



Rainfall Assessment and Water Harvesting Potential in an Urban area for Artificial Groundwater Recharge with Land Use and Land Cover Approach

Ali Reza Noori^{1,2} · S.K. Singh¹

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Abstract

Cities in arid and semiarid regions face the dual challenges of managing urban floods and water shortages, threatening their sustainability. Urban areas are particularly vulnerable to flooding despite minimal rainfall and are prone to drought. This is evident in the capital of Afghanistan, Kabul, where groundwater decline and urban floods pose severe challenges. This study investigates the possibility of utilizing rainwater harvesting (RWH) to manage urban floods and recharge groundwater. The research examines various aspects of rainfall patterns, such as variability, rainy days, seasonality, probability, and maximum daily precipitation. The analysis of precipitation statistics reveals that rainfall exceeding 30 mm occurs approximately every 3–4 years. Rainfall in Kabul follows a seasonal pattern, with a coefficient of variation of 127% in October and 46% in February during the wet period. The study then assesses the potential of RWH in Kabul City as a solution for stormwater management and groundwater recharge. Based on the typology of land use and land cover, implementing a rainwater harvesting and recharge system (RWHRs) could increase mean annual infiltration from 4.86 million cubic meters (MCM) to 11.33 MCM. A weighted Curve Number (CN) of 90.5% indicates impervious surfaces' dominance. The study identifies a rainfall threshold of 5.3 mm for runoff generation. Two approaches for collecting rainwater for groundwater recharge are considered: RWHRs for a residential house with an area of 300m², which yields approximately 88m³/year, and RWHRs for a street sidewalk to collect water from streets and sidewalks. These findings highlight the potential of RWHRs as an effective strategy for managing urban floods and recharging groundwater artificially.

Keywords Kabul · Groundwater · Rainwater Harvesting · Groundwater Recharge

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1 Introduction

Water, vital for life, faces major challenges in quantity and quality. These challenges are due to climate change, population growth, and urban and industrial expansion in cities worldwide. In arid and semiarid regions, people rely mainly on groundwater as their primary water source (Noori and Singh 2021a). Unfortunately, excessive usage and continuous extraction often lead to the depletion and scarcity of this valuable resource. Approximately 2.5 billion people rely solely on groundwater for their daily needs, accounting for 50% of the global drinking water supply. The growing dependence on these resources has resulted in a global dilemma regarding access to clean groundwater (Sarma and Singh 2021). Roughly 26% of the world's renewable freshwater supplies come from.

Kabul, a city with a population of over four million, relies heavily on groundwater resources to meet its water needs. However, a recent trend analysis conducted by (Noori and Singh 2021b) suggests that the water levels in the aquifers of the Kabul Plain have significantly decreased. The study highlighted that certain observational wells in Kabul experienced a decline rate of more than 2 m per year. Findings of previous studies indicate that the quantity and quality of Kabul's groundwater are seriously threatened (Mack et al. 2009, 2013; JICA 2011; Taher et al. 2013; Zaryab et al. 2017; Brati et al. 2019; DACAAR 2019; Jawadi et al. 2020, 2022). Groundwater challenges in the Kabul Plain stem from population growth, excessive water consumption, urbanization, soil impermeability, and climate change. A pilot project called the Kabul Managed Aquifer Recharge Project (KMARP) was implemented in Kabul, specifically at four designated sites (Noori and Singh 2021a). This project aimed to evaluate the feasibility and effectiveness of managing groundwater recharge (MAR) as a potential solution to combat water scarcity in the city.

Rainwater harvesting is a traditional technique used to tackle water scarcity in arid and semiarid regions. Ancient civilizations have employed it to meet their drinking and agricultural water needs (Mahmoud et al. 2014).

Rainwater harvesting has become popular for increasing surface and groundwater supplies to meet water resource needs. Numerous research studies have recently been conducted regarding rainwater collection techniques and their applications (Dhakate et al. 2013; Gwenzi and Nyamadzawo 2014; Jung et al. 2015; Sayl et al. 2016; Tiwari et al. 2018; Wu et al. 2018; Sadeghi et al. 2019; Matomela et al. 2020). In modern times, rainwater harvesting is recognized as a sustainable adaptation strategy in urban areas, helping to mitigate water scarcity and manage flooding problems (Gado and El-Agha 2020; Zabidi et al. 2020; Krishna et al. 2021; Ranaee et al. 2021). In urban areas, hydrological issues arise from changes in surface runoff and river flow, reduced infiltration and groundwater recharge, and the presence of impermeable surfaces (Nachshon et al. 2016). Traditional rainwater harvesting involves collecting and using rainwater for various purposes. However, a new approach to collecting rainwater to replenish underground aquifers has gained attention (Ghazavi et al. 2018; Hussain et al. 2019; Qi et al. 2019; B R and Lokeshwari 2021; Huang et al. 2021).

Inadequate management of rainfall and surface runoff can result in severe urban flooding. These floods can have numerous detrimental effects, including disruptions to daily life, damage to infrastructure, erosion of riverbanks and riverbeds, contamination of water resources, and loss of life. Urban floods also have significant economic and environmental consequences, impacting traffic systems, water and electricity supply, and telephone lines and causing socio-cultural disturbances. Urban flooding poses a significant problem

in Kabul City. According to a study by (Manawi et al. 2020) there have been substantial changes in land use and land cover pattern in North Kabul from 1964 to 2009. The study reveals a 15% reduction in green areas, a 27% decrease in bare soil, and a 51% increase in impervious surfaces. The primary factors contributing to urban floods in Kabul are unsustainable urbanization, inadequate drainage systems, and significant alterations in land cover.

Implementing a water harvesting strategy can help mitigate water loss from surface runoff and enhance water resource availability in various settings, including watershed systems, metropolitan areas, and regions with unequal water distribution. As urban populations grow and develop, land surfaces become less porous, leading to floods even with minimal rainfall. Rainwater harvesting (RWH) can serve as a supplementary water source in arid and semi-arid urban areas, helping to address water scarcity challenges. The current study will concentrate on rainwater harvesting strategies incorporating infiltration of the captured water to groundwater, referred to as a “rainwater harvesting and recharge system” (RWHRs). This study aimed to exhibit the precipitation variability and concentrations and look for appropriate management strategies for urban flooding and groundwater recharge using RWHRs approaches in the Kabul basin. The study’s discoveries provide additional understanding of the rainfall patterns in Kabul city and the use of rainwater harvesting strategy, particularly the RWHRs, to tackle water scarcity and control urban flooding in urban areas. The RWHRs methods can be adapted to support sustainable water resources management in arid and semiarid areas to overcome water scarcity, MAR, and urban flooding problems.

