards the basin’s center, subsequently flowing north and east in the eastern basin. According to Figure 6, groundwater from the Paghman-Darulaman aquifer was discharged into the central Kabul aquifer through the narrow Shir Darwaza pass. By 2020, the flow direction in the western basin had shifted, with groundwater now flowing towards the central part of the basin. While the groundwater flow direction in the eastern basin remained similar to 2004, changes are evident in the central and northwestern parts of the basin, where flow has become concentrated towards the northwest. These changes in groundwater flow direction are primarily attributed to excessive pumping and rapid, irregular urbanization.

Additionally, Figure 7 illustrates a decline in groundwater levels in the Kabul aquifer from 2007 to 2020. The most significant reductions have occurred in the southwestern region of the Paghman-Darulaman aquifer and the northwestern part of the central Kabul aquifer. This decline is primarily due to reduced aquifer reserves, increased population, and heightened groundwater use for urban and agricultural purposes. Conversely, the areas with the smallest decline are in the eastern and northeastern parts of the central Kabul aquifer, where groundwater levels have remained relatively stable throughout the study period.

To address the groundwater depletion in the Kabul Basin, it is essential to implement effective management strategies. These should focus on reducing groundwater exploitation, enhancing natural recharge, and ensuring the sustainability of groundwater resources. Key measures

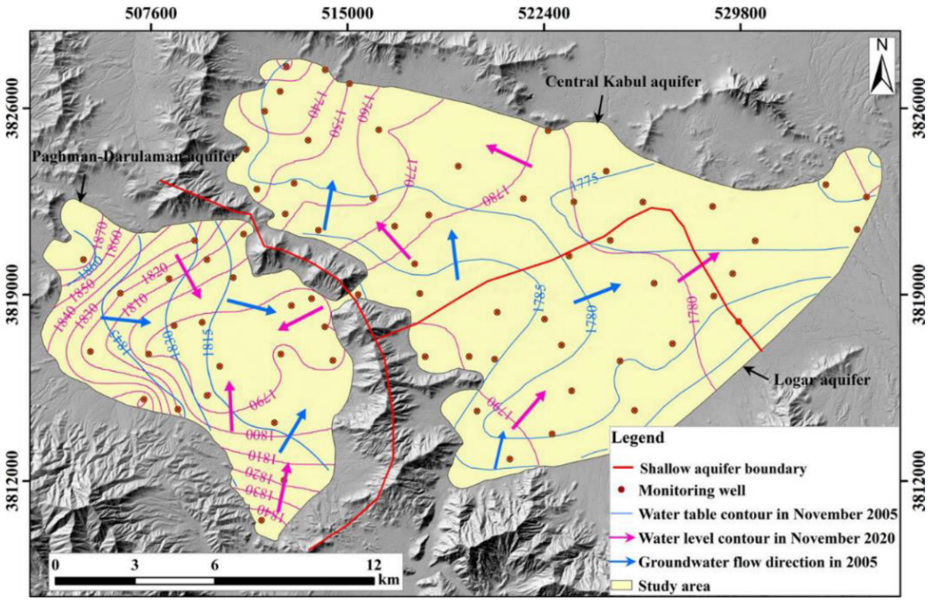


Fig 6. Horizontal distribution of hydraulic head (meters) and groundwater flow directions in December 2004 and December 2020.

include promoting water conservation, adopting artificial recharge techniques, and developing alternative water sources. Additionally, efficient monitoring and regulation of groundwater extraction are crucial to prevent overexploitation.

Figure 8 shows that, over the 13-year study period, groundwater levels throughout the Kabul Basin have generally decreased, with the exception of a small area in the Begrami section, where water levels have increased by approximately 2 meters (MeldebeKova et al., 2020). This increase in the Begrami section is likely due to river recharge and the return of irrigation water (Saffi, 2019). The decline in groundwater levels has led to the drying up of most shallow wells in the northwestern and southwestern parts of the study area (Saffi, 2019; Zaryab et al., 2022).

Given the current trends, groundwater resources in the Paghman-Darulaman and central Kabul aquifers are expected to continue declining. As illustrated in Figure 7, the Afshar and Alauddin water lands in the Paghman-Darulaman aquifer (Mills, 2020) are significant sources of groundwater, with substantial annual discharge through public water supply wells. Additionally, rapid and unplanned urbanization in the western basin has led to a proliferation of private and public wells in the Paghman-Darulaman aquifer (Noori & Singh, 2023; Pereira et al., 2009). Notably, almost all deep wells (>150 meters) drilled in the past decade have been located in the Paghman-Darulaman and central Kabul aquifers. The surge in water demand due to rapid urbanization has exacerbated groundwater overexploitation, particularly in the southwestern Paghman-Darulaman and northwestern central Kabul aquifers. To mitigate this, it is crucial to reduce water extraction from the Afshar and Alauddin water lands while increasing extraction from the Logar water lands.

A more precise approach to estimating the volume of declining groundwater resources involves combining groundwater level change maps with maps of aquifer thickness and properties. Several studies have assessed the rate of groundwater decline in the Kabul aquifer using various methods, including water level measurements, groundwater modeling, and remote sensing data.

