



Spatial and temporal trend analysis of groundwater levels and regional groundwater drought assessment of Kabul, Afghanistan

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Abstract

Groundwater is the dominant source of water supply in Kabul city in Afghanistan, but water levels in the region are steadily declining. This study was undertaken to assess groundwater level trends and examine its drought dynamics in Kabul city. The observation wells were classified using cluster analysis to categorize long-term trends of groundwater water level data. The seasonal and annual variations in groundwater depth have been determined utilizing the Mann–Kendall statistical test. To measure groundwater drought, the Standardized Groundwater Level Index (SGI) was utilized. Based on trend analysis, the water levels in 82% of the observation wells were significantly decreasing. From 2014 to 2020, most of the wells in the study area suffered increasingly severe and persistent drought, as per the SGI results. The analysis of land use and land cover (LULC) indicates that the built-up area is increased from about 15% in 2005 to 32% in 2020 in the study area. Bare land had decreased from about 67% in 2005 to 52% in 2020. The severe decline in groundwater level can be attributed to changes in LULC, overexploitation of groundwater, and declining annual precipitation. The findings of this study indicate that long-term groundwater management measures are required in the city area to maintain groundwater availability.

Keywords Groundwater trend analysis · Mann–Kendall · Cluster analysis · Groundwater drought · Kabul city · SGI

Introduction

The ready availability of water resources is important for human development. In particular, the availability of groundwater resources is essential in many parts of the world for agriculture, industrial use, and drinking water source. The dependence on groundwater for water supply has also been rapidly increasing, especially in arid and semiarid areas, due to the variability and unequal distribution of precipitation and reduced surface flows (Pathak and Dodamani 2019; Shan et al. 2020; Raghav and Singh 2021). Groundwater is primarily being used for municipal water supply and agriculture in many places around the globe. Therefore, its response

and operation in drought conditions are becoming increasingly relevant (Peters et al. 2005).

In many regions, groundwater resources are rapidly depleting due to overexploitation, the effects of urbanization, increased farming production, population growth, and industrial development (Malik et al. 2010; Jain and Singh 2014; Kanakiya et al. 2015; Kumar and Singh 2015; Sharma et al. 2015). Climate change, along with widespread excessive abstraction from aquifers for different purposes, is one of the primary causes of groundwater shortages and water level declines. In addition to anthropogenic activities, drought on a regular basis can impede groundwater recharge and control its extraction, resulting in a reduction in the groundwater table. The drying of the riverbed causes inadequate infiltration or penetration into the subsurface soil, making it difficult to maintain the river's stage and health. And the effects of climate change have recently resulted in a rainfall decline in many regions and an increase in evapotranspiration, which can directly impact the groundwater recharge mechanisms (Halder et al. 2020).

The approach for trend evaluation of groundwater level is an effective tool for groundwater conservation practices. It supports the fundamental concept of groundwater

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hydrographs. Groundwater trend assessment uses time-series analysis to provide a deeper understanding of long-term changes in groundwater levels. It can help determine whether groundwater storage in an aquifer is stable, increasing, or decreasing. Several researchers have used trend analysis techniques to assess how groundwater levels have changed over time (Peters et al. 2005; Yi and Ahn 2006; Daneshvar Vousoughi et al. 2013; Patle et al. 2015; Singh et al. 2015; Anand et al. 2020). Drought is stated as a transient reduction in water resources over an extended period. The term "groundwater drought" refers to a form of hydrological drought that impacts groundwater resources (Mustafa et al. 2017). Groundwater drought is another significant issue for engineers and policymakers of water resources, which has often been addressed in recent years (Li and Rodell 2015; Goodarzi et al. 2016; Mustafa et al. 2017; Thomas et al. 2017; Shah and Mishra 2020).

Kabul city has a population of more than four million (CIA 2020; NSIA 2020). The city is highly dependent on groundwater resources and groundwater supplies almost all of the water demands of the inhabitants. Some studies have been done on the groundwater source of Kabul city (Broshears et al. 2005; Tünnermeier and Houben 2005; Saffi 2007; Mack et al. 2009, 2013, 2014; USGS 2010; DACAAR 2011, 2019; JICA 2011; Taher et al. 2013; Zaryab et al. 2017; Mack 2018; Brati et al. 2019; Noori and Nasimi 2019; Jawadi et al. 2020; Noori and Singh 2021). An analysis by Mack et al. (2013) indicates that the depth of groundwater decreased on average (1.5 m/year) from 2008 to 2012, as well as (0–0.7 m/year) from 2004 to 2008. According to a study by Zaryab et al. (2017), groundwater levels in Kabul have dropped by more than 10 m in the foothills and 5–6 m in the city. Between 2003 and 2016, water levels in the upper Kabul basin dropped by more than 15 m. Investigating the annual and seasonal trend of groundwater and its magnitude, groundwater drought, and the factors affecting the degradation of groundwater levels are the cases that have been less addressed.

Thus, the main focuses of this study include: (1) to use cluster analysis to group observation wells relying on variability scenarios using agglomerated hierarchical cluster analysis (HCA); (2) to analyze and identify the variability and magnitude of groundwater level variations by the application of annual and seasonal (spring, summer, autumn, winter) trend analysis utilizing the nonparametric statistical approach of Mann–Kendall test and Sen's slope estimators for 66 observational wells in the research area; (3) to investigate the condition of land use and land cover (LULC) change in the research area to visualize the driving mechanism for groundwater recharge; and (4) to identify the effect of climatic fluctuations on the water table and groundwater drought utilizing standard groundwater level index (SGI). Such studies can yield valuable insights and provide

stakeholders and policymakers with a reflection groundwater scenario in the study area to develop sustainable water resources management measures for the city.

Methodology

Physical characteristics of the study area

Kabul is the most important city in Afghanistan. The city is divided into 22 municipality districts and is geographically located between latitudes 34°39'20" N to 34°17'40" N and longitudes 69°31'40" E to 69°52'40" E (Fig. 1). Its total area is 1030 km². Kabul has a semiarid climate. Precipitation in Kabul is seasonal and mostly occurs as rain and snow during winter (December, January, February) and in early spring (March, April). The annual average precipitation is about 330 mm per year (Source: Afghanistan meteorological department, data recorded 2008–2018). The mean monthly temperature ranges from a maximum of 32 °C in July and a minimum of –7 °C in January (Zaryab et al. 2017). Much of the study area is covered by urban development, and groundwater is the dominant water source. It is the leading national commercial base in the country. The population of the city area has dramatically increased due to the return of many refugees. Also, a considerable number of people from other provinces have come to Kabul to find a career.

Three waterways flow through the city of Kabul. Paghman stream flows in a westerly direction through the city. The Maidan River (Kabul River) enters the city from the south and joins the Paghman river 21 km downstream. The Logar river, a large tributary of the Kabul River, flows in a northerly direction and enters the Kabul River around 17 km downstream of the Paghman waterway's mouth (Fig. 1). In recent years, flows in the Kabul and Paghman rivers have only occurred during rainfall events in late winter and the spring due to snow melting and rainfall. Infiltration of water riverbeds has seemed to be the primary medium of groundwater recharge in Kabul. Regional groundwater recharge from precipitation through infiltration accounts for a small percentage of the overall recharge due to the low precipitation rate, the high rate of evapotranspiration, and the large proportion of the area covered by urban land use clayey soils (Tünnermeier and Houben 2005).