2 Materials and Methods

2.1 Study Area

The study area is the Kabul Basin (JICA 2011), which encompasses most of Afghanistan’s capital city of Kabul. The study area is situated between 34°36’30” and 34°24’40” N latitude and 69°01’25” and 69°22’30” E longitude in the country’s central-east (Fig. 1). The basin has a total area of 487 km². The research region has arid to semiarid climatic conditions. The basin’s highest and lowest average temperature ranges were 32°C in July and –7°C in January (Zaryab et al. 2017). Built-up is the most prevalent land use type in the study area. It is the country’s leading national commercial base, and many refugees returned to their homeland after 2001, mostly settling in Kabul city.

Additionally, many neighboring provinces’ residents migrated to Kabul for employment. Mountain ranges that are low yet relatively steep surround the basin. The elevation of the basin ranges from 1763 to 2823 m. Generally, the mountains in the southern and southwestern boundaries are higher than the others.

Three rivers are entering the city of Kabul. Paghman River spills out from east to west. The Maidan River (Kabul River) arrives at the study area from the south and flows 21 km before joining the Paghman River. The Logar River, an enormous tributary of the Kabul River, flows south-north and joins the Kabul River around 17 km downstream of the Paghman waterways mouth.

The common surficial geological forms confirmed in the Kabul basin are conglomerate and sandstone, loess, metamorphic rocks, limestone, fan alluvium and colluvium, gneiss, limestone and dolomite, sandstone and siltstone, ultramafic intrusions and river channel

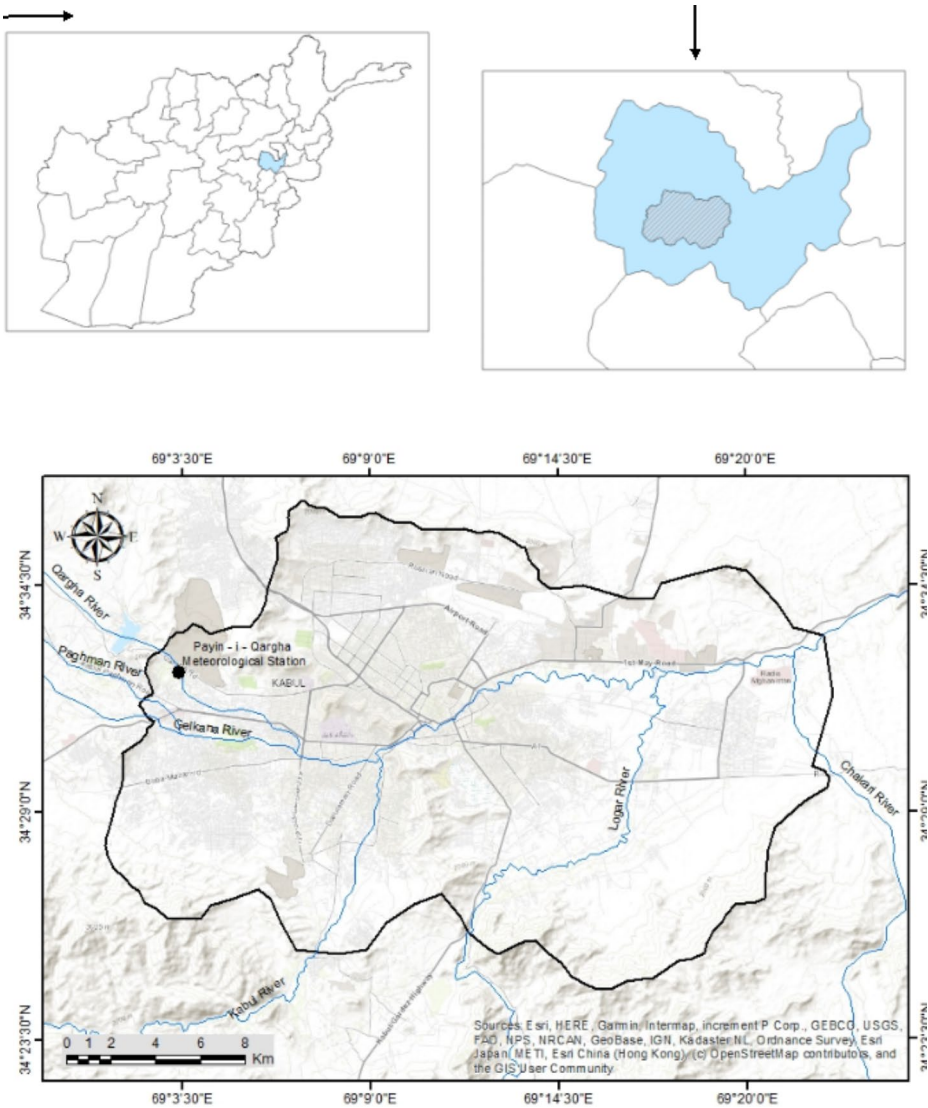


Fig. 1 Location map of the study area

alluvium. A collection of terrestrial and lacustrine deposits, primarily uncemented and semi-consolidated lacustrine, fluvial, and aeolian sedimentary rocks, including sand, gravel, and silt from the Quaternary and Neogene eras, is present across the Kabul Basin (Tünnermeier and Houben 2005; Mack et al. 2009; Zaryab et al. 2017).

According to (JICA 2011), there are three main aquifer clusters in the study region: The shallow aquifer is located within the alluvial deposits and a deeper aquifer in Neogene layers (“the upper Neogene aquifer”), and a deep aquifer (“the lower Neogene Aquifer”). According to some available literature, the city encompasses four major interconnected aquifers (Uhl and Tahiri 2003; Pell Frischmann 2012; Zaryab et al. 2017). Meanwhile, shal-

low aquifers, also known as “Alluvial Aquifers” or “Quaternary Aquifers,” may be found across the city at different depths, albeit the deposits that store such groundwater are denser and have a larger groundwater potential near river systems.

2.2 Data Acquisition

Precipitation figures of six meteorological stations in Kabul province were obtained from the Department of Meteorology, General Directorate of Water Resources, Ministry of Energy and Water of Afghanistan for 2008–2020. The gathered data were in the form of daily logs from 2008 to 2020, which were then transformed into monthly and yearly totals for study. Only one meteorological station (Payin-i-Qargha), located within the research region, is considered out of the six stations for the current study. Since the data for 2008 and 2020 were incomplete, they were omitted from the analysis, and it was intended to consider the records from 2009 to 2019 only. Landsat imagery was downloaded to create land use and land cover (LULC) identity maps for 2020. The required satellite data were obtained from USGS Portal (<https://earthexplorer.usgs.gov/>) using the address “path 153 and rows 36.”

2.3 LULC Development

The availability and sustainability of groundwater are impacted by several variables, including land use and land cover (Machiwal et al. 2011; Martin et al. 2017). Expanding impermeable land surfaces, such as asphalt, concrete roads, streets, and waterproof roof materials, would hinder groundwater recharge. To create the LULC map of the study area, remotely sensed Landsat-8 satellite data was analyzed. “Supervised classification approach with maximum likelihood algorithm” in ENVI 5.3. was applied to create the LULC of the study area (Fig. 2). The research area has bare land and rock, cropland and vegetation, settlements (built-up area), water bodies, and marshland. Built-up areas reduce the effect of groundwater recharge, whereas vegetation-covered regions provide better prospects for groundwater recharges.

2.4 Rainfall Analysis

In this study, many precipitation characteristics have been examined: variability, the number of rainy days, their distribution across the season, the likelihood of daily precipitation, and the highest amount of rainfall ever recorded in a day.

The precipitation concentration index (PCI) and seasonal index (SI) were introduced by (Oliver 1980; Walsh and Lawler 1981), and the contribution index (CI) (Mahmoud et al. 2014) were utilized to identify the irregularity and seasonal distribution of precipitation over the year.

Equation 1 was used to calculate the PCI using RStudio, while Eq. 2 was used to get the SI.

$$PCI = 100 \times \sum_{n=1}^{12} \left(\frac{X_n^2}{R^2} \right) \quad (1)$$

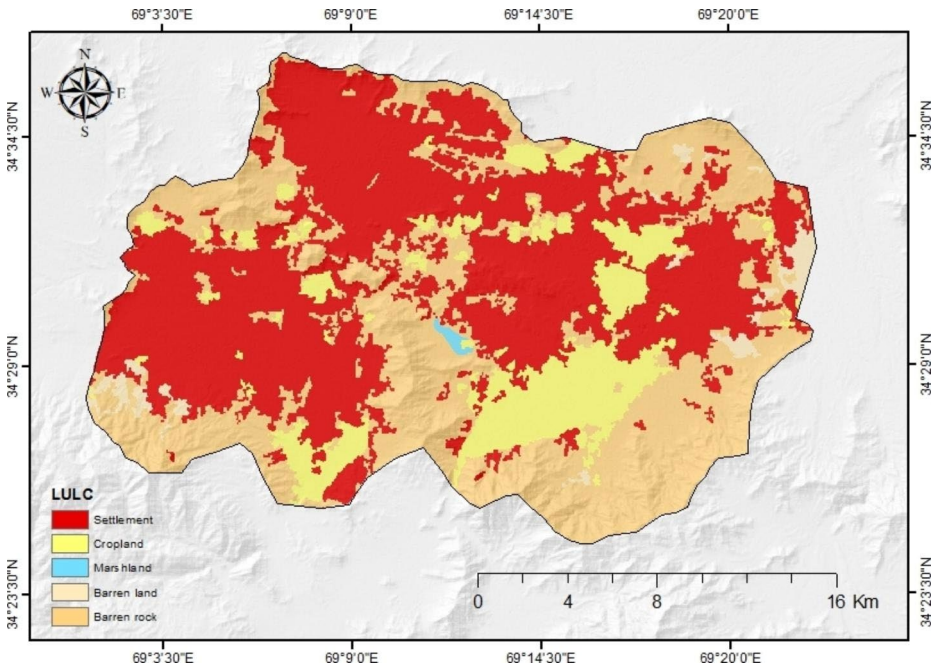


Fig. 2 LULC map of the study area

$$SI = \frac{1}{R} \sum_{n=1}^{12} \left| \frac{X_n - R}{12} \right| \quad (2)$$

R displays the yearly precipitation, and X_n indicates the rain in month n . The daily, monthly, or seasonal rainfall is calculated as a percentage of the annual total precipitation for the contribution index. By employing the Weibull method (Mansell 2003), daily precipitation data collected from Payin-i-Qargha meteorological station from 2009 to 2019 were statistically evaluated:

$$P = \frac{m}{N+1} \times 100 \quad (3)$$

Where P shows the probability of the precipitation (%), N is the data size, and m is the rank given to the data when sorted in descending order.

The probability of maximum daily precipitation and its return period were analyzed employing the Gumber distribution approach. The method is the limiting form of a large number of uniformly sized samples with an exponential starting distribution. The cumulative distribution is used to calculate the likelihood (percent) that a rainfall depth X (mm) will be greater than a specified rainfall depth x_0 (mm). (Mahmoud et al. 2014):

$$P(X \geq x_0) = 1 - e^{-e^{-y}} \quad (4)$$

Where y is a dimensionless variable and calculated as follows:

$$y = \frac{1.286(x - \bar{x})}{\sigma_x} + 0.577 \text{ where } x \text{ is variate} = \frac{\sigma_x(y_T - 0.577)}{1.2825} + \bar{x} \quad (5)$$

\bar{x} is the mean value and σ_x is the standard deviation of variate x , as well as y_T is the reduced variate for a given T

$$y_T = - \left[\ln. \ln \frac{T}{T-1} \right] \quad (6)$$

By determining the reduced mean y_n and reduced standard deviation S_n using tables based on the sample size, the frequency factor K can be calculated as follow:

$$K = \frac{(y_t - \bar{y}_n)}{S_n} \quad (7)$$

The following equation may be used to compute X_t by providing the value of K .

$$x_t = \bar{x} + K \sigma_{n-1} \quad (8)$$

2.5 Rainwater Harvesting Potential Based on LULC

Land use is a fundamental factor determining the likelihood of surface runoff, which directly affects how quickly rain and other precipitation permeates the ground. More porous surfaces become impenetrable as cities expand. Different sources have reported the permeability coefficients of various materials. (Nachshon et al. 2016), quoted from (Pauleit and Duhme 2000), illustrated the infiltration coefficients for the built-up and asphalt areas at 5%, pavement areas at 20%, woody and vegetation area at 25%, meadow, and pastures at 35%, arable land 40%, and bare soil 50%. Also, according to the argument by (Nachshon et al. 2016), the permeability coefficient for the built-up areas with (RWHRs) increases up to 80% and the remaining 20% they consider as the reason for evapotranspiration. As aforementioned, contrary to conventional rainwater harvesting (RWH) systems, which store the water on the land for individual use by the property owners, some researchers recently addressed the potential of rainwater for recharging the nearby aquifers through infiltration wells.

The site's hydrological, climatic, and surface area characteristics must be considered while building the infiltration well structure tools for the rainfall. Considering the hydraulic conductivity of the medium at the specific site of infiltration, it is necessary to create a deep enough infiltration well with a long filter length to allow sufficient water flow from the well into the ground to ensure the effective infiltration of collected rainwater into the aquifer without flooding the infiltration well system.

2.6 Groundwater Recharge

Estimating the rainwater infiltrating the underground water and the vadose zone depends on the target area's infiltration coefficients. And the infiltration coefficient is related to various factors such as soil hydraulic characteristics, topography, land surface coverage, etc. (Nach-

shon et al. 2016). For the different types of substrates mentioned in Table 1, (Nachshon et al. 2016) used an illustration from (Pauleit and Duhme 2000) to show the infiltration coefficients (Ic) values in percent, which indicate the portion of yearly rainfall that infiltrated underground.

Here, it is projected that 80% of the water is seeping into groundwater for RWHRs that route the gathered water from the collecting sites straight into the subsurface, either into the vadose zone or the aquifer. In other words, instead of the 5% shown in Table 1 for non-RWHRs situations, the Ic of constructed areas where RWHRs is applied is 80%. This cautious estimate permits a 20% water loss due to evaporation and retention along the RWHRs system. This percentage is most likely significantly lower than 20%.

By using the weighted arithmetic mean of various infiltration coefficients from regions with different land cover qualities (Ic(i)) and taking into account the associated surface areas (A(i)) of each LULC (e.g., built-up, bare soil, cropland, etc.), the effective infiltration coefficient (Ic_(eff)) can be calculated.

$$I_{c(eff)} = \frac{\sum (A_i \times I_{c(i)})}{\sum A_i} \tag{9}$$

The exact amount of infiltrated water into groundwater I (m³) is determined as:

$$I = A \cdot R \cdot I_{c(eff)} \tag{10}$$

Where A is the surface area (m²) through which infiltration is occurring, and R is the yearly rainfall (m). By assumption of three main land cover components in urban contexts (i.e., built-up, bare soil, and arable land), it is straightforward to estimate Ic_(eff) for any given area with any combination of the three components by knowing the Ic values for each of these constituents. According to Table 1, the infiltration coefficients (Ic) of built-up areas without RWHRs are equivalent to 5% and 80% for regions developed with RWHRs, 50% for bare soil, and 40% for arable land.

2.7 Surface Runoff

Due to drainage systems failing during extreme rain, extreme flooding events occur more frequently in urban contexts due to the combined effects of global climate change and the impervious nature of modern cities. Flooding threatens structures, additional public and private infrastructure, and people’s lives. Surface runoff must be decreased in urban settings to lessen the risk of flooding and the cost of drainage systems (Nachshon et al. 2016). RWHRs

Table 1 Infiltration coefficient of different surfaces (Nachshon et al. 2016)

Land cover	Ic (%)
Built up (without RWHRs)	5
Asphalt	2
Pavement	20
Woody Vegetation	25
Meadow and pastures	35
Arable lands	40
Bare soil	50
Built up (with RWHRs)	80

may be beneficial since it increases the quantity of water that permeates the subsurface instead of flowing as surface runoff.

A variety of circumstances influence runoff and rainfall relationships. Some refer to meteorological properties such as precipitation intensity, duration, and evapotranspiration. In contrast, others relate to physical factors of the surfaces receiving the precipitations, like their permeabilities and slopes. These elements function in how much of the rainfall depth is absorbed by the atmosphere, the surface of the earth, or both. Runoff coefficients were established to calculate the potential runoff from a given depth of rainfall. These coefficients show how much of the precipitation depth should be subtracted and accounted for as a loss to runoff.

The “Natural Resources Conservation Services (NRCS)” equation for rainfall runoff has been employed to determine the possible runoff from a rainstorm. The equation, formerly known as the “Soil Conservation Service (SCS)” approach for estimating direct runoff from rainstorms, was created by the “United States Department of Agriculture (USDA) in 1972” (Mahmoud et al. 2014). It is seen as either a probabilistic or deterministic model.

Since the only relevant rainfall data for this study were daily rainfall time series, applying this approach is ideal for the study region because it eliminates rainfall intensity and removes time as a component. The correlation between the land cover, the “Hydrologic Soil Group (HSG),” and the “Curve Number (CN)” is included in the model. A soil class with high CN values is impermeable and will have more runoff than infiltration:

$$Q = \frac{(P - I_a)^2}{P - I_a + S} = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (11)$$

Q represents the amount of daily runoff in mm, P represents the amount of daily precipitation in mm, S represents the region’s potential maximum storage (mm), and I_a represents the initial abstraction (usually taken as 0.2 S) in mm. The following equation indicates how much rainfall is directed to surface runoff by using CN, the runoff curve number of a hydrologic soil group and land cover combinations:

$$S = \frac{25,400}{CN} - 254 \quad (12)$$

According to (USDA 2009), the average CN values for impervious surfaces (built-up area) are about 98. For cropland, it is taken around 76; for bare land, it is assumed to be about 86. The following equation gives the weighted calculated curve number (CN_w) considering different land-use classifications of the study area.

$$CN_w = \frac{\sum CN_{wi}}{100} \quad (13)$$

Where CN_{wi} stands for the weighted curve number of the specific land cover.

2.8 Models for Rainwater Harvesting and Groundwater Recharge

Two models have been designed to use precipitation to replenish groundwater, avoid waste in terms of surface flows, and stop urban floods. The first model is used to collect and direct rainwater from residential houses to feed underground water, and the second model is employed to manage and control rainwater from the surfaces of roads and streets for groundwater recharge. The first case considers a typical residential home, where rainfall is collected and channeled to the groundwater recharge well (absorbing well) from the roof and the yard. The rainwater collecting channels collect the water from the roof and the yard and send it to the grease and oil trap basin.

Grease and oil traps allow water accumulation to be separated from grease and oil residues. It is constructed from a tank with a baffle wall in the middle. Water enters the basin from one side; solid particles sink to the bottom, while grease and oil float to the top. The clear water enters the basin's other side from under the baffle wall and exits to the sand filter.

Sand filters refine the water by passing it through fine sand to eliminate the tiniest contaminants. It comprises of a basin with a fine-sand layer and a gravel layer. The water enters the basin from above and passes through both of these layers to be purified. In order to prevent pore clogging, this filter also has to be backwashed sometimes. For backwash water that can have its overflow linked to municipal rainfall channels, a backwash water drying basin is also taken into consideration. The filtered water then enters in the recharge well which typically equipped with a casing, screen, gravel pack, and gravel bed.

Similarly, the second model is considered for collecting rainwater from roads and streets to direct it to groundwater recharge wells. The system of groundwater recharge wells can be constructed at a distance on the sides of the streets (pedestrian area). The rainwater from the road surface and sidewalk is collected through the closed channel on the side of the road equipped with screens and enters the sedimentation basin through specific chambers. The settling tank is separated into two separate parts by a buffer wall. The first part is the grease and oil separator, and the second is the settling tank. The settling tank is connected to a recharge well similar to recharge wells of residential houses based on construction. The settling tanks can be cleaned out regularly during the year.