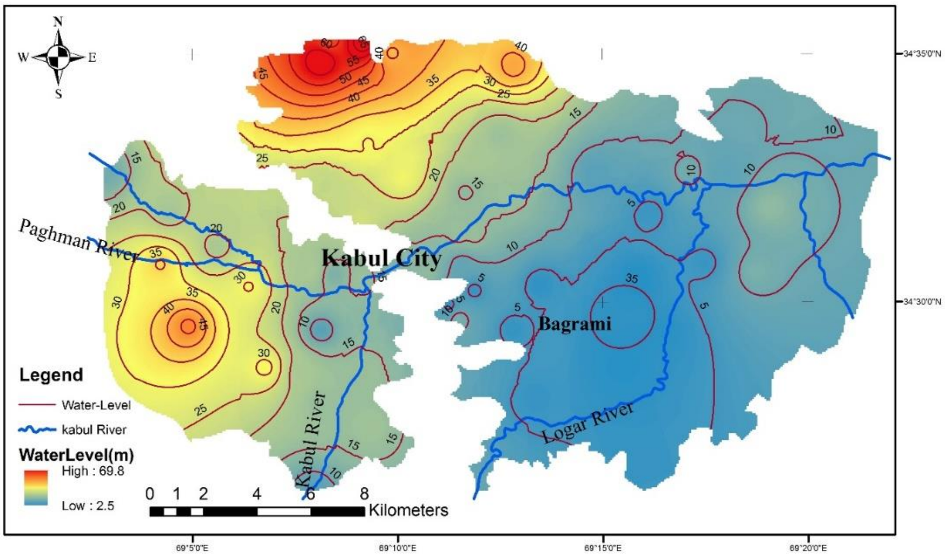


Fig 7. Changes in groundwater level from November 2007 to November 2020

Fluctuations Of Groundwater Level

According to Figure 8, the average groundwater level in the Kabul Basin decreased by approximately 16.5 meters from 2007 to 2020. The aquifer spans a total area of 271 square kilometers, with a specific yield estimated at 0.08. This results in an estimated loss of 358 million cubic meters of water from the Kabul aquifer over the study period. The decline in groundwater resources is closely linked to rapid urbanization within the Kabul Basin.

The hydrograph for the city, along with maps showing changes in the groundwater level of the Paghman-Darulaman aquifer, indicates that the average static water level at a depth of 20 meters decreased by about 0.55 meters from 2007 to 2020 (Figure 8). Research suggests that high population densities have led to localized reductions in groundwater levels, attributed to increased net recharge from domestic sewage wells, industrial and agricultural activities, and intensified water extraction compared to the overall groundwater level in the Kabul Basin.

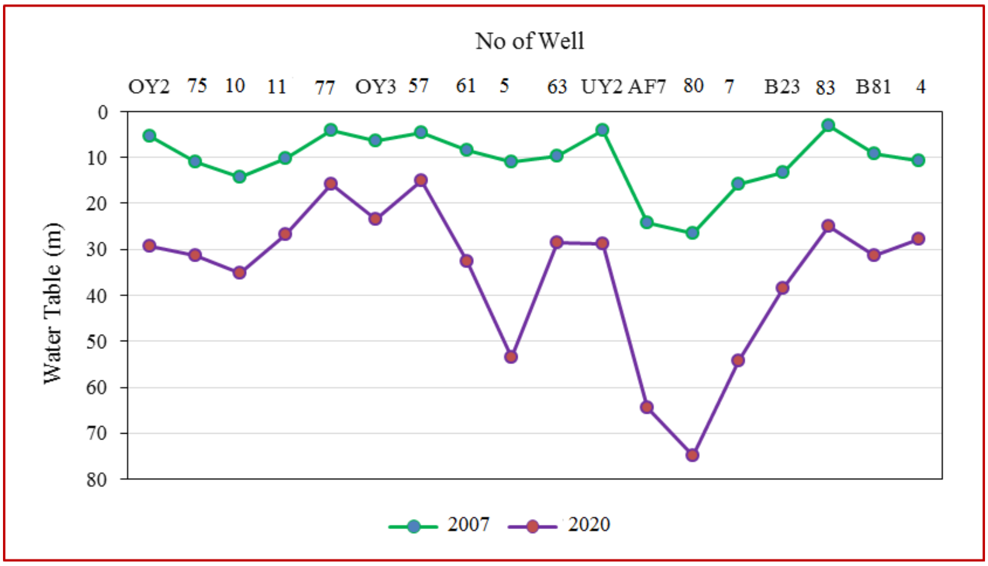


Fig 8. Changes in groundwater level of upper Kabul (Paghman-Darulaman)

The water levels in wells observed in Kabul city have been analyzed (Figure 8). Recent groundwater extraction has caused a gradual decline in groundwater levels. Changes in water levels for wells 148 (OY2), 152 (OY3), and 140 (TW3) are illustrated in Figure 9.

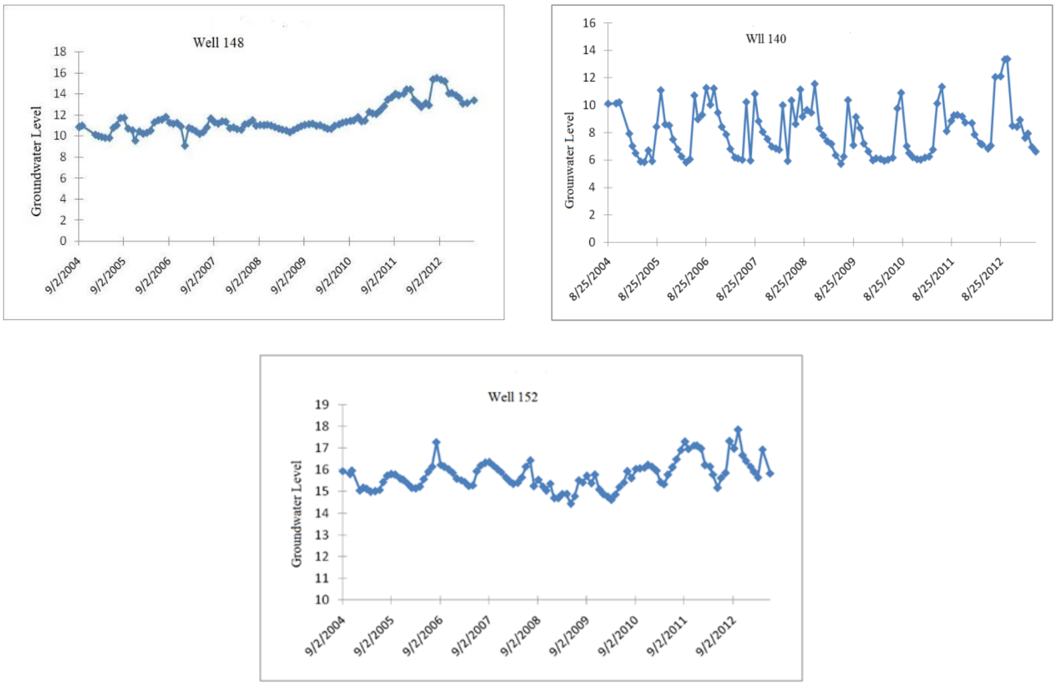


Fig 9. Fluctuations of underground water depth in observation wells 140, 148 and 152

Rapid urbanization and the overexploitation of groundwater resources in the Kabul Basin have adversely affected both dryland and aquatic ecosystems. Extensive groundwater extraction has led to the complete desiccation of the Heshmat Khan wetland (Saffi, 2019). According to a study by MeldebeKova et al. (2020), vertical subsidence of up to 5.3 centimeters per year was observed in the southwestern part of the Paghman-Darulaman Basin, where groundwater levels have significantly declined due to overuse. Additionally, rapid urbanization has significantly altered groundwater flow patterns in both the Paghman-Darulaman and Central Kabul aquifers.

Water Balance Of Kabul Basin

According to research conducted by the Japan International Cooperation Agency in 2011, the total and average water balance of the Kabul Basin over a 10-year period is presented. The data show that the surface water balance has been slightly negative on average over the past decade, with a deficit of 746 million cubic meters per year, which is approximately 0.5% of total precipitation. The total water balance for the Kabul Basin can be expressed by Equation 2:

$$\Delta S = P + Q_{in} - E - ET - Q_{out} – A \quad (2)$$

Where:

ΔS = Change in storage

P = Precipitation

Qin = Surface water inflow

E = Evaporation

ET = Evapotranspiration

Q_{out} = Surface water outflow

A = Abstraction (groundwater withdrawal)

This equation encompasses all major components of the water balance in the basin, including inputs (precipitation and surface water inflow), outputs (evaporation, evapotranspiration, surface water outflow, and groundwater abstraction), and the resultant change in storage.

The primary source of surface water inflow, derived from river flow, amounted to 351.8 million cubic meters per year (70.2%), followed by precipitation, which contributed 146.6 million cubic meters per year (29.2%). Major runoff losses were 325.2 million cubic meters per year (64.8%), with evaporation and transpiration accounting for 115.4 million cubic meters per year (23.0%). Recharge from the surface system was 25.2 million cubic meters per year, representing approximately 5% of total surface losses and 17.2% of precipitation (Japan International Cooperation Agency, 2011).

Total water balance of surface and groundwater in the Kabul Basin (2000–2009). This table summarizes key hydrological components, including precipitation, surface water inflow, recharge, and groundwater abstraction. Data show a slightly negative water

Table. 1 -The total water balance of surface and groundwater in the Kabul Basin for the years 2000-2009 (JICA).

Surface Water Balance

Unit; TCM/year

Basin	Rain	Run-in	Inlet	Inundate	Recharge	Evap	Run Off	Dam Out	Sur Bal
Darulaman	30722.0	293919.7	123788.6	182.1	7578.3	22161.8	418839.8	0.0	33.0
Central Kabul	28706.2	681391.8	0.0	13699.7	6953.0	22056.9	661958.1	20668.0	-138.8
Logar	39180.2	469239.4	228025.0	1509.1	10698.1	31065.9	681494.1	15761.2	-1066.8
Total	98608.5	1444550.8	351813.6	3091.0	25229.3	75284.5	1762292.0	36429.2	-1172.6
Basin Total	146611.0	0.0	351813.6	3091.0	25229.3	115387.0	325216.0	36429.2	-734.0

Unit; TCM/year

Groundwater balance

Basin	Recharge	Inflow	Inundate	PmpUp	Outflow	SubBal	Volume
Darulaman	7578.3	6242.1	182.1	12759.6	2333.8	-1455.1	5509653.9
Central Kabul	6953.0	6276.1	1399.1	4138.4	8800.0	-1109.1	3830789.4
Logar	10698.1	5406.4	1509.1	8129.8	6632.2	-166.7	4846915.9
Total	25229.3	17924.6	3091.0	25027.7	17766.2	-2730.9	14187359.2
Basin Total	25229.3	4369.0	3091.0	25027.7	3210.0	-2730.9	13028448.0

balance in the basin, highlighting an average annual deficit of 746 million cubic meters. Surface water runoff accounts for a significant loss, while groundwater abstraction contributes to the declining storage trend. These findings emphasize the urgent need for water conservation measures and improved management practices in the Kabul Basin and Summary of physical and chemical results of groundwater samples from the Kabul aquifers (2004 and 2020). This table compares critical water quality parameters, including pH, electrical conductivity (EC), and dissolved oxygen (DO), across two sampling periods. The data reveal a marked increase in EC values, indicating rising groundwater salinity. These changes suggest worsening water quality, likely due to over-abstraction and contamination from urban and agricultural activities. The findings underscore the need for improved water quality monitoring and targeted interventions to mitigate salinity risks in the Kabul aquifers (Table 1).

In the groundwater system, the primary source of recharge was 25.2 million cubic meters per year (85.2%) from surface water, followed by subsurface inflow at 4.4 million cubic meters per year (14.7%). The main groundwater loss was due to pumping, which accounted for 25 million cubic meters per year (79.8%), with groundwater outflow contributing 3.2 million cubic meters per year (10.2%). The total groundwater storage was 7,860 million cubic meters. Over a 10-year period, the average annual decline in groundwater storage was 2.7 million cubic meters, with approximately 9.2% attributed to groundwater abstraction and 1.9% to precipitation.

Figure 10 illustrates that the volume of surface water in the Kabul Basin significantly exceeds that of groundwater. The negative balance in groundwater storage is reflected in the overall decline in groundwater levels.

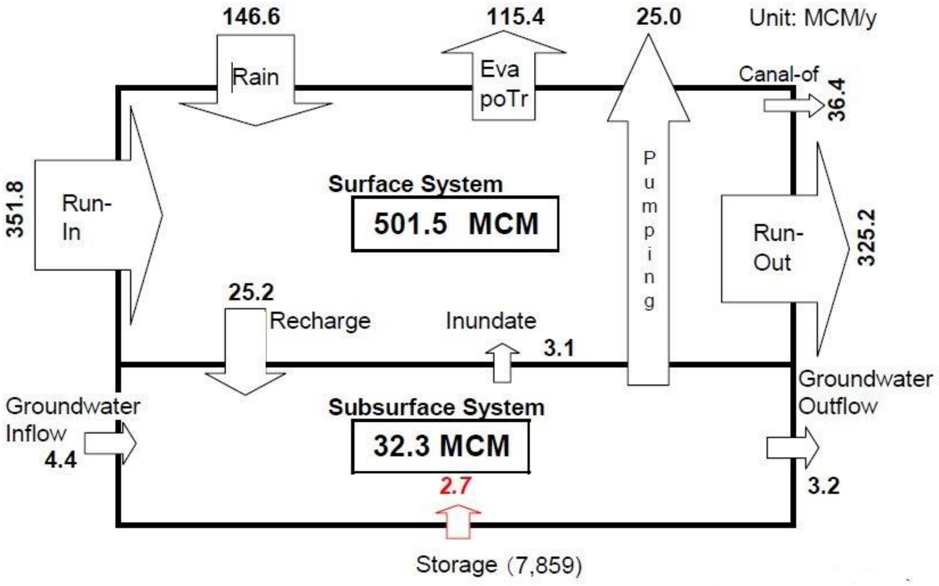


Fig 10. The total water balance of the Kabul basin (average of 2009-2000)

Figure 11 illustrates the factors influencing natural groundwater recharge in the Kabul aquifers. Data from river flow measurements indicate that in 2020, approximately 587 million cubic meters of water entered the Kabul Basin from the Paghman, Kabul, and Logar rivers. Of this, river infiltration into the subsurface accounted for about 9% of the total volume of water entering the basin in 2020.

Natural recharge data from river flows indicate that in 2020, approximately 587 million cubic meters of water entered the Kabul Basin from the Paghman, Kabul, and Logar rivers. Additionally, river infiltration into the subsurface constituted about 9% of the total water volume entering the basin that year.

Groundwater Recharge Rate

Rapid urbanization and the overexploitation of groundwater resources in the Kabul Basin have adversely impacted both dryland and aquatic ecosystems. The extensive overuse of groundwater has led to the complete desiccation of the Heshmat

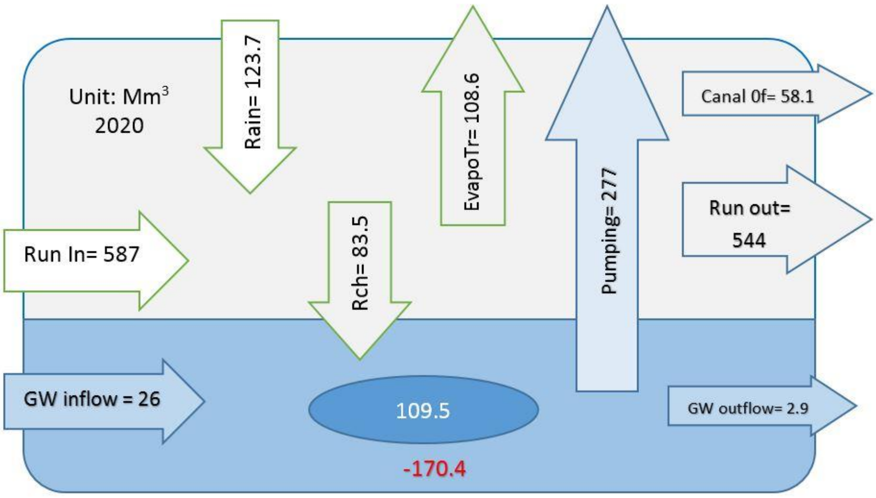


Fig 11. Total water balance of the Kabul basin (2020)

Khan wetland (Saffi, 2019). Research by MeldebeKova et al. (2020) indicates that the maximum vertical subsidence in the southwestern part of the Paghman-Darulaman Basin reached 5.3 centimeters per year, attributed to rapid groundwater level declines caused by overexploitation. Additionally, urbanization has significantly altered groundwater flow in the Paghman-Darulaman and Central Kabul aquifers.

To address these issues, urgent measures are needed to mitigate groundwater depletion and enhance recharge. Strategies should include promoting water conservation practices, implementing artificial recharge methods, and developing alternative water sources. Groundwater extraction must be regulated to match recharge rates, and a comprehensive water allocation policy for Kabul should be established. Those exceeding the prescribed water limits should face penalties three times the standard rate.

Moreover, adjustments in industrial practices are necessary to resolve conflicts between water supply and demand. Potential water resources in the Kabul Basin, such as the Maidan, Panjshir, and Salang rivers, should be utilized to ease the pressure on Kabul's aquifers. Managed Aquifer Recharge (MAR) projects, like the pilot project conducted by DACAAR in Kabul from 2017 to 2020, which demonstrated local increases in groundwater levels, should be expanded to reduce aquifer stress.

Additionally, rainwater and surface water collection through recharge wells, pits, and channels can bolster groundwater levels during the rainy season. Prioritizing collected rainwater for household use before recharging groundwater and raising awareness about rainwater collection's importance are critical steps.

The key factors contributing to the decline in groundwater resources in the Kabul

Basin include:

Conversion of Irrigated Lands: Formerly irrigated lands and orchards around Kabul have been converted to residential areas, reducing natural water infiltration and groundwater replenishment.

Loss of Water Bodies and Grasslands: Historical wetlands and grasslands, such as the Ab-e-Chakan wetland and various grasslands around Kabul, which once played a significant role in groundwater regulation and purification, have been destroyed or degraded.

Increase in Impermeable Surfaces: The proliferation of concrete dams, roads, and other impermeable structures in Kabul has decreased groundwater recharge. Additionally, insufficient attention to engineering standards in construction and a lack of proper water and sewage infrastructure contribute to the problem.

Neglect of Conservation Buffers: Encroachment on conservation buffer zones around water stations exacerbates the issue.

Population Growth and Poor Management: The rapid increase in population, now exceeding 5.3 million, combined with inadequate management practices, has led to unsustainable groundwater extraction. Unauthorized well drilling further exacerbates the depletion.

Drought and Climate Change: Despite Afghanistan not being classified as a drought-prone country, persistent droughts and climate change have reduced snowfall, leading to decreased water availability and altered recharge patterns.

Decline in Vegetation Cover: The loss of vegetation in the Asmai Mountains and surrounding hills has increased rainwater runoff and decreased infiltration rates.

Inefficient Water Use: Inefficient and unregulated use of available water resources, coupled with a lack of conservation efforts, highlights the need for improved water management and conservation practices across various sectors.

Addressing these factors through targeted interventions and comprehensive management strategies is essential to reversing the trends of groundwater depletion and ensuring sustainable water resources for the Kabul Basin.

The Quality Status Of Groundwater Resources

The statistical parameters of groundwater samples collected from the Kabul aquifer in July to November 2004 and November 2020 are summarized in Table 2. The pH of the groundwater was neutral during both sampling periods. The average temperature of the groundwater samples remained consistent across both periods. Dissolved oxygen (DO) measurements indicated that the groundwater was aerobic in both sampling periods. Electrical conductivity (EC) values ranged from 497 to 8,290 µS/cm in 2004 and from 618 to 9,600 µS/cm in 2020. The highest EC values were recorded at sampling points 166.2 in 2004 and W15 in 2020, with values of 8,290 and 9,600 µS/cm, respectively. In 2004, approximately 73% of the groundwater samples had EC values exceeding 1,000 µS/cm, while in November 2020, 82% of the samples had EC values above this threshold. This increase may suggest a gradual rise in groundwater salinity, potentially driven by population growth and over-abstraction.

The majority of groundwater samples from the Kabul central and Logar aquifers exhibited moderately saline to saline characteristics, whereas nearly all samples from the Paghman-Darulaman aquifer were classified as fresh water. The broad range of EC values might be attributed to the presence of brackish lake deposits in the Kabul central aquifer, which could influence the variability in EC readings. Pollution maps based on various parameters are illustrated in Figure 12.

Shallow groundwater depths and sewage infiltration into the aquifer have led to various types of groundwater pollution. This contamination is a significant factor contributing to the high infant mortality rates in these areas. The following sections will assess the quality of pollutants in the water wells of Kabul city. A critical issue in this watershed is the inadequate water supply and sewage collection infrastructure in residential areas. In many residential areas, particularly in villages, drinking water is sourced from shallow

Table 2. Summary of the physical and chemical results of sampling points in the Kabul aquifers.

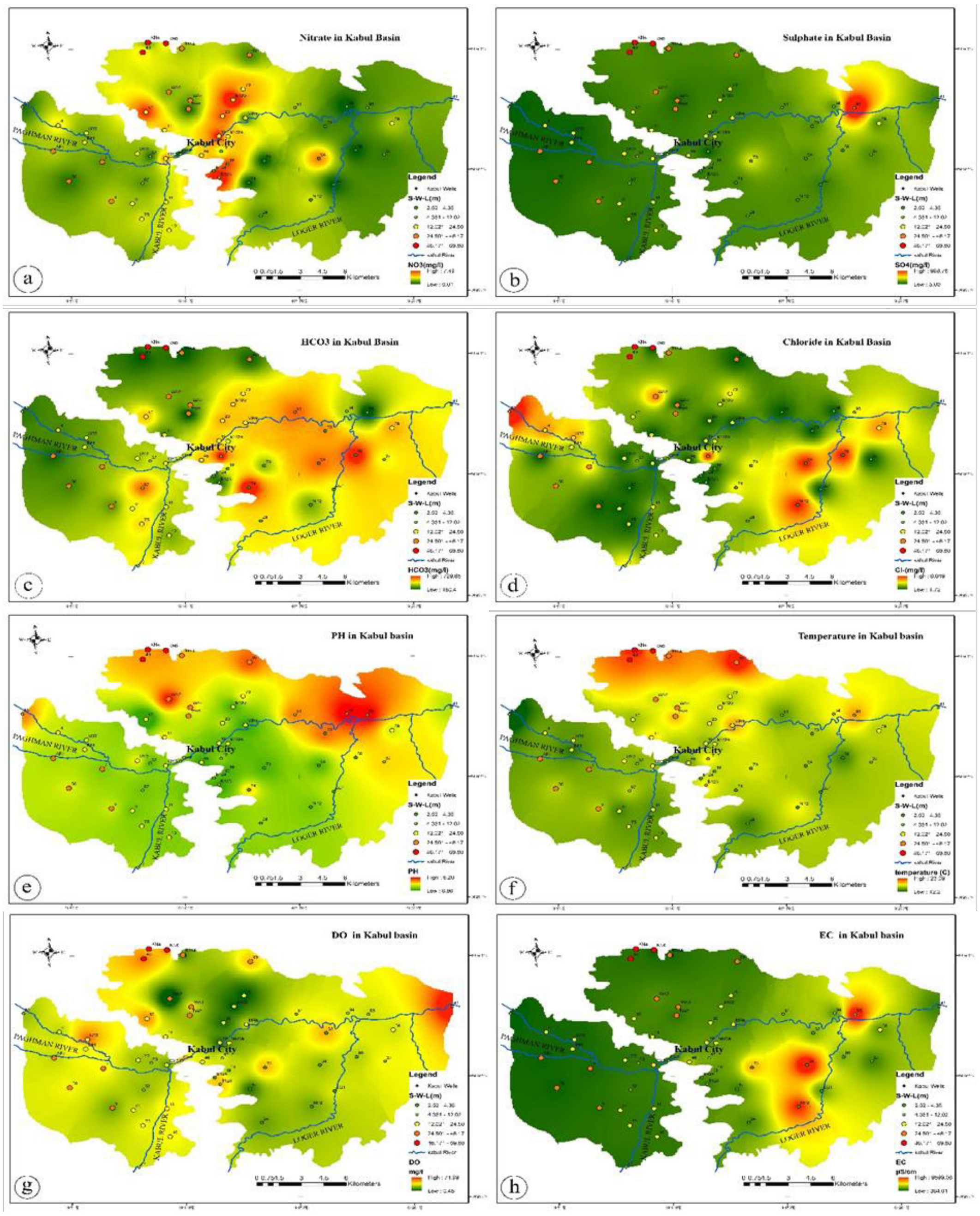
parameter	Unit	Measured in July to November 2004				Measured in November 2020			
		Minimum	Mean	Maximum	SD	Minimum	Mean	Maximum	SD
PH		6.94	7.50	8.37	0.3	7.00	7.60	8.10	0.23
T	C°	10.90	15.50	21.60	1.90	6.00	15.40	17.80	2.10
DO	mg/L	0.40	7.10	14.90	3.40	2.10	5.25	9.60	1.88
EC	µS/cm	497.00	1760.0	8290	837.0	618.0	1640.00	9600	3149.1
Ca^{2+}	mg/L	35.00	81.50	334.00	51.80	20.50	76.65	362.70	63.70
Mg^{2+}	mg/L	6.60	92.00	590.00	104.80	12.30	82.40	684.0	139.4
Na^{+}	mg/L	14.60	145.40	1630.00	244.30	20.50	94.15	3014.00	567.8
K^{+}	mg/L	2.00	8.30	31.60	5.50	2.16	7.05	74.00	14.00
HCO_3^-	mg/L	102.50	402.20	651.10	141.60	183.00	429.90	840.00	173.40
Cl^-	mg/L	8.20	208.90	2750.00	3030.00	7.30	135.00	3997.00	838.60
SO_4^{2+}	mg/L	16.10	233.80	3030.00	492.00	19.80	114.00	4573.00	988.40
NO_3	mg/L	1.00	31.00	182.00	33.20	3.98	13.72	120.41	21.00

hand-dug wells that are situated near sewage absorption wells, exacerbating the risk of contamination.

It should be noted that the results of this study are consistent with the previous studies that conducted research in this field, such as (Tani & Tayfur, 2021; Manawi et al. 2020).

The comprehensive analysis of groundwater dynamics in the Kabul Basin from 2005 to 2020 reveals several critical issues that warrant in-depth discussion:

The observed average decline of 16.5 meters in groundwater levels over the



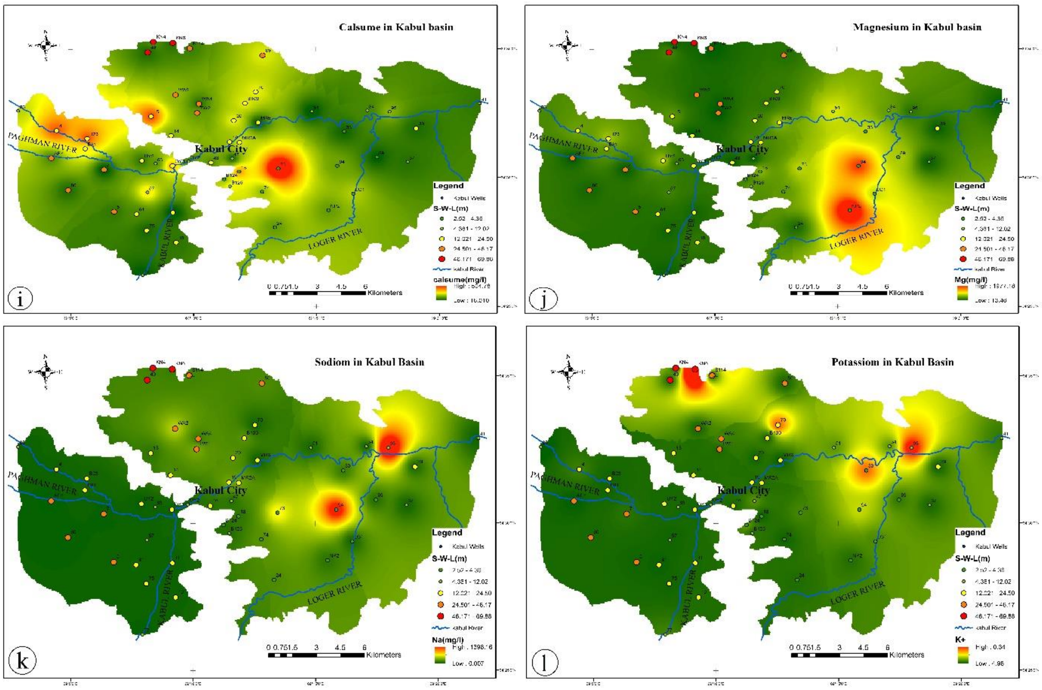


Fig 12. Map of result: a) Nitrate, b) Sulphate, c) HCO3, d) Chloride, e) PH, f) Temperature, g) DO, h) EC, i) Calcium j) Magnesium, k) Sodium, l) Potassium

13-year study period, with localized declines of up to 12 meters, is a significant concern. This depletion rate, averaging 80 cm per year in some areas, exceeds natural recharge rates by a factor of two to six. The alteration in groundwater flow directions, particularly in the Paghman-Darulaman and Central Kabul aquifers, suggests a fundamental shift in the basin's hydrogeological dynamics. These changes are likely driven by intensive pumping and unregulated urban expansion, which have disrupted the natural groundwater flow patterns.

The dramatic land use changes observed, with urban areas expanding from 160.9 km² to 410.2 km² between 2000 and 2020, have significantly altered the basin's hydrological balance. The reduction in agricultural areas and increase in impervious surfaces has likely decreased natural recharge rates and accelerated surface runoff. This urbanization-induced hydrological alteration presents a challenge for sustainable groundwater management, as it reduces the system's natural resilience to over-extraction.

The increase in groundwater samples with electrical conductivity (EC) values exceeding 1,000 µS/cm from 73% in 2004 to 82% in 2020 indicates a concerning trend of increasing salinity. This trend may be attributed to several factors, including over-extraction leading to the mobilization of deeper, more saline water, and potential contamination from urban and agricultural sources. The spatial variability in EC values, particularly in the Central Kabul aquifer, suggests complex hydrogeochemical processes that warrant further investigation.

The water balance analysis revealing groundwater extraction (277 million m^3 in 2020) significantly exceeding natural recharge rates highlights the unsustainable nature of current water use practices. The identification of river infiltration as the main recharge component (9% of total inflow) underscores the importance of surface-groundwater interactions in the basin's hydrology. This imbalance raises questions about the long-term viability of current extraction rates and the need for integrated surface and groundwater management strategies.

The desiccation of the Heshmat Khan wetland and observed land subsidence (up to 5.3 cm/year in some areas) are tangible manifestations of the ecological impacts of groundwater depletion. These environmental changes may have cascading effects on local ecosystems and potentially on the structural integrity of urban infrastructure. The loss of wetlands also reduces the natural water purification and flood mitigation services these ecosystems provide.

While not explicitly quantified in the study, the mention of recurrent droughts and climate variability suggests an additional stressor on the groundwater system. The interplay between climate-induced recharge variability and increased extraction demands during dry periods likely exacerbates the observed groundwater depletion trends.

The rapid population growth in Kabul, from approximately 1 million in 2001 to 5.3 million in 2021, with over 70% residing in unplanned settlements, presents significant challenges for water resource management. The socio-economic implications of groundwater depletion, including potential water scarcity and quality issues, may disproportionately affect vulnerable populations and could lead to social and economic instability if not addressed.

The study's findings highlight the urgent need for robust groundwater management policies and practices. The current imbalance between extraction and recharge, coupled with the complexities of rapid urbanization and climate variability, necessitates a multi-faceted approach to water resource management. This may include demand management strategies, artificial recharge initiatives, and the development of alternative water sources.

Conclusion

Since 2001, Kabul city has experienced rapid urbanization, with groundwater serving as the primary source for residential, agricultural, and industrial use. The results indicate that groundwater resources in Kabul have been depleting faster than they are being replenished. Analysis reveals significant changes in land use and vegetation cover within the Kabul basin. Notably, agricultural areas have substantially decreased, while urban areas have expanded significantly.From 2005 to 2011, the decline in groundwater levels was gradual. However, between 2011 and 2020, this decline accelerated markedly. Groundwater levels have decreased considerably across most parts of the basin, particularly in the northwestern section of the central Kabul aquifer and the southeastern Paghman-Darulaman aquifer. The hydrograph illustrates that groundwater levels in some areas have fallen by 12 meters from 2005 to 2020, at an average rate of 80 centimeters per year, significantly altering local groundwater flow patterns during the study period. Additionally, changes in groundwater flow, especially in the Paghman-Darulaman and central Kabul aquifers, reflect substantial disruptions to the natural hydrogeological system. These changes are more pronounced than those observed in other rapidly urbanizing basins, suggesting a higher vulnerability of the Kabul aquifer system to anthropogenic influences. These findings collectively indicate that the Kabul Basin is approaching a critical threshold of water resource sustainability. The situation demands immediate and comprehensive action to avert an impending water crisis. Key recommendations include:

- Implementing stringent groundwater extraction regulations
- Investing in artificial recharge projects and water-efficient technologies
- Developing alternative water sources such as rainwater harvesting and wastewater reuse
- Improving urban planning to enhance natural recharge

While the study provides valuable insights, it also reveals knowledge gaps that require further investigation. These include a more detailed understanding of the spatial and temporal variability in recharge processes, the impact of climate change on long-term groundwater dynamics, and the potential for managed aquifer recharge in mitigating depletion trends. The results clearly indicate that the extensive decline in groundwater in the Kabul basin is significantly attributed to anthropogenic factors. If appropriate measures are not taken at this stage, the decline in groundwater is likely to continue rapidly, especially in densely populated urban areas. Ultimately, the residents of Kabul will face severe water scarcity in the near future.This emphasizes the urgent need for implementing effective management strategies to ensure sustainable use of groundwater resources in the region. The results highlight the importance of sustainable groundwater management in the face of rapid urbanization, increasing water demand in the Kabul basin, and the necessity of joint efforts to address this issue. Moreover, Future research should focus on developing predictive models to forecast long-term groundwater trends under various management scenarios, enabling proactive and sustainable water resource management in this rapidly evolving urban environment.

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