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HYDROLOGIC EVALUATION OF MONTHLY AND ANNUAL GROUNDWATER RECHARGE DYNAMICS FOR A SUSTAINABLE GROUNDWATER RESOURCES MANAGEMENT IN QUETTA CITY, PAKISTAN

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ABSTRACT

Quetta is an important urban center and administrative capital of the Balochistan province of Pakistan. Due to its arid climate and absence of reliable surface water resources, the city heavily relies on groundwater, where rainfall is a prominent source of recharge. As per the past studies, due to increased population and unregulated extraction, groundwater levels in Quetta are declining at a rate of 1.5−5.0 m/year, which calls for a detailed assessment of recharge regime for a sustainable resource protection. Therefore, the monthly and annual groundwater recharge in Quetta from rainfall was computed in this research using the Water Balance Approach for the period 1990−2023. The analysis showed a significant reliance of groundwater recharge on the climate patterns, with the highest monthly recharge in January (21.6 mm) due to high rainfall and low ET, while lowest recharge was found in July (3.31 mm) due to low rainfall and high ET losses, with the mean annual total recharge as 108.6 mm. Further, the Recharge to Precipitation ratio estimated from the daily water balance showed that 15% of annual rainfall contributes to groundwater recharge in Quetta. By evaluating the daily water balance, the study comprehensively explained the monthly and annual groundwater recharge regime, along with the rainfall and ET patterns in Quetta. The outcomes of this research would essentially serve to formulate an effective policy and strategy to optimize the groundwater extraction in Quetta without encroaching the aquifer's safe yield and to sustainably manage the available groundwater resources for the coming years.

Keywords: Hydrogeology, Groundwater recharge, Water balance, NRCS CN method, SDG12.

INTRODUCTION

Water is the most abundant and an important state of matter on earth due to its significance for the existence of living beings, making up nearly 71% of earth surface (Azharuddin et al., 2022; Kezzar and Souar, 2024; Mehta et al., 2024). Out of the total global water resources, 97% is brackish (TDS between 3,000 to 10,000 mg/L) to saline (TDS above 10,000 mg/L) and 3% is freshwater (TDS below 3000 mg/L) (Remini, 2021; Musie and Gonfa, 2023). Based on the natural freshwater distribution, about 68% of global freshwater is present as glaciers and snowpack, 30% as groundwater, and 2% as surface water, with nearly 99% of world's liquid freshwater is present as groundwater (Mishra, 2023; Shah et al., 2024). Groundwater refers to the water available below the earth surface in the soil pores and fractures of rock formations (Faye et al., 2020; Scanlon et al., 2023). Groundwater flows serve as an important component of global and regional water balance and plays a significant role to sustain the streamflows and surface water bodies, particularly during droughts and low flow periods (Bahir et al., 2015; Lachache et al., 2023). Based on consumption, about half of the water consumed for drinking, 40% for irrigation, and 33% for industrial uses worldwide comes from groundwater. Furthermore, groundwater is the sole source of water for roughly 2.5 billion people worldwide (Loaiciga and Doh, 2023). Due to the increasing world population and varying streamflows due to changing climate and land use, the dependence on groundwater has noticeably increased across the world, where the global groundwater decline has been estimated to be approximately100−300 km^3 /year (Costantini et al., 2023). Regionally, Asia-Pacific is ranked as the largest extractor of groundwater, with seven of the ten countries in the world that extract most groundwater namely Turkey, Iran, Indonesia, Pakistan, India, China, and Bangladesh. These countries together account for approximately 60% of the world's total groundwater use (Bordbar et al., 2023).