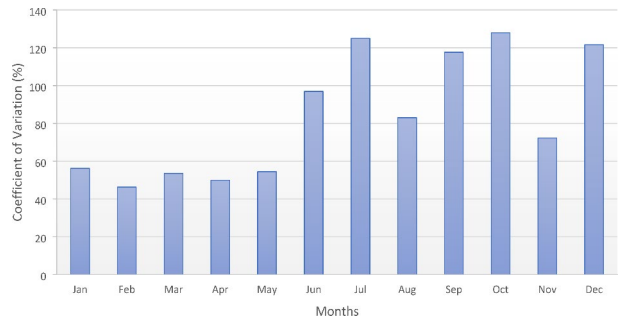
3 Result and Discussions

3.1 Rainfall Conditions

The rainfall in Kabul varies over the months, as seen in Fig. 3. The last six months of the year are the wettest according to the coefficient of variation, and the coefficient of variation for the rainfall during these months reached as high as 127% (October). In contrast, it is decreased during the first six months of the year and the coefficient of variation has a minimum value of 46% (February).

According to many indexes, Kabul has inconsistent, seasonal, and intense precipitation (Fig. 4). The most rainfall occurred during February, March, and April. In 2019, the first five months (January through May) had more than 83% yearly rainfall. In 2019, the two wettest months (February and April) alone saw up to 45% of the annual precipitation.

Fig. 3 Variability of precipitation during normal times as determined by the coefficient of variation



Given the region's yearly rainy days, concentration feature, and low overall quantity of precipitation, understanding how much rain falls over a day is crucial. For the time series depicted in Fig. 5, the mean annual rainfall is 368 mm, with an average rainy day of about 80 days each year.

According to Figs. 5 and 2019 had the most precipitation, totaling 486.21 mm. The minimum amount of rainfall happened in 2018, with a total record of 269.4 mm. The maximum daily rain has recorded on 17 March 2014 with a rainfall amount of 80.77 mm, which caused floods with an inundation level of 60 to 80 cm (Manawi 2020). According to the maximum rainfall record of the meteorological station, the minimum (from the daily ultimate precipitation record) precipitation was observed on 28 January 2010 with a precipitation amount of 18.04 mm. According to observations of rainy days, the research region experienced a minimum of 30 rainy days in 2017 and a maximum of 102 rainy days in 2019.

The Weibull approach's probability analysis for 2009 to 2019 (Fig. 6) shows a return period of 3 to 4 years for daily rainfall of less than 30 mm. Therefore, the previously described urban issues, such as street floods, would happen every 3–4 years. The quantity of 80.77 mm, which has a return cycle of ten years, was the largest amount of rainfall recorded in 2014 thus far.

The statistical analysis used the Gumbel technique for rainfall extremes and produced mean and standard deviation values of 36.87 mm and 18.23 mm, respectively. Consequently, the constants y_n and S_n Eq. (7) had respective values of 0.4996 and 0.9676. Figure 7 depicts the probability curve for the highest daily precipitation.

Using Eq. (6), a return period of 1 to 5 years is calculated for the threshold rainfall depth of 55 mm, which is expected to enhance the danger of flooding in the city. For the 122 mm record, a return time of about 150 years has also been discovered. The findings described above demonstrate a high likelihood that the problematic runoff from the 55 mm precipitation will reoccur. As a result, there is a very high likelihood that RWH will occur in the urban region of the Kabul basin.

3.2 RWHS vs. non-RWHS Conditions

Based on a developed LULC map, the $I_{c(\text{eff})}$ was estimated for the research region under the circumstances with and without RWHS. As stated previously, it is expected that the primary land covers of the urban environment are built up having I_c of 5% without RWHS, and 80% with RWHS, arable land with I_c of 40%, and barren soil with I_c of 50% has been applied. After segregation of LULC of the study area, built-up, bare land, and arable land,

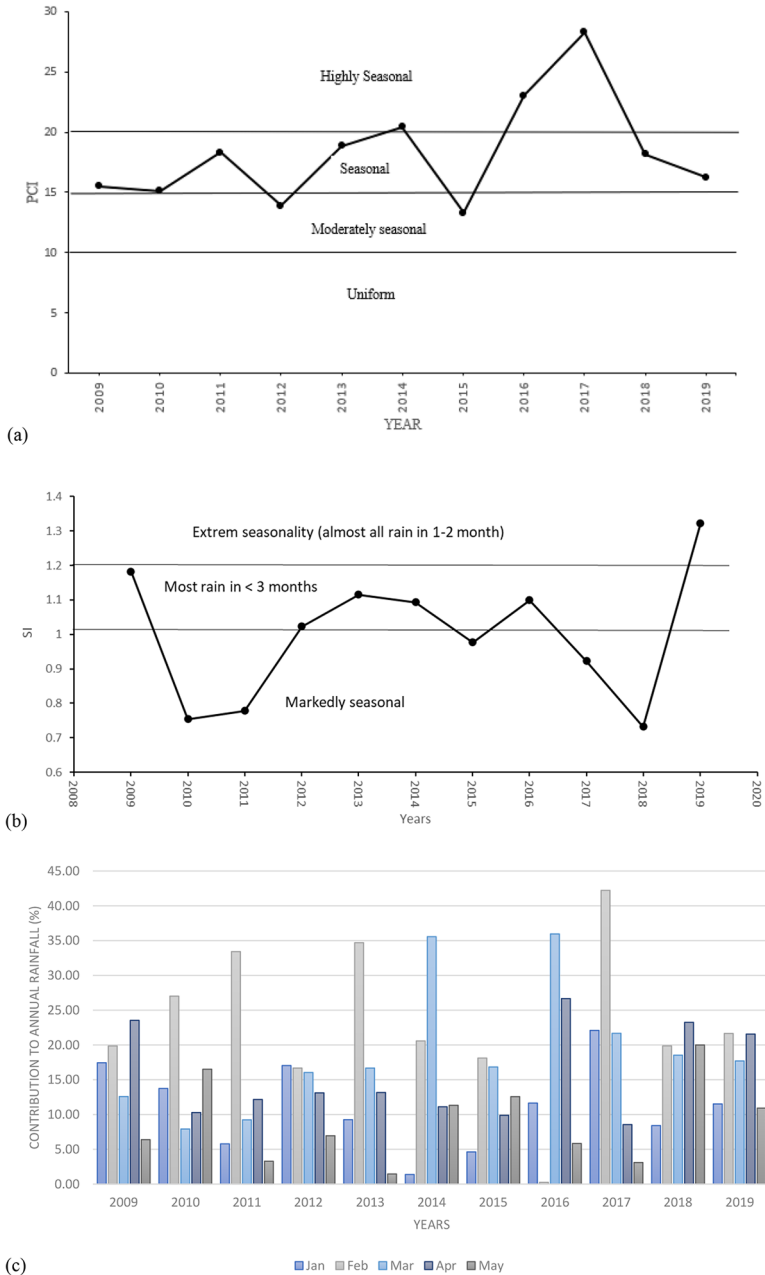


Fig. 4 The seasonality and concentration of precipitation (a) precipitation concentration index, (b) seasonality index, and (c) average percent contribution to annual rainfall

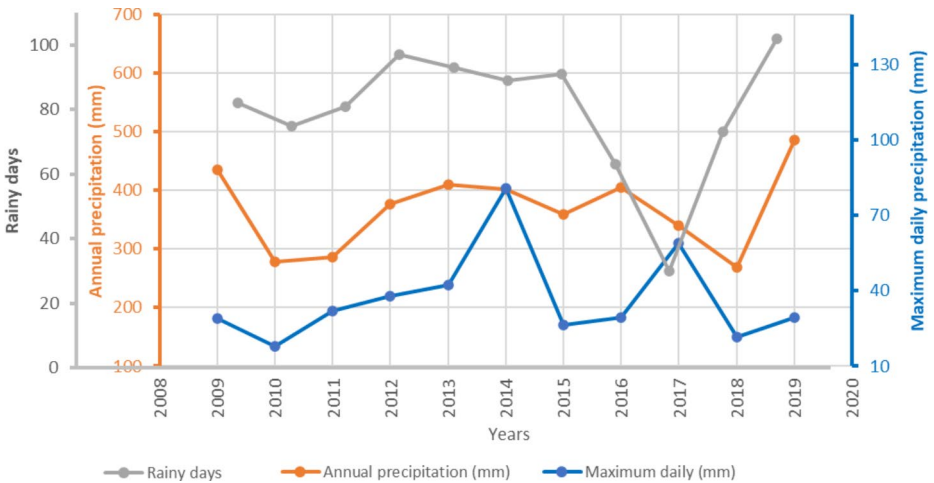


Fig. 5 Time series of annual precipitation, daily maximum precipitation, and yearly rainy days

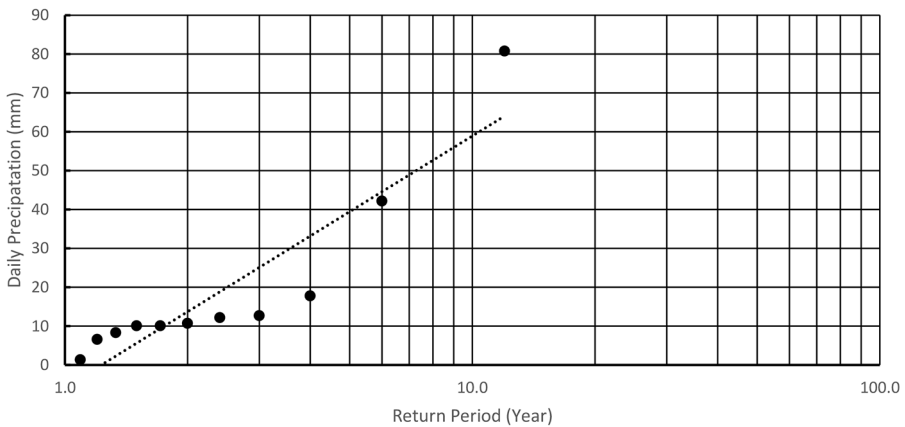


Fig. 6 Daily precipitation probability curve from Jan 2009 to Dec 2019

as well as their I_c , it was possible to compute the total $I_{c(eff)}$ of the entire region employing (Eq. 9).

The spatial proportion of each LULC is illustrated in Table 2, including the computed $I_{c(eff)}$ and groundwater infiltration rates for RWHRs and non-RWHRs situations with $R=368$ mm (average yearly rainfall at the region from 2009 to 2019 data from Payin-i-Qargha meteorological station). The significance of groundwater recharge by RWHRs for the regional and municipal water cycles is illustrated in Table 2. According to Table 2, compared to non-RWHRs circumstances, RWHRs will increase $I_{c(eff)}$ by factors of 2.33 for the studied area.

Implementing RWHRs across the entire built-up area of the city may increase average annual infiltration from 4.86 MCM (million cubic meters) to 11.33 MCM for $I_{c(eff)}$ values of 27.13% and 63.18%, which are calculated for study area for non-RWHRs and RWHRs con-

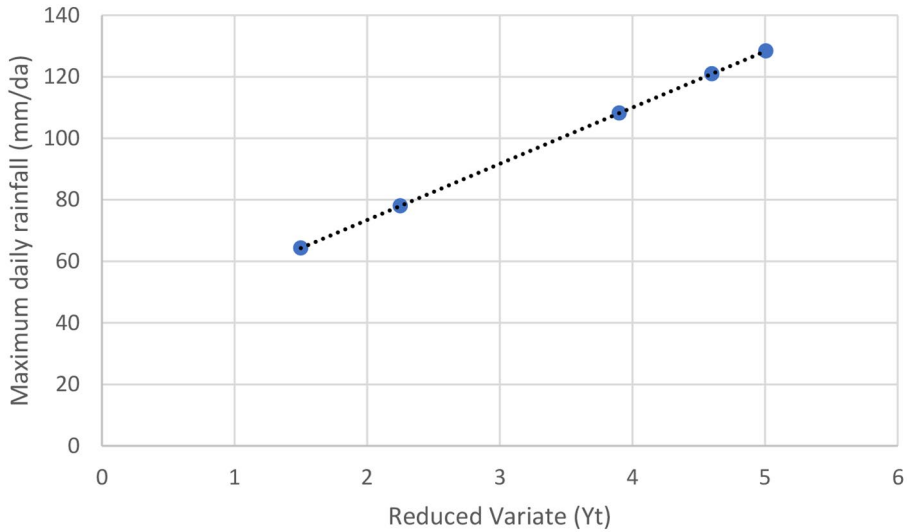


Fig. 7 Maximum daily rainfall probability curve (2009–2019)

Table 2 Calculated spatial proportion of LULC and their influence on $I_{c(eff)}$ and groundwater recharge in the Kabul basin

LULC	Total area	Spatial fraction (%)	Calculated $I_{c(eff)}$		Calculated groundwater recharge (cu.m)	
			Without RWHRS	With RWHRS	Without RWHRS	With RWHRS
Built up	234.2079	48.06	27.13%	63.18%	4,864,510	11,328,409
Arable land	60.381	12.39				
Bare Soil	192.6495	39.53				

Table 3 Curve Number values based on LULC.

No.	LULC	Area (sq. km)	Land cover area (%)	CN (%)	CNwi (%)
1	settlement (impervious area)	234.21	48.07	98	4710.707
2	cropland	60.38	12.39	76	941.8297
3	barren land	9.63	1.98	86	170.0537
4	barren rock	183.01	37.56	86	3230.306
Total		487.2384	100		9052.896

ditions, respectively. This value is obtained according to the total size of Kabul City (487.24 km²) and the annual rainfall (368 mm). This straightforward calculation indicates how the Kabul Basin’s groundwater recharge might rise by 6.5 MCM due to the deployment of RWHRS, which is more than 200% greater than groundwater recharge under non-RWHRS conditions. The computed $I_{c(eff)}$ of 63.18% has a limited potential to create severe flood

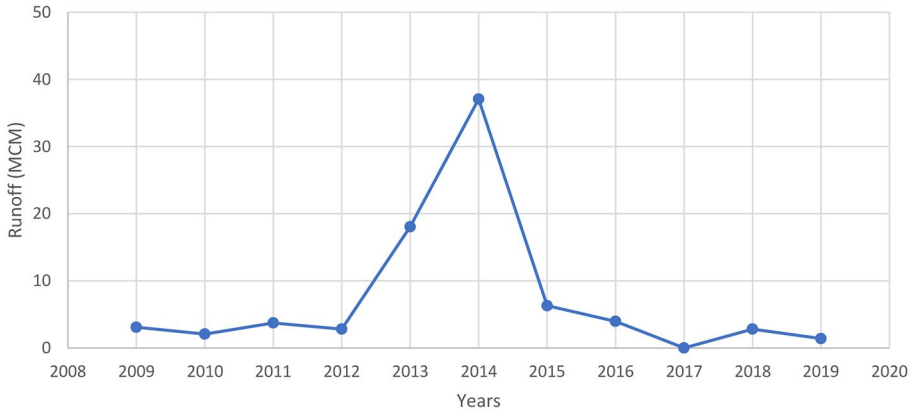


Fig. 8 Potential runoff time series

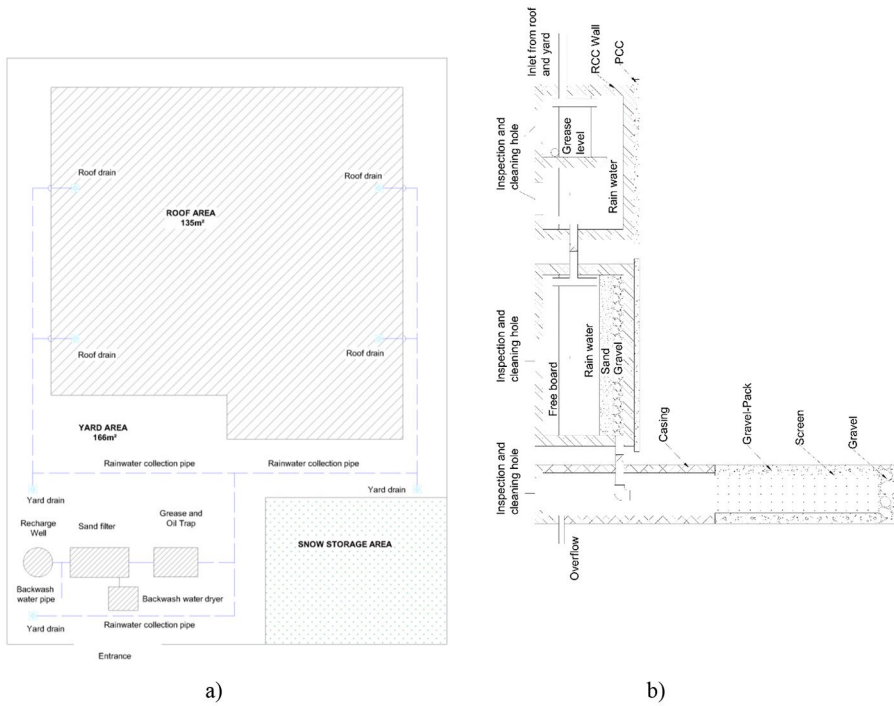


Fig. 9 The proposed RWHS structure for residential houses a) location plan b) cross-section of recharge structures

events concerning surface runoff. Based on Eqs. (3) , (4), and (11), (12) it is predicted that implementing RWHS in the study region will result in a 36% reduction in surface runoff volumes for an average land cover of 48% built-up, 12% arable land, and 40% barren land. Please remove the text from here to the end of this paragraph. (11) (12),r

3.3 Surface Runoff Estimation

The land-use map of the Kabul Basin is depicted in Fig. 2. The correlation between rainfall and runoff is determined by the land cover, which equates to the soil's ability to retain water. The region is divided into five types: settlements, cropland, marshland, barren land, and barren rocks. According to soil characteristics studied by (Ahmadzai and Omuto 2019) the soil is deep and varies in texture from sandy loam to loam and clay. Therefore, based on soil classification by (USDA 2009) the hydrological soil group of the area is assigned to group B. Soils in this group have moderately low runoff potential when thoroughly wet.

The CN_{wi} values for each land use class are displayed in Table 3 concerning the associated region. The area's domination of impervious surfaces is confirmed by the CN_w value, which is determined to be 90.5% (Eq. 13). The initial abstraction and maximum soil retention are equal to 26.6 mm and 5.3 mm, respectively when the CN_w value is substituted in Eq. (12). This allows for the determination of the probable runoff depth for the daily precipitation. The amount of rainfall required to generate runoff is discovered to be 5.3 mm.

The highest daily precipitation for the year 2014 was 80.77 mm (Fig. 5). The accompanying runoff depth (potential) is calculated to be about 74.7 mm, resulting in a surface runoff volume of roughly 37 MCM (Fig. 10). Since many rainfall-runoff models employ a rainfall threshold of 5 mm/event for runoff production, the US-NRCS technique provides a fair approximation of the rainfall-runoff relationship in the research region (Mahmoud et al. 2014) A projected runoff volume of 18.06 MCM would result from the 42 mm rainfall that occurred in 2013 as an intense rainstorm event. This volume is far more than the capacity of the urban drainage system and has a return period of 5 years (Figs. 6 and 10). Consequently,

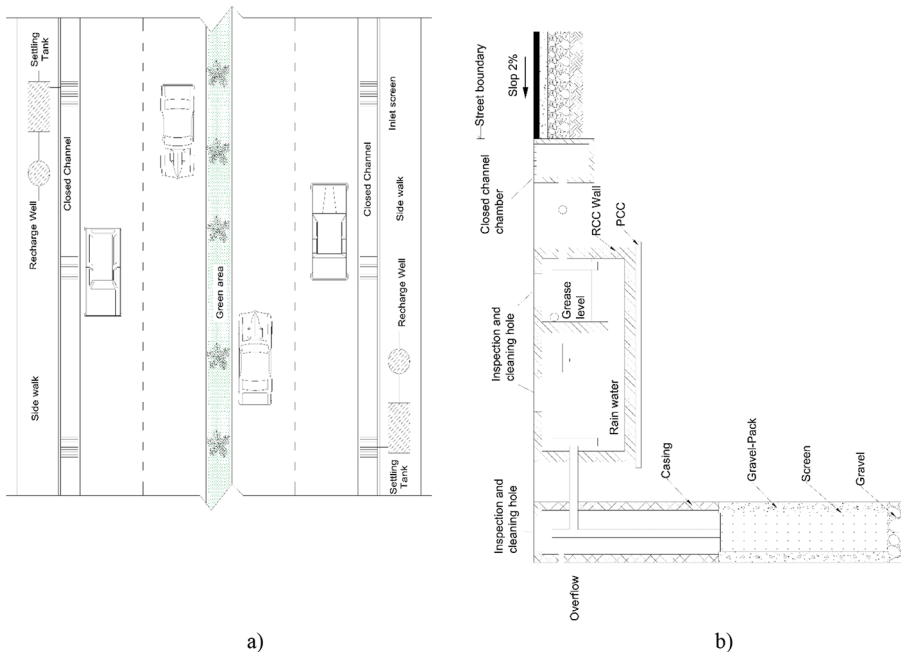


Fig. 10 The proposed RWHR structure for roads and streets a) location plan b) cross-section of recharge structures

it can be said that water harvesting in the research region has great potential to manage water deficits and mitigate drought.

3.4 Rooftop and Street Surface Rainwater Harvesting for Groundwater Recharge

Residential houses in Kabul city typically have an area of 200–400 m² and 2–4 stories. This study analyzed a residential home with a total area of 300 m². About 60% of its total land area is considered for building, and the rest is considered a yard. The groundwater recharge well with its accessories, fed by roof and yard rainwater, is regarded inside the yard (Fig. 8a).

Considering the rainfall amount of 368 mm/year and taking into account the area of 300 m², the total size of the residential house, including its yard, and taking into account 80% of the ability to collect rainwater, the total volume of rainwater that can be ordered for groundwater recharge is about 88 cubic meters. To prevent oil and silt from entering the absorption well, rainwater, after collection, enters the grease and oil trap basin, whose dimensions have been taken 150×150×100 cm, with an overflow height of 120 cm (Fig. 8b). The oil trap basin has a capacity of 1.8 m³. The sand filter basin installed after the oil trap basin has a dimension of 150×300×100 cm. Its lower part is contained filter material with a depth of 45 cm, and the upper portion includes a freeboard with a depth of 30 cm. The top layer (fine sand) has a thickness of 24 cm, and the bottom layer, which consists of gravel, has a thickness of 20 cm.

The maximum daily precipitation is about 81 mm/day with a return period of 12 years (Fig. 6). Since the soil characteristic in the Kabul basin has good hydraulic conductivity (Noori and Singh 2021a) the recharge wells have a total diameter of 1 m which its casing is about 0.8 m diameter. The recharge depth will be typically considered 20 m based on the maximum daily rainfall and the total catchment area (total residential house area).

To collect rainwater from roads, streets, and their sidewalk areas, the system of groundwater recharge wells with its accessories can be constructed at a distance of 100–150 m on the sides of the road (pedestrian area) (Fig. 9a). The distance between the wells depends on the side of the streets and the hydraulic conductivity of the soil. A settling tank has been considered before adding water to absorption wells to prevent silt and clay entry. The settling tank is separated into two parts by a buffer wall (Fig. 9b). The first part acts as the grease and oil separator, and the second is for solid particle settlement. The tank is 350×150×100 cm with a 20 cm freeboard. The settling tank is connected to a recharge well similar to recharge wells of residential houses based on construction.

4 Conclusions

An effort has been made to discuss the principles of rainwater harvesting systems and their potential for contributing to sustainable water management in urban areas. The study also examines the variability and concentration of precipitation in the specific study area. However, the expansion of cities and the rapid transformation of virgin lands into urban settings necessitate applying rainwater harvesting techniques in these locations to minimize the negative impact of urbanization on the local and regional water cycle. The benefits of

rainwater harvesting, such as groundwater recharge, reduction of surface runoff, and mitigation of flooding risks in metropolitan areas, are thoroughly discussed.

The rainfall pattern in Kabul is seasonal, with most rainfall occurring in February, March, and April. For instance 2019, the two wettest months (February and April) accounted for approximately 45% of the total annual precipitation. On average, the yearly rainfall is 368 mm, typically distributed over 80 wet days. Considering the land use and land cover typology, the effective imperviousness (I_c) was calculated for the study area under two conditions: with rainwater harvesting systems (RWHRS) and without RWHRS. Utilizing RWHRS could increase yearly infiltration from 4.86 million cubic meters (MCM) to 11.33 MCM. Using the “US-NRCS” approach, a weighted CN value of 90.5% was determined, indicating the dominance of impervious surfaces. Furthermore, the threshold for runoff formation was found to be 5.3 mm of rainfall. Probability analysis using the Weibull approach predicts a return period of 3–4 years for daily rainfall below 30 mm.

Two approaches for collecting rainwater to recharge groundwater are described in the study. The first method involves implementing RWHRS for a residential house with an area of 300 m², which can yield approximately 88 m³ of water for groundwater replenishment. The second approach involves implementing RWHRS in street sidewalks to recharge the local aquifer. It is also suggested to consider implementing RWHRS for commercial buildings and public institutions. Additionally, it is recommended to prioritize the use of RWHRS in urban environments where a local aquifer is present, as it is an environmentally friendly approach that eliminates the need for complex pumping systems, reduces the space required for water storage tanks, and allows for fair distribution of the available rainwater resource to the entire urban population. The study also proposes the development of collection systems and absorption wells on a larger scale to capture rainwater in public and impervious areas.

These findings underscore the significant potential of rainwater harvesting and storage systems (RWHRS) as an effective strategy for managing urban floods and artificially recharging groundwater. By implementing RWHRS, cities can mitigate the impact of excessive rainfall and reduce the risk of flooding. The stored rainwater can also replenish groundwater levels, which is crucial for sustaining water resources in urban areas. This research emphasizes the importance of adopting RWHRS as a proactive and sustainable approach to address the challenges of urban flood management and groundwater recharge.

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Data Availability The data used in the current research will be available through the corresponding author based on request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

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