The research area covers part of the Kabul basin, which is surrounded by metamorphic mountain ranges. The Kabul basin was formed as a result of Paleocene tectonic activity. The Herat-Bamyan-Panjsher main fault bounds the basin in the west and north-west, the Sorobi fault in the east, and the Chaman fault in the southeast that has cut through the rocks, which are part of the Kabul block. Bedrock in the area consists of gneisses, amphibolites, quartzites, slates, schists, granites, metasandstones of the Precambrian age,

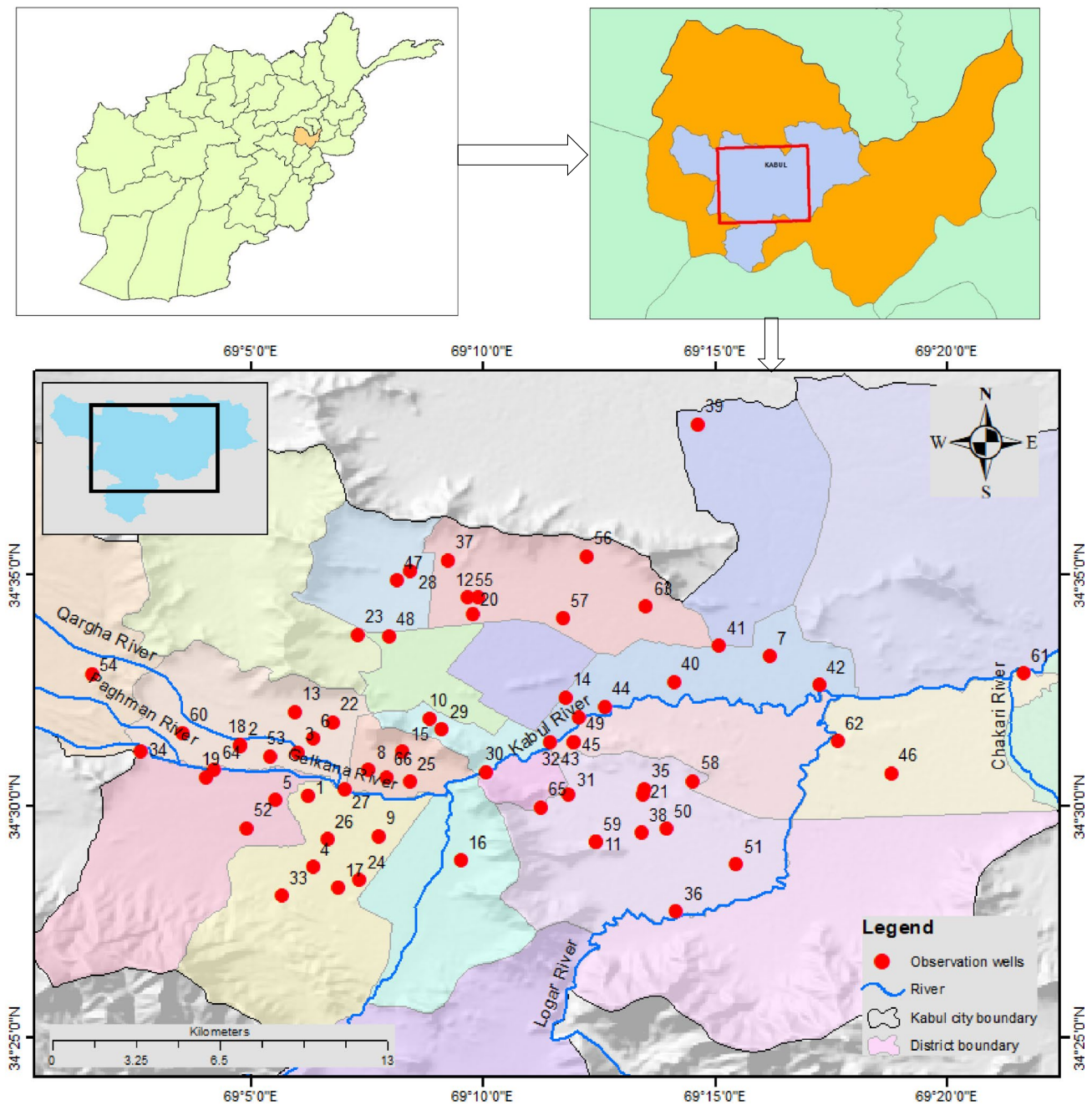


Fig. 1 Location map of the research area

and carbonates (limestones, dolomites) of the Permian–Triassic age. The Kabul basin is filled with an assemblage of terrigenous and lacustrine sediments mostly of Quaternary and Neogene age and unconsolidated and semi-consolidated lacustrine, fluvial, and aeolian sediments (Saffi 2007; Lashkaripour and Hussaini 2008; Zaryab et al. 2017). The Holocene River valley and intermountain basin dominate the geomorphological study region, followed by high-mountain relief, mountain relief, high-mountain glacial relief, and

piedmont diluvial relief. Most soils in the area are classified as either well-drained or partially drained (Ahmadzai and Omuto 2019). Kabul is now one of the top 100 biggest cities in the world due to its rapid urbanization (City Mayors 2020; Wikipedia contributors 2020). Its LULC indicators were classified as bare land, waterbody, marshland, agricultural area, trees, and built-up.

Based on JICA (2011), there are three principal groups of aquifers in the Kabul basin: shallow aquifers in alluvial

sediments, a deeper aquifer in sediments of Neogene age (the upper Neogen aquifer), and a deep aquifer (the lower Neogene Aquifer). Water in the deep aquifer is referred to as "Fossil Water" since it is separated from regular circulation. According to Mack et al. (2010), shallow groundwater (i.e., less than 100 m deep) is generally 20 to 30 years old, while groundwater in deeper aquifers is estimated to be thousands of years old. Most of the public water supply wells are established near rivers where much of the recharge takes place. Some existing literature emphasizes that Kabul has four interconnected Quaternary aquifers (Uhl and Tahiri 2003; Pell Frischmann 2012; Zaryab et al. 2017). However, in the Kabul Basin, the shallow aquifers, which is the same as the "Alluvial Aquifer or Quaternary Aquifer," is found in nearly all parts of the basin, but the sediments that contain these aquifers are thicker and have a greater groundwater potential along current and historical river channels.

For most parts of the basin, the water table surface reflects surface topography, and generally, groundwater flows in the surface-water discharge direction (Broshears et al. 2005). The mean thickness of the Logar aquifer is estimated between 30 and 40 m, with a limit of 70 m. According to pump test findings, the hydraulic conductivities of this aquifer are high, although they are subject to some heterogeneity (12–112 m/day). The thickness of the aquifer alongside the Kabul River ranges between 40–80 m. The permeability of this aquifer zone ranges between 4.32 and 64.8 m/day. The mean thickness of the Paghman aquifer is around 45 m. The hydraulic conductivity ranges from 1.73 to 25.92 m/day (Houben et al. 2009). As the altitude increases from the center to the sides of the basin, the depth to the groundwater level also increases from the middle of the basin to its sides. The depth of the observation wells reaching to Quaternary sediments. This study analyses groundwater level and its drought condition using static water level data of the shallow aquifer in the basin.

Data collection

The National Water Affairs Regulation Authority (NWARA) of Afghanistan provided monthly groundwater-level data for 128 wells in the research region used in this study. Observations and records of groundwater levels are available from November 2006 to May 2009. No figures were available from June 2009 to October 2013. Observational data are again available from November 2013 to April 2020. To compensate for this shortcoming and eliminate the data gaps, the process of data imputation has been done. During the observations, some wells, for various reasons such as drying, destruction, and collapse, have been replaced by alternative wells in their vicinity, which is mentioned in the available figures. The obtained data were checked for the maximum length of observations with continuous records. Many wells

have been excluded from the present study for the following reasons: (a) wells with observations for a period of less than 45 months were removed; (b) wells with unknown geographical coordinates; (c) wells without measurements before 2013; and (d) wells with incomplete data after the data imputation step. Finally, after the exclusion and the data imputation process, the observations of 66 wells (Fig. 1) for 15 years have been considered for the analysis.

Precipitation data for six stations in Kabul province were also collected from NWARA. Collected data were in the form of daily records from 2008 to 2020, which have been converted into monthly and annual total figures for analysis. Out of six stations, only two stations (Payin-i-Qargha and Tang-i- Sayedan) are located within the study area. The data for 2008 and 2020 are not complete. Therefore, it was intended to analyze the records from 2009 to 2019. Landsat imagery was downloaded to create LULC identity maps for 4 different years: 2005, 2010, 2015, and 2020. The required satellite data were obtained from USGS Portal (<https://earthexplorer.usgs.gov/>) using the address "path 153 and rows 36." (Table 1). Gap filling was done by ENVI 5.3 by downloading the Landsat Gap-fill IDL model for data downloaded from Landsat 7 satellite. "Supervised classification approach with maximum likelihood algorithm" in ENVI 5.3. environment was applied to create LULCs of the study area (Table 3).

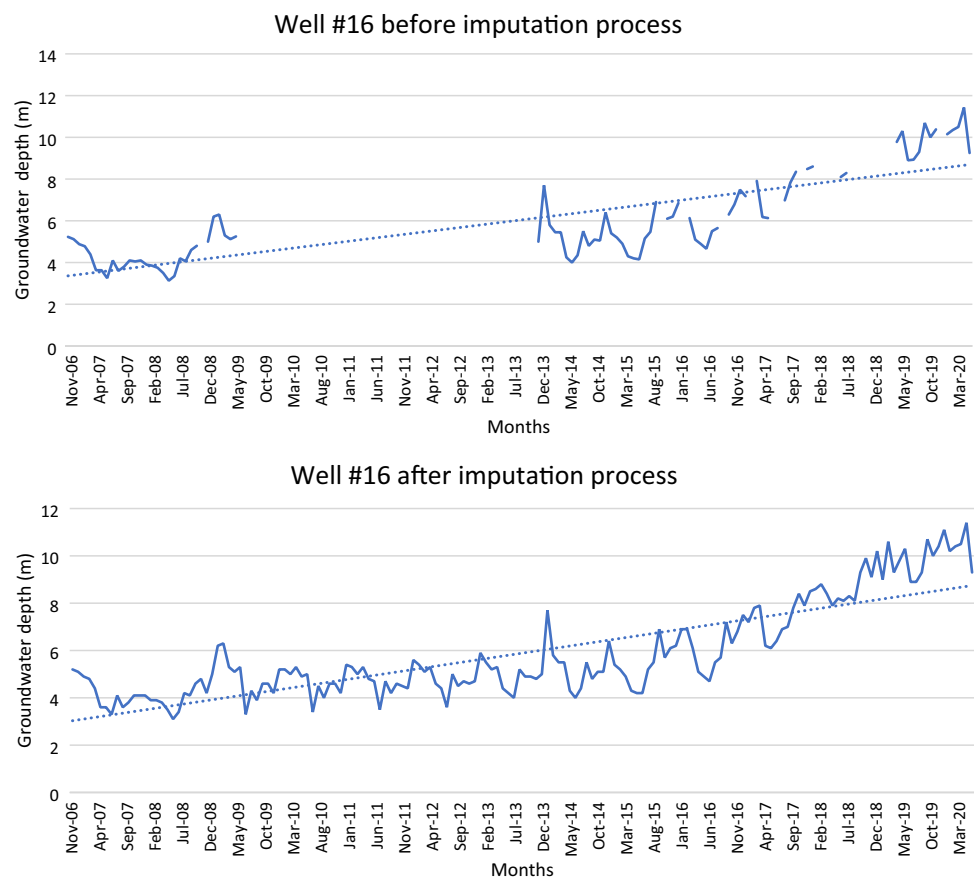
Data imputation

The lack of consistent evidence or a gap between observations is a common problem in statistical analysis. As a consequence, imputation is necessary to provide sufficient measurements. The data imputation approach is widely used to fill the observational gap between monitoring figures with substituted values (Efron 1994; Zhang et al. 2017; Manago et al. 2019; Evans et al. 2020). A univariate time series imputation approach was utilized in this study to impute missing values aided by the "imputeTS" package in "R Studio" environment (Moritz et al. 2015; Moritz and Bartz-Beielstein 2017). The function "na_seasplit" with the algorithm of "Kalman" was used to consider both seasonality and trends in the imputation process. The primary status of observed records on well #16 and imputed figures results are depicted in (Fig. 2).

Table 1 Satellite data acquisition details

Acquisition date	Address (path & row)	Spacecraft ID
01/06/2005	153/36	"L7_ETM"
23/06/2010	153/36	"L5_TM"
05/06/2015	153/36	"LANDSAT_8"
18/06/2020	153/36	"LANDSAT_8"

Fig. 2 Well #16 observational data illustration pre and post imputation



Hierarchical cluster analysis

Groundwater levels used in trend analysis differ dramatically across the wells. Clustering is a method of classifying observations based on their similar observed variables (Sinharay 2010). The observational wells in the present study were classified based on their water table characteristics. Monthly observation of groundwater over a long period of time (15 years) was used as a clustering variable. Hierarchical clustering is a fundamental method for groundwater studies that is widely used among the various clustering methods (El-Hames et al. 2013; Pathak and Dodamani 2019; Halder et al. 2020; Rahbar et al. 2020). The "Ward's linkage method" of hierarchical clustering was utilized to locate homogeneous wells using static water tables in this analysis (Yidana et al. 2010; Vijaya et al. 2019). The square "Euclidean Distance" measure was applied to assess the degree of correlation across the observational water level data (Yidana et al. 2010; Pathak and Dodamani 2019). The distance matrix based on the groundwater table is determined first in a hierarchical cluster analysis, and each well is assigned to a separate category. The "Ward's linkage mechanism" is then used to merge each group with the groups nearest to

it. Cluster analysis has been conducted using the "*hclust*" package in the "RStudio" statistical framework.

Groundwater levels and groundwater drought: a nonparametric trend test

The "*Mann–Kendall (MK)*" test is mainly utilized to whether there is a significant upward or downward trend in a group of time-series data. (Ribeiro et al. 2015; Kumar et al. 2018; Venegas-Quiñones et al. 2019). Mann first suggested the MK test as a nonparametric trend detection test, which Kendall later adopted as a test statistic (Pathak and Dodamani 2019). Statistically, the null hypothesis (H_0) suggests that the variable has no trends, while the alternative hypothesis (H_1) indicates trends. The value of Z indicates the state of the statistic test in the MK test. Positive trends are shown by $Z > 0$, negative trends are demonstrated by $Z < 0$, and $Z = 0$ signals no trend. The lag 1 autocorrelation of data at 95% level of confidence interval should be checked before utilizing the MK test. The annual and seasonal groundwater levels in Kabul city have been studied in this analysis utilizing the nonparametric MK statistical test. All observational wells were subjected to a trend test with a 95% confidence interval,

and Sen's slope (Sen 1968) approach had been utilized to evaluate the amplitude of trend.

In this study, the SGI was used to quantify the degree and significance of groundwater drought that was indicated by water level data. The SGI was suggested by Bloomfield and Marchant (2013) to evaluate groundwater droughts utilizing groundwater depths. The SGI is a nonparametric approach in which typical monthly groundwater information values are converted with a reciprocal ordinary cumulative distribution function, and scores are organized simultaneously, as per months to provide an SGI time series. The identification through SGI was performed similarly to the "Standardized Precipitation Index" as given by Rahman et al. (2017). This was done taking into account a given threshold (− 1 throughout this research) for SGI to describe groundwater drought features, including frequency, period, and strength. When the SGI value is less than zero, it indicates groundwater drought, but a value lower than the threshold indicates a moderate drought. The methodological flowchart of the present study is illustrated in Fig. 3.

Results and discussion

Cluster analyzing of the wells

The observational wells were characterized using cluster analysis based on the similarity of their water level measurements. The dendrogram that resulted from hierarchical clustering with Ward's linkage approach is shown in Fig. 4.

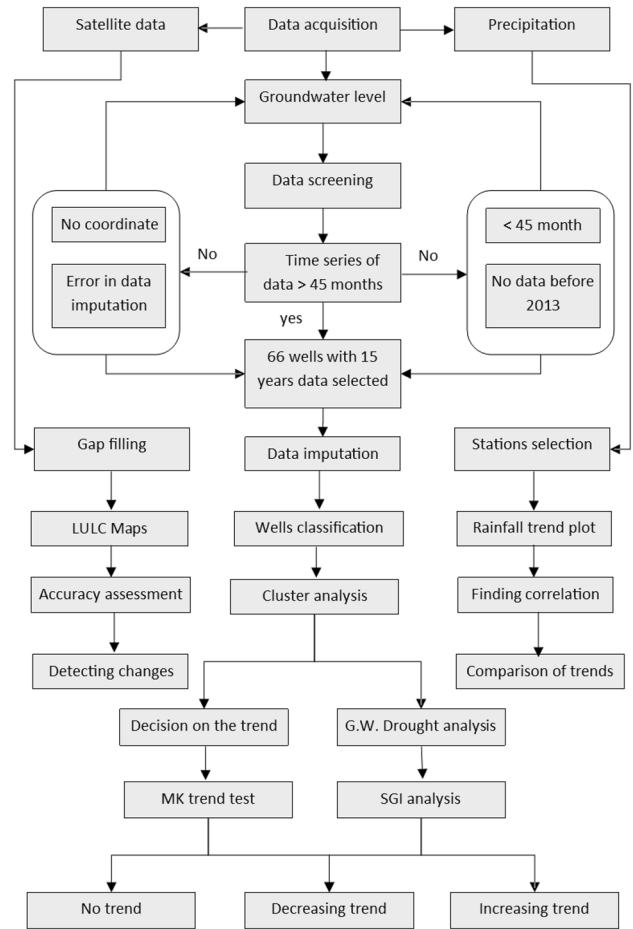


Fig. 3 Methodological flow chart

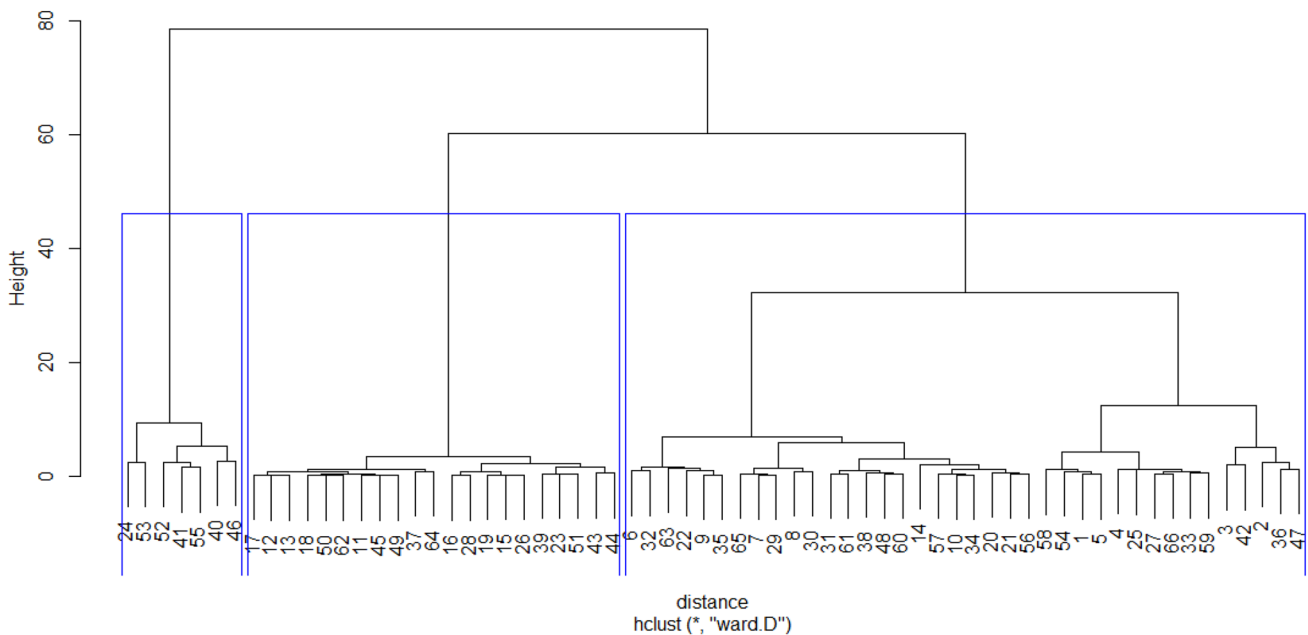


Fig. 4 Dendrogram of hierarchical cluster analysis

The dendrogram must be split at a certain amount of linkage gap called threshold to achieve various clusters. Threshold selection is a personal decision that differs from one person to the next. For example, a threshold of 40 results in 3 clusters, while a threshold of 20 results in 4 clusters.

A specific approach is required to prevent confusion when selecting a threshold. The optimal clustering algorithm became determined using the "Elbow method" (Kodinariya and Makwana 2013; Yuan and Yang 2019). The aim of cluster grouping techniques, also known as "total within-cluster sum of square (WSS)," is to find clusters with the least amount of intra-cluster variation. The "Elbow method" calculates the cumulative WSS as a function of cluster size: The cluster numbers should be chosen such that adding another cluster would not increase the total WSS significantly.

A WSS plot is constructed based on the number of clusters "k" (Fig. 5). The position of a bend (knee) in the plot determines the number of clusters needed. From (Fig. 5), it is seen that the hook is located at $k=3$, and it indicates that the optimal clustering algorithm throughout all wells is three. Based on the wells' geographical heterogeneity in the various cluster (Fig. 6), a group of seven wells in the east,

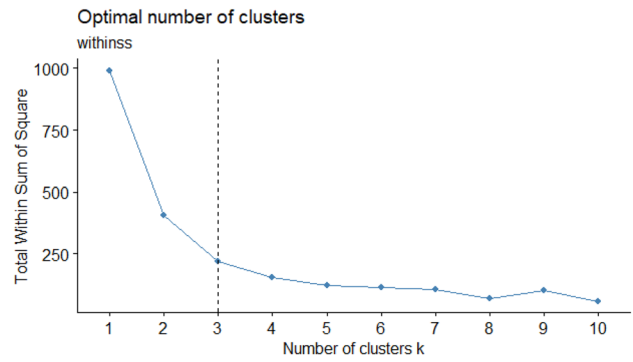


Fig. 5 Elbow method for hierarchical cluster analysis

west, and north parts of the study area shaped cluster 3. Cluster 2 consists of 22 wells with the same geographic distribution of east, west, and north. Cluster 1 is made up of the remaining 37 wells that are scattered across the region.

The average annual static water level in cluster 1 varies from 9 to 28 m below ground level, with a median of 17 m and a mean of 18 m (Fig. 7). Cluster 2 has a mean and median yearly averaged static water depth of

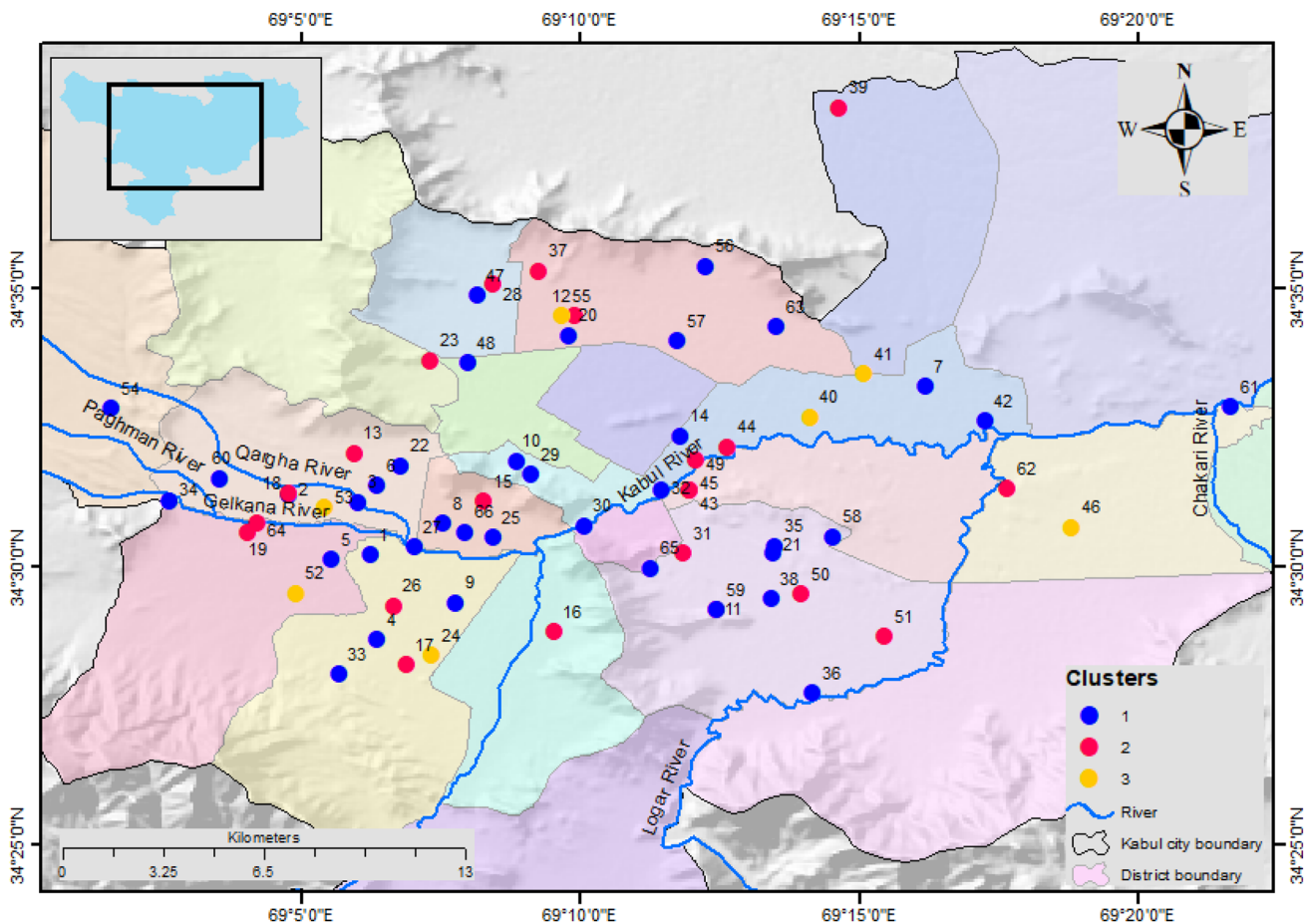
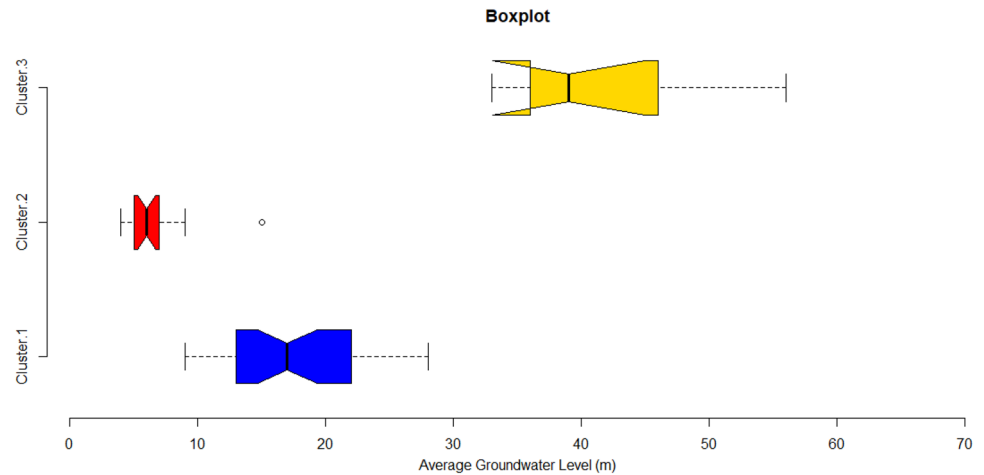


Fig. 6 Spatial distribution of wells classified based on cluster analysis

Fig. 7 Variability of groundwater levels in various clusters



6 m below ground level, with a least of 5 m and utmost of 9 m. The static water level in cluster 3 is slightly different. It has a minimum (33 m) variation and maximum (56 m) yearly averaged static water table below ground level. The mean and median value in clusters 3 is 42 and 39 m, respectively.

Trends of groundwater table on an annual and seasonal basis

Seasonal; spring (March–May), summer (June–August), fall (September–November), winter (December–February), and annual trends of groundwater-table for all observational points in the study area were evaluated using the nonparametric Mann–Kendall test with a significance level of 0.05. The seasonal and yearly groundwater level data were subjected to an autocorrelation test before including in the Mann–Kendall trend-test. Most of the wells had a significant lag 1 serial correlation with both seasonal and annual groundwater levels. The "Modified Mann–Kendall (MMK)" test was utilized to integrate serial correlation effects on trend assessment of groundwater level variability. As there is no alter in variance and p value of test using "mkttest" and "bcpw" test, therefore "mkttest" trend analysis is run on the initial time series of the groundwater table for all stations in each cluster.

Table 2 displays the findings of groundwater level trends and their magnitudes based on Sen's slope procedure. Both annual and seasonal groundwater level measurements showed significant trends. According to the trend report, just 6 wells out of 66 observational wells with annual groundwater levels show increasing trends. In comparison, according to the trend report, the remaining 60 wells show decreasing trends, often with significant trends (Fig. 8).

A total of 32 observational wells included in cluster 1 had a significant decrease with an average magnitude of 1.38 m yearly. Additionally, 2 other clusters (2 and 3) both have 15

and 8 wells. Cluster 2 has a significant negative trend value of 0.31 m per year, while cluster 3 has a significant negative trend value of 2.84 m per year. Conversely, four wells in the region showed a significant increase in annual groundwater depth, with an annual average of 0.7 m. The results of trend assessments indicate that the majority of wells in both clusters are declining. The wells of clusters 1 and 3 have more significant trends than cluster 2. With an average decline of 4.26 m per year for all seasons, the well 53rd in cluster 3 recorded the greatest decrease in groundwater level among all observation points. Similarly, the highest increasing groundwater level is recorded in the well 42nd of cluster 1 with an average value of 1.68 m per year. The water level in 89% of cluster 1 wells and 82% of the overall wells in the research region is significantly decreasing annually and, in all seasons, based on a trend evaluation of groundwater depth in different clusters.

In general, the depth of groundwater in more than 90% of the monitoring wells is decreasing, with an average annual decline of 1.18 m, which may be attributed to a variety of factors, including heavy groundwater use, changes in LULC, low precipitation, and poor water resource management. The depth of groundwater level in few wells in both clusters of 1 and 2 shown increasing conditions. Wells with positive groundwater levels are located near riverbeds in the Kabul area, most likely due to the important role these features play in providing groundwater recharge.

Extent and severity of groundwater drought conditions

Groundwater drought index (SGI) values were calculated for all of the 66 observational points of the research area to determine the severity and spatial distribution of groundwater drought conditions in the region. It is complicated and impossible to illustrate the groundwater drought

Table 2 Annual and seasonal trend analysis results based on the MK statistics and Sen's slope values

Wells	Spring		Summer		Autumn		Winter		Yearly	
	Z	Sen's slope	Z	Sen's slope	Z	Sen's slope	Z	Sen's slope	Z	Sen's slope
1	4.38	2.48	4.70	1.61	4.93	1.53	4.49	1.77	4.65	1.79
2	1.64	1.57	1.16	1.23	0.88	0.83	1.42	1.23	1.09	1.00
3	- 3.61	- 0.25	- 3.11	- 0.30	- 2.52	- 0.29	- 3.18	- 0.31	- 4.35	- 0.34
4	4.71	2.80	4.70	2.47	4.71	2.34	4.93	2.54	5.05	2.52
5	4.60	2.20	4.70	1.74	4.71	1.60	4.38	1.97	4.45	1.85
6	2.74	1.39	3.48	1.43	2.85	1.23	2.96	1.17	3.27	1.26
7	4.93	1.89	4.70	1.58	4.49	1.62	4.66	1.39	4.75	1.56
8	4.71	1.75	4.70	2.49	4.82	2.21	4.60	1.96	4.85	2.10
9	4.27	0.81	4.45	0.73	4.60	0.67	4.71	0.67	4.75	0.69
10	4.93	0.74	4.52	0.71	4.55	0.68	4.49	0.62	4.95	0.66
11	1.20	0.08	3.49	0.32	3.50	0.20	3.61	0.28	3.46	0.15
12	- 1.42	- 0.08	4.21	0.28	3.61	0.21	2.30	0.10	2.67	0.11
13	3.94	0.23	4.28	0.26	3.56	0.16	3.34	0.10	3.17	0.15
14	- 2.74	- 0.30	- 1.96	- 0.37	- 2.41	- 0.53	- 2.63	- 0.42	- 2.97	- 0.32
15	4.49	0.40	3.32	0.26	4.05	0.35	4.49	0.44	4.45	0.32
16	3.23	0.36	4.58	0.39	4.11	0.39	3.61	0.35	4.06	0.34
17	3.28	0.18	3.72	0.19	3.07	0.13	4.17	0.13	2.87	0.13
18	- 1.04	- 0.03	2.83	0.08	1.43	0.10	1.09	0.06	0.79	0.03
19	4.16	0.35	4.21	0.57	3.72	0.50	3.07	0.37	4.16	0.40
20	3.14	0.13	3.79	0.28	3.34	0.16	1.33	0.09	3.27	0.15
21	4.77	0.70	4.33	0.55	3.94	0.76	2.69	0.33	4.16	0.54
22	4.71	1.29	4.33	1.20	3.61	1.03	4.60	1.00	4.65	1.11
23	3.45	0.20	3.11	0.28	4.05	0.33	4.16	0.29	3.56	0.25
24	4.60	3.63	4.70	3.74	4.93	3.41	4.71	3.40	5.05	3.43
25	4.93	2.05	4.45	2.08	4.82	2.07	4.93	2.28	4.95	2.05
26	4.27	0.72	4.33	0.55	4.60	0.49	4.49	0.55	4.55	0.56
27	4.88	2.40	4.70	2.39	4.93	1.98	4.82	2.25	4.95	2.18
28	4.28	0.37	4.70	0.52	4.55	0.45	4.49	0.51	4.75	0.42
29	4.49	1.89	4.70	1.57	4.93	1.28	4.49	1.67	4.85	1.54
30	4.93	1.98	4.33	1.62	4.93	1.44	4.93	1.41	5.05	1.62
31	4.71	1.61	3.97	1.29	3.61	1.15	4.60	0.95	4.55	1.19

results for all monitoring wells in this paper so that only key trends will be outlined here. According to Fig. 8, all observational wells are divided into four main groups based on trend similarities, and a representative well within each category was chosen to reflect the groundwater drought outcomes. These are: the well identified as ID 1, which is typical of the group of wells that have significant decreasing trends; the well identified as ID 60, which also has a significant decreasing trend; the wells ID 50 and ID 14 that have significant increasing trends. According to the SGI results, drought in groundwater has developed in the study area in recent years and is progressively worsening. Negative SGI values marked in red (Fig. 9) indicate drought months, while values above zero indicate normal conditions, as shown in blue.

The drought conditions in well 1 started in 2014 and continued to 2020. The SGI value increased gradually. During recent years (2019–2020), this well experienced extreme drought conditions. As represented in this well, the drought conditions in most wells started in 2014 and continued to deteriorate until 2020. This well illustrates the drought condition in most of the wells of the study area. Extreme drought conditions in the well were recorded in 2019 with an SGI value of 2.2. The situation for well 60, which represents the wells with decreasing trends, is similar to well 1. The drought conditions in this well commenced in 2016 and continued to intensify until 2020. During 2019–2020, this well experienced extreme drought conditions with an SGI value of 2.2. The condition for well 50 is different. It has undergone several months of drought conditions during its operation. The drought

Table 2 (continued)

Wells	Spring		Summer		Autumn		Winter		Yearly	
	Z	Sen's slope	Z	Sen's slope	Z	Sen's slope	Z	Sen's slope	Z	Sen's slope
32	3.61	1.42	3.30	0.98	4.93	0.69	3.34	1.20	4.26	1.05
33	4.60	2.46	4.70	2.92	4.82	2.65	4.82	2.33	5.05	2.54
34	4.71	0.78	4.45	0.79	4.38	0.84	4.71	0.84	4.65	0.77
35	4.66	0.58	4.45	0.63	4.49	0.58	4.71	0.57	4.85	0.60
36	2.08	1.17	2.50	0.89	1.76	0.45	2.08	0.83	1.98	0.79
37	3.83	0.31	3.60	0.41	3.50	0.42	4.38	0.29	4.26	0.35
38	2.19	0.75	2.50	0.96	1.64	0.67	1.86	0.61	1.98	0.68
39	3.07	0.19	2.26	0.41	0.11	0.04	-0.11	-0.01	0.89	0.06
40	4.38	1.77	4.58	2.02	4.38	1.84	4.05	2.05	4.35	1.86
41	4.05	4.04	4.58	2.85	4.27	3.48	3.94	3.67	4.16	3.29
42	-3.50	-1.80	-4.21	-1.81	-4.05	-1.75	-3.94	-1.53	-4.45	-1.68
43	0.66	0.08	0.24	0.02	-1.75	-0.19	-2.30	-0.36	-1.39	-0.15
44	-2.80	-0.33	-2.87	-0.54	-3.61	-0.55	-2.74	-0.42	-2.77	-0.48
45	2.36	0.11	3.55	0.12	1.04	0.05	2.97	0.06	2.57	0.09
46	4.16	1.73	3.60	1.54	3.39	1.29	3.61	1.48	3.76	1.33
47	4.38	1.51	4.58	2.05	1.97	2.73	1.70	1.31	3.17	1.63
48	3.18	1.11	3.42	0.70	2.63	0.69	4.05	1.13	3.17	0.91
49	1.53	0.17	3.97	0.21	1.87	0.09	2.58	0.17	2.97	0.15
50	-1.59	-0.11	2.75	0.19	0.00	0.00	2.36	0.06	-0.55	-0.01
51	-1.20	-0.14	-1.47	-0.22	2.08	0.28	-0.60	-0.07	0.20	0.02
52	4.82	3.52	4.45	3.92	4.82	3.32	4.27	2.96	4.85	3.29
53	4.82	3.80	4.58	4.51	4.93	4.61	4.82	4.28	5.15	4.26
54	4.44	1.00	3.97	2.87	4.38	2.00	4.71	2.30	4.85	2.03
55	4.71	2.49	4.58	2.23	4.93	2.75	4.93	2.43	5.05	2.42
56	3.23	0.76	4.21	0.50	3.50	0.76	2.19	0.73	4.11	0.62
57	4.82	0.67	4.58	0.52	4.38	0.53	4.77	0.49	4.55	0.55
58	3.67	1.61	3.97	1.64	3.89	1.62	4.11	1.93	4.55	1.59
59	4.60	2.06	4.58	2.41	4.38	2.38	4.49	2.68	4.65	2.35
60	2.25	1.16	1.77	0.96	1.31	0.87	1.65	1.07	1.68	0.95
61	2.69	1.57	4.58	1.54	3.83	1.51	2.30	1.19	3.56	1.28
62	3.15	0.07	1.65	0.09	3.72	0.15	1.98	0.03	1.93	0.06
63	4.93	1.15	3.18	1.02	4.16	1.13	4.11	0.98	4.65	0.91
64	-2.85	-0.21	1.83	0.17	4.77	0.45	2.96	0.12	2.38	0.11
65	3.18	2.08	4.70	1.69	4.82	1.87	4.82	1.51	5.15	1.88
66	4.05	2.43	4.45	2.23	4.82	2.34	4.88	2.42	5.05	2.30

Values that are bolded illustrate significant trend at 95% confidence interval

conditions appeared in this well alternatively from 2006 to 2011 and 2014 to 2020. A particularly high SGI value of 3 occurred in 2008 in this well.

The condition for well 14 is entirely different because it shows the positive trends in its group of wells. Drought in this well started in 2006 and ended in 2014. Again, it

appeared in 2018 and continued to 2020 but generally with much lower SGI values than in the previous group of wells, although this well experienced extreme drought had an SGI value of 2 in 2014. There are only a limited number of wells in the study area that show positive water level trends.

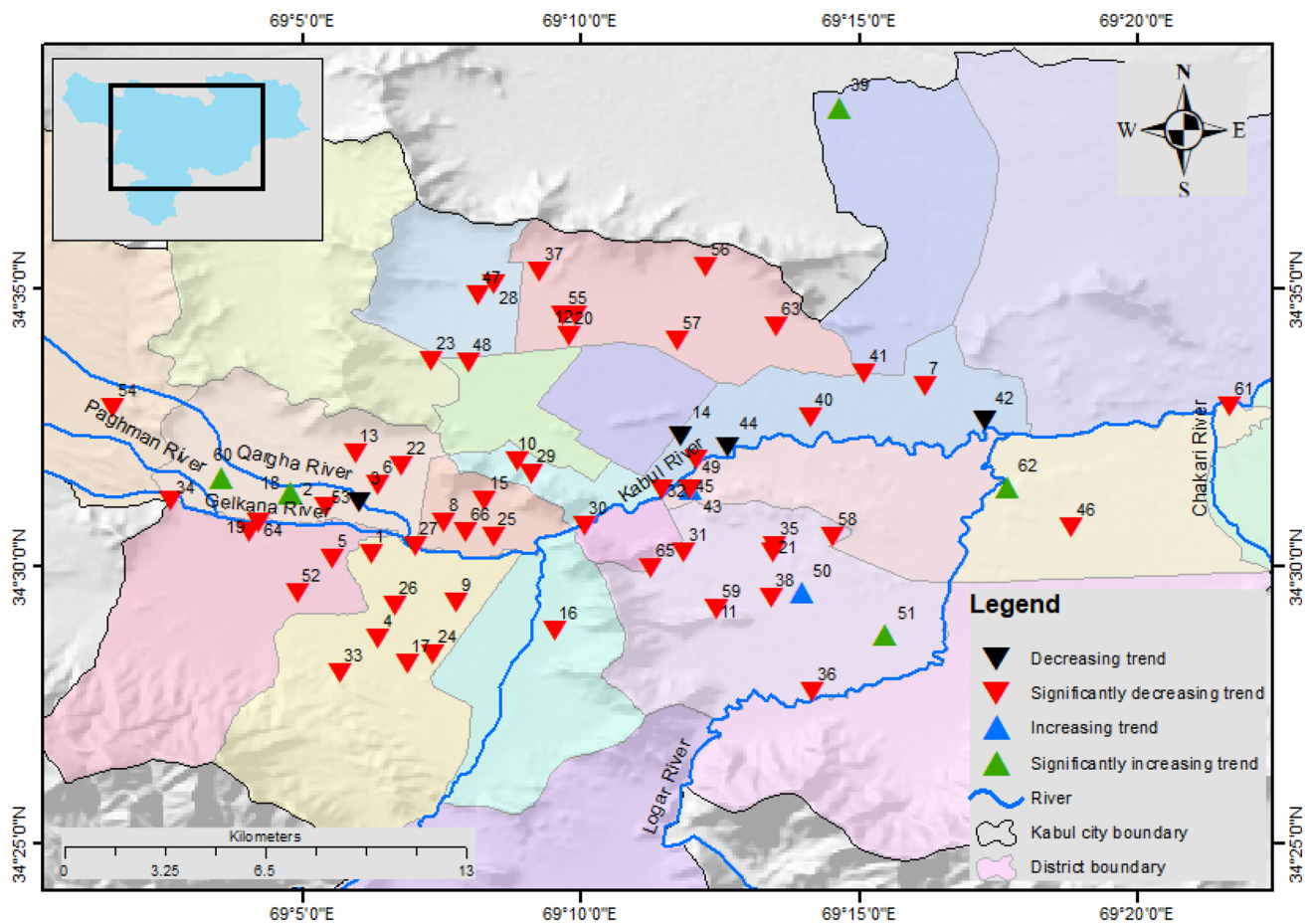


Fig. 8 Annual groundwater level trends

The SGI evaluation revealed that most of the wells in the city have been experiencing severe and ongoing drought since 2014. However, from a climate change perspective, rainfall in one of the meteorological stations shows a decreasing trend. It cannot be said that the decrease in groundwater level and drought in groundwater is due only to the reduction of rainfall. Consequently, analyzes linking meteorological factors to groundwater drought are needed to understand the dynamic nature of groundwater drought by considering LULC changes and groundwater aquifer structures. This helps reduce the effects of groundwater drought vulnerability in a given area.

It can be inferred that the wells with IDs of 1 and 60, which have significant declining water levels, have been experiencing severe and continuous drought since 2014 and 2016. The groundwater drought is similar to all other wells of these two groups. The condition in well 50 is different. This well belongs to a group of wells that showed an increasing water level trend. Therefore, the well 50 experienced several short periods of drought conditions which can be very intense. Well 14, which belongs to a group of wells

showing significant increasing water levels, experienced continuous drought conditions before 2014. Subsequently, water levels increased in the well up to 2017. The signs of drought again appeared in 2018 and continued to 2020.

The observation of persistent and frequent drought conditions that have been observed in representative wells in each group is of concern for the ongoing management of groundwater resources in Kabul. The calculated SGI values in well numbers 1 and 60, which represent a large part of the study wells in the city, are indicative of the extent and severity of groundwater depletion in the region and indicate that management measures are urgently needed to address the situation.

Rainfall conditions and groundwater levels

Groundwater levels in the region are likely to be influenced by variations in the magnitude, duration, and intensity of rainfall events. Daily precipitation data from 2009 to 2019 have been collected from NWARA. Among six

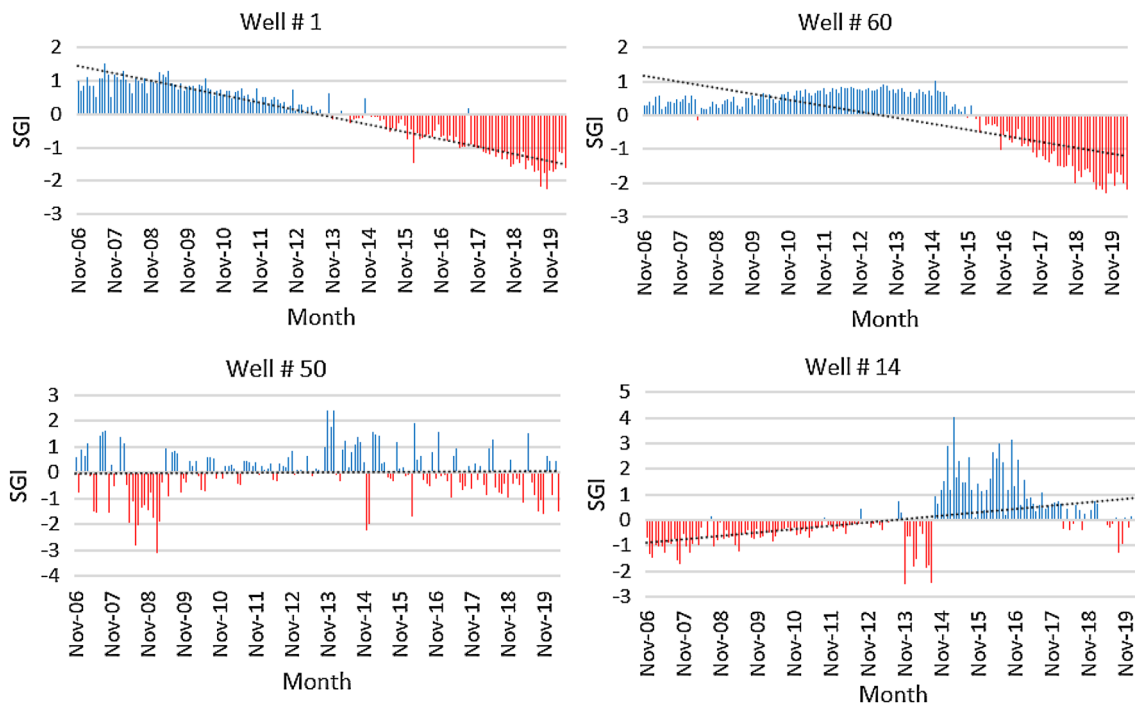


Fig. 9 SGI time series for representative wells

meteorological stations in the Kabul province, two stations (Payin-i-Qargha & Tangi-i-Sayedan) are located within the study area. The annual total precipitation and annual mean groundwater levels of all the wells have been plotted to visualize their relationships. As illustrated in (Fig. 10), total yearly rainfall has been plotted with annual mean groundwater level separately for both meteorological stations where the continuous lines present the groundwater depth; bar charts indicate precipitation, and dotted lines show linear trends.

Precipitation and groundwater depth have been graphically illustrated from 2009 to 2019. The chart displays the spatiotemporal distribution of two variables. From the chart, it can be seen that there is a correlation between precipitation and groundwater depth. The Payin-i-Qargha meteorological station shows a slightly increasing trend in precipitation, but the station in Tang-i-Sayedan indicates a decreasing trend in rainfall. The mean depth of groundwater, from the other side, is going deeper and shows a gradual trend. As seen from the graph, the annual rise in rainfall does not positively impact groundwater levels. For instance, the total precipitation in 2012 and 2014 has risen, but the average depth to groundwater still shows the same linear trend. Even the slightly increasing trend that appeared in the western part of the city (Payin-i-Qargha station) does not positively affect groundwater depth. As already illustrated in the trend evaluation of groundwater, some wells in the study area show positive trends. Such temporal variance can include a rough estimate of groundwater

recharge, although it will also be influenced by the LULC features, which can be measured concurrently.

Influence of land use/land cover on groundwater recharge

The extent to which groundwater recharge can take place in a rainfall event may also be influenced by land use and land cover (LULC). Human interactions such as the construction of roads and residential areas can increase the area of impermeable surfaces that may reduce groundwater recharge. Consequently, the process of urbanizing of agricultural land may reduce groundwater recharge.

Due to these factors, LULC patterns in the Kabul area were examined for 2005, 2010, 2015, and 2020 (Fig. 11). Six separate classes of LULC have been developed, and their accuracy has been measured using overall accuracy assessment and the Kappa index. The overall accuracy index for LULC classification in the study area for the years of 2005, 2010, 2015, and 2020 was determined to be 94%, 90%, 90%, and 90%, while the Kappa accuracy index was 91%, 86%, 86%, and 86%, respectively. The summary of LULC analysis of the study area is illustrated in (Table 3).

The urbanized area is a critical component of LULC, as it has a significant negative effect on groundwater recharge. The proportion of the study area that was covered by urban

development was determined to be about 15% in 2005, 20% in 2010, 27% in 2015, and about 32% in 2020.

The agricultural area is an important LULC component that can have a key role in groundwater recharge. A decrease in agricultural areas can be due to increased urbanization or decreased rainfall and desertification of agricultural land (conversion of agricultural areas to bare land). However, from 2005 to 2020, the area of agricultural land in Kabul decreased by only about 2%. On the other hand, the bare land is more permeable than built-up areas. Water melted by snow can cause the gradual feeding of groundwater in the bare land area. The area covered by bare land in the study area has decreased from about 67% in 2005 to 52% in 2020. The percentage of water bodies (Qargha Lake) has not changed over time. The marshland area also has decreased. The LULC analysis indicated that the number of trees in the study area has increased.

To sum up, the development of the city and built-up area will cause the reduction of agricultural and bare land area. City development would result in increased region coverage by impermeable surfaces and a decrease in groundwater recharge. Most monitoring wells are located in urban areas where artificial groundwater recharge measures would be required to increase groundwater availability.

Summary and conclusions

An extended period of seasonal and annual groundwater level trends has been assessed at 66 observational wells in Kabul city. Groundwater drought index (SGI) values were also calculated to measure the severity of drought in groundwater. After data imputation processing was performed, the trends were undertaken to fill the measurement gaps in water level records. Cluster classification was used to label the wells based on correlations with groundwater table variations. Evidence from the elbow approach indicated that three clusters are necessary to classify the water level variability into distinct groups. Cluster 1 consists of 32 wells with an average annual rate of groundwater decline of 1.38 m. Clusters 2 and 3 contain 15 and 8 monitoring wells, respectively, with significant negative average groundwater level trends of 0.31 m and 2.84 m per annum. A substantial increase in annual groundwater level was found in four observational wells, with an overall gain of 0.7 m/year.

According to the results of annual and seasonal trend assessments, most of the groundwater levels in wells in the area are declining. Based on the trend analysis of wells in the various clusters, the water levels in 89% of cluster 1 wells and 82% of all study area wells consistently declined. The calculation of SGI values has indicated that most wells in the research region have been experiencing severe and ongoing drought since 2014. The drought conditions in most

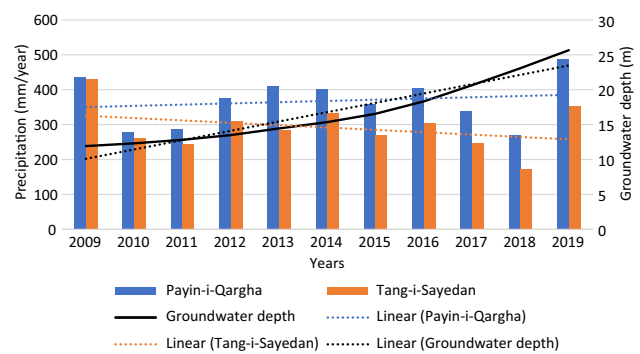


Fig. 10 Rainfall and groundwater level time series

wells started in 2014 and have generally intensified to 2020. Most of the wells experienced extreme drought conditions during 2019–2020. Additionally, some wells in different clusters have shown the effects of groundwater drought. For instance, well 50 has experienced several months of drought conditions during its operation. The SGI values for this well indicated that drought conditions appeared in this well alternately from 2006 to 2011 and 2014 to 2020. The extreme drought in this well was recorded in 2008 with a magnitude of greater than 3 SGI.

Wells with positive water level trends show different behavior. For instance, in well 14, drought conditions started in 2006 and ended in 2014. They reappeared in 2018 and continued to 2020, but the SGI values were generally low compared to many other wells. However, this well-experienced extreme drought conditions in 2014 when the SGI value was greater than 2. Only a few wells in the study area exhibited this type of water level behavior.

Land use and land cover (LULC) patterns for the Kabul area were investigated for 2005, 2010, 2015, and 2020. The built-up area, which has a significant negative impact on groundwater recharge, increased from about 15% in 2005 to 32% in 2020 in the study area. From 2005 to 2020, the area of agricultural land use decreased from about 17% to 15%. The area covered by bare land in the study area has decreased from 67% in 2005 to 52% in 2020. Precipitation records, especially in the southern region of the study area, show a decline in the annual rainfall amount. Changes in LULC and decrease in precipitation are the two influential factors in reducing groundwater levels.

Overexploitation of groundwater due to population increase, the dryness of the riverbeds, the extent of urban development, the reduction of rainfall, and the mismanagement of groundwater resources are likely to be the leading causes of groundwater level declines in the area. To avoid further deterioration of valuable groundwater resources, this report suggests artificial groundwater recharge and advanced groundwater resource management, as well as the parallel utilization of surface and groundwater. This study would

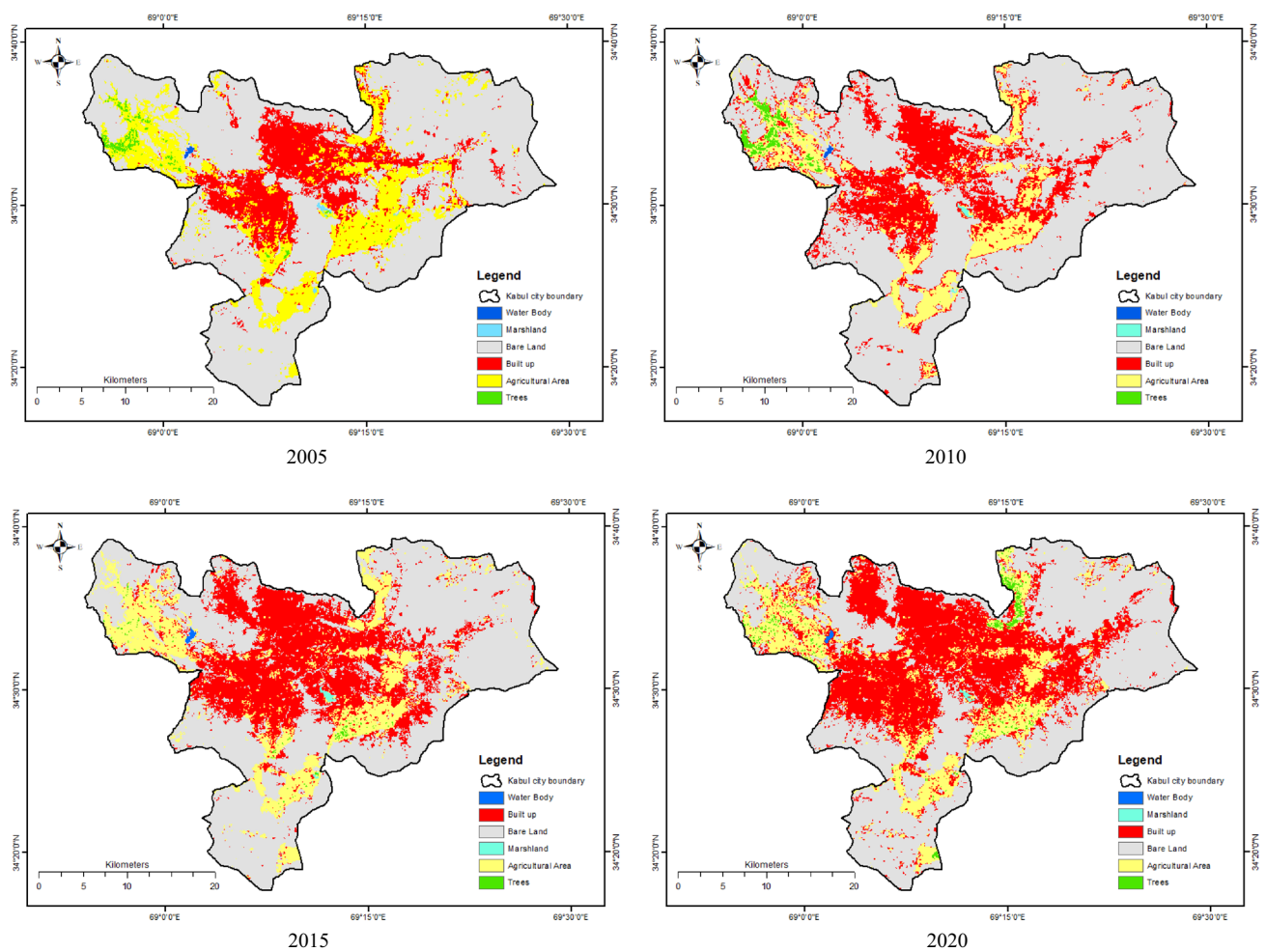


Fig. 11 LULC maps of the study area

Table 3 Areal specification of LULC class

Classes	2005		2010		2015		2020	
	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)	Area (km ²)	Area (%)
Water body	0.76	0.07	0.70	0.07	0.9621	0.09	0.70	0.07
Marshland	1.09	0.11	1.02	0.10	1.3833	0.13	0.79	0.08
Built up	157.90	15.33	209.79	20.36	275.0058	26.70	328.45	31.88
Bare land	687.52	66.73	691.66	67.14	589.8357	57.26	538.17	52.24
Agricultural area	175.73	17.06	117.09	11.37	160.4259	15.57	151.50	14.71
Trees	7.32	0.71	9.98	0.97	2.5479	0.25	10.51	1.02
Total	1030.32	100.00	1030.22	100.00	1030.16	100.00	1030.13	100.00

help implement regional groundwater policies for long-term water supply development in the Kabul Basin.

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Declarations

Conflict of interest Authors do not have any conflict of interest.

Availability of data and material The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code availability Not applicable.

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