In response to the changing climate and land use coupled with rising population, the groundwater resources are highly susceptible across the globe (Ouhamdouch et al., 2016; Verma et al., 2021; Assemian et al., 2021; Chadee et al., 2023). Hydrologically, groundwater originates through infiltration of precipitation, seepage from reservoirs and water bodies, and artificial recharge through recharge wells (El Moukhayar et al., 2015; Remini, 2018; Remini, 2019; Remini and Ouled Belkhir, 2019; Abaidia and Remini, 2020; Remini, 2021; Later and Labadi, 2024). Infiltration is a process in which water enters the soil and moves vertically in the soil profile under gravity. The principal factors governing the soil infiltration rate include soil texture, land cover, and the initial soil moisture levels (Ali Rahmani et al., 2017). The groundwater recharge via precipitation generally depends on the precipitation characteristics (form and amount), land treatment and cover, soil texture, topography, location of water table, geological formation, and the aquifer characteristics. For a sustainable management of groundwater resources, the assessment of existing recharge regime is essential. The commonly used methods for groundwater recharge estimation are chloride mass balance, soil physics methods, environmental and isotopic tracers, groundwater-level fluctuation methods, water balance methods, Hydrological based models, and the estimation of baseflow (El Moukhayar et al., 2015; Chibane and Ali Rahmani, 2015; Bemmoussat et al., 2017; Adhikari et al., 2022). The Water Table Fluctuation method (WTF) is the widely used field-based method, according to which the increase in water table is contributed by infiltrated water depth reaching the water table. In this method, recharge is estimated by computing the difference between groundwater levels before and after the recharge using the water level meters and piezometers. Malakar et al. (2022) employed WTF approach for groundwater recharge assessment in USA. Boumis et al. (2022) used WTF method to compute the groundwater recharge. Genevieve et al. (2020) also employed WTF method to assess aquifer recharge in selected states of Canada, with recharge equation shown as under (Geneviève et al., 2020):

$$R = \frac{S_y \Delta_h}{\Delta_t} \tag{1}$$

Where, R is the recharge (mm/d), S_y is the specific yield, Δh is the change in water table height (mm), and Δt is the time interval (day).

Infiltration is the sole process for groundwater recharge. However, not all infiltrated water or rainfall contributes to water table, as some part of it is stored within the soil pores or crop root zone as effective or useful rainfall, some contributes to lateral flow in the aeration zone, and remaining travels further down and becomes a part of water table. This portion of rainfall which contributes to groundwater recharge is known as the Effective Infiltration (EI), and the hydrologic process is called deep percolation or deep drainage. In order to estimate effective infiltration, both direct and indirect methods have been proposed (Rossi and Donnini, 2018). The direct method involves calculating EI by dividing the annual average water discharge volume from the springs by the area that serves as their recharge, and has been used in numerous studies in the past (Kessler, 1957; Aronis et al., 1961; Kessler, 1965). According to Mastrorillo et al. (2009), the geological formations may be characterized by deep groundwater circulation with unknown springs and hydraulic connections with other groundwater bodies. This makes the application of EI direct estimation challenging and could result in skewed estimates. Due to the restricted accuracy in determining the borders of aquifer recharge zones and the limited availability of spring discharge data, the direct technique also has several drawbacks. In indirect method, a coefficient called Effective Infiltration Coefficient (EIC) is computed, which is the ratio of volume of spring discharge (effective rainfall) and total rainfall (P) as shown below (Rossi and Donnini, 2018):

$$EIC = P_e/P \tag{2}$$

Where, P_e is the effective rainfall. The value of EIC ranges from 0.0−1.0. Due to the monthly rainfall variability, EIC also varies accordingly and thus, needs to be computed on monthly as well as on annual scale. After the assessment of EIC, the gross rainfall is multiplied with the coefficient to obtain the effective infiltration (Rossi & Donnini, 2018). This approach is employed in different studies to calculate the groundwater recharge from rainfall. For example, Guo et al. (2022) numerically evaluated the relationship between infiltration and the groundwater recharge rate via EIC. Bonacci et al. (2015) estimated

EIC on the monthly and annual scale in Gradole karst spring in Istria for monthly and annual groundwater recharge computation from rainfall. Alloca et al. (2013) estimated the mean annual EIC for recharge estimation in the Karst aquifers of southern Apennines (Italy).

As per the Food and Agriculture Organization (FAO), effective rainfall is the portion of rainfall which is actually added and stored in the soil and can be subsequently utilized by the crops and plants for Evapotranspiration (ET). The value of effective rainfall depends on the rainfall features, land use, initial soil moisture, soil texture, topography, and the crop characteristics. However, effective rainfall in the sense of hydrologists and hydro geologists corresponds, in its broadest sense, to the "part of the rainfall that contributes to runoff". In the broad sense, effective rainfall is the rainfall that gives rise to a flow, superficial or underground, immediate or delayed (Vittecoq et al., 2010; Kouassi et al., 2017).

However, rainfall transformed as interception, depression storage, surface runoff, and deep percolation is not effective. For effective rainfall, numerous field-based and empirical methods have been proposed in the past studies. The most widely used field-based method is the lysimetric study. Apart from field measurements, an empirical method for estimating P_e was proposed by the Natural Resource Conservation Services (NRCS) and the United States Department of Agriculture (USDA) in 1970 as shown below (Ali and Mubarak, 2017):

$$P_e = SF\ (0.70917\ P^{0.824} - 0.11556)\ (10^{0.2426ET}) \tag{3}$$

Where, P_e is the mean monthly effective rainfall (in), P is the mean rainfall for a month (in), SF is the soil storage coefficient, and ET is the mean monthly crop evapotranspiration (in). As infiltration rate also depends on the prior moisture level, SF indicates the impact of initial soil moisture on the effective rainfall and is computed using the following expression (Ali & Mubarak, 2017):

$$SF = 0.5317 + 0.295D - 0.057D^2 + 0.003D^3 \tag{4}$$

Where, D is the soil moisture storage taken as 40 to 60 % of the available water capacity of soil and can be computed using the expression shown below (Ali and Mubarak, 2017):

$$AWC = (FC\text{-}PWP)D_t/100 \tag{5}$$

Where, AWC is the available water capacity (mm or inch), FC is the field capacity of soil (%), PWP is the soil's permanent wilting point (%), and D_t is the root zone depth (Ali and Mubarak, 2017). FAO also proposed empirical relationships for P_e computations for different arid and semi-arid climates as shown below (Allen et al., 1998):

For monthly rainfall ≤ 70 mm

$$P_e = 0.6P\text{-}10 \tag{6}$$

For monthly rainfall > 70 mm

$$P_e = 0.8P\text{-}24 \tag{7}$$

Where, P is the gross rainfall (mm). However, it is important note that the Equations 6 and 7 are used where 80% probability of exceedance is required. The Renfro Equation for P_e computation is shown as under (Ali and Mubarak, 2017):

$$P_e = (E \times P) + I \tag{8}$$

Where, E is the ratio of ET to rainfall during the crop growth period, P is the rainfall during growth period, and I is the average irrigation depth.

In addition, some direct methods for groundwater recharge from rainfall namely Chaturvedi formula (1973), Rao (1970), Sehgal (1973), Kirchner (1991), Bredenkamp (1995), Kumar and Seethapati (2002), and Maxey and Eakin (1949) have also been suggested in previous studies as shown in the Table 1. The Chaturvedi formula (1973) was proposed for the tropical climate, with the mean annual precipitation above 400 mm. Similarly, Rao (1970) also proposed an empirical relationship for the areas having scarce climate data, which yields reliable estimates for the semi-arid to humid regions. Sehgal Equation, also known as Amritsar Equation (1973) was developed using the regression analysis for different doabs in Punjab (India) and is reliable for the areas with mean annual precipitation ranging from 600−700 mm. Kirchner (1991) proposed a relation for groundwater recharge by focusing on the saturated volume fluctuations and the soil cover thickness and established that the recharge amount noticeably varies with the soil cover characteristics (Ali et al., 2017).

Table 1: Different empirical methods for rainfall-groundwater recharge estimation. Source: (Ali et al., 2017)

Method	Mathematical Expression
Chaturvedi (1973)	$R= 2(P-15)^{0.5}$ Where R is the net annual groundwater recharge (in) and P is the annual precipitation (in).
Modified Chaturvedi (2002)	$R =1.35 (P-14)^{0.5}$
Sehgal (1973)	$R= 2.5 (P-0.6)^{0.5}$
Krishna (1970)	For 400 <P<600 mm R = 0.2(P-400) For 600<P<1000 mm R = 0.25(P-400) For P>1000 mm R= 0.35 (P-600)
Kirchner (1991)	For Alluvial Cover R= 0.12 (P-20) Where P is the mean annual rainfall in mm. For Thin Soil Cover R= 0.06 (P-120) For Thick Soil Cover R= 0.023(P-51)
Bredenkamp (1995)	R = 0.32 (P-360) Where P is the mean annual precipitation in mm.
Kumar and Seethapati (2002)	$R =0.63 (P-15.28)^{0.76}$

	Where P is the annual precipitation (inch)
Maxey and Eakin (1949)	R =P x a Where P is the annual rainfall (mm), and a is the recharge coefficient.

Nevertheless, the major limitations of these methods is that they may not always fit on the climate and geological conditions other than those under which they were developed. Secondly, the temporal variation of rainfall was ignored in these methods. Therefore, the water balance approach is more reliable to estimate the groundwater recharge. Theoretically, water balance refers to the balance between the incoming and outgoing water from a system (river, lake, or an aquifer). The law of water balance states that the amount of incoming water to a system (I) equals the amount leaving it (O) plus the change in storage (ΔS) over a certain period of time (t) as shown below:

$$I = O + \Delta S \qquad (9)$$

$$P = ET + R + DP + \Delta S \qquad (10)$$

Where P is the precipitation, ET is the evapotranspiration, R is the surface runoff, DP is the groundwater recharge (or Deep Percolation) and ΔS is the soil moisture storage. The idea of mass conservation in a closed system is the foundation of the water balance equation, where water entering a system as precipitation (P) is quantitatively distributed into the major components of water balance as ET, soil moisture storage, deep percolation, and runoff (Fig.1), where the quantity of precipitation transformed in each of these components depends on the precipitation and watershed characteristics. Water balance is the quantitative representation of hydrological cycle, which is the continuous exchange of water between the earth surface and atmosphere (Kamagate et al., 2017; Qureshi et al., 2023). The hydrological cycle begins with ET, where the warm air carrying moisture from soil, water bodies, and vegetation rises into the air, cools and condenses, form clouds, and then falls as precipitation (Dhiwar et al., 2022).

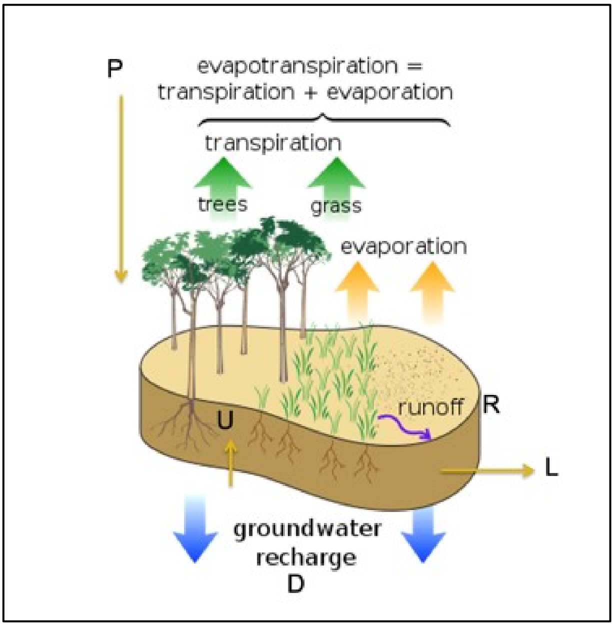

Figure 1: Visual representation of water balance equation. Source: (Neitsch et al., 2011)

In hydrology, evaporation refers to the transport of water from soil and water bodies into the air, whereas transpiration is a process in which plants extract water via roots, consumes through photosynthesis and then release remaining water back into the air. ET is the combined transportation of water from earth surface into the air as evaporation and transpiration. ET is an important part of hydrological cycle and significantly impacts the water balance of a region. Apart from the weather conditions, ET also relies on the land cover, soil texture and vegetation type and growing phase. Reference evapotranspiration (ET_o) is a parameter which shows ET from a reference crop surface (grass or alfalfa), and indicates the evaporative demand of atmosphere at a location. For water balance evaluation, the computation of ET_o is essential. The commonly used methods for ET_o computation are Blaney-Criddle Equation (1950), FAO Modified Blaney-Criddle Equation (1977), Pan Evaporation Method, Penman Method (1948), FAO Modified Penman Method, and FAO Penman-Monteith (FAO PM) Equation (Aschale et al., 2022).

Hydrologically, when rainfall occurs, some part of it is intercepted by the building structures and vegetation before reaching the ground surface. This fraction is known as interception. The remaining rainfall when reaches the ground surface, some portion of it is detained in the natural depressions and low-lying areas as depression storage, some infiltrates into the soil, and the rest flows over the land surface as runoff. When rainfall ends, ET proceeds and most of the intercepted rainfall eventually evaporates back into the air. Similarly, the rainwater stagnated on the soil surface and depressions goes to evaporation or infiltration. It is important to note that the infiltration rate of soil decreases with time as the rainfall continues and the process ceases once the soil pores are completely saturated with water. Once the soil pores and surface depressions are completely filled with water, surface runoff commences. Thus, before runoff, rainfall is required to satisfy the demands of interception, evaporation, depression storage and infiltration, collectively known as the hydrologic losses (or initial abstraction). The fraction of rainfall left after these losses contributes to runoff and is known as the excess rainfall (Neitsch et al., 2011).

The water balance approach has been used in different studies to estimate the groundwater recharge. For instance, Hossain et al. (2022) used the water balance approach to estimate groundwater recharge at the Barind area in Bangladesh. Kisiki et al. (2022) employed the water balance approach to estimate the groundwater recharge in the Makutupora Basin in the semi-arid region of Central Tanzania. Yun et al. (2023) also used the water balance approach to estimate the groundwater replenishment in the Nakdong River Watershed in South Korea, which shows that reliable groundwater recharge estimates can be obtained by using water balance approach.

Pakistan is among the largest users of groundwater globally for drinking, industrial production, and agriculture. For agriculture, Pakistan is the 3rd largest user of groundwater, where about 73% of its irrigated land is watered using groundwater (Qureshi, 2020). As per the Water and Power Development Authority (WAPDA) of Pakistan, the mean annual groundwater recharge from the Indus Basin is about 55 MAF, with the country extracts nearly 50 MAF every year (Ahmad et al., 2023). As per the World Bank, groundwater in Pakistan supplies nearly 90% of domestic water in the rural areas, 70% of domestic water, and over 50% of agricultural water (Ling et al., 2022). Quetta city is among the major and densely populated urban centers of Pakistan and relies heavily on groundwater for its water use due to the scarce water resources. The major source of groundwater recharge in Quetta is precipitation. In Quetta, groundwater decline was first noticed by WAPDA in 1989 at a rate of 0.25 m/year. Later, a decline of 0.23-1.09 m/year was noticed during 1990s by the same authority. As per the Balochistan Irrigation Department, the annual groundwater replenishment in Quetta valley was estimated to be 61.15 Million Cubic Meter (MCM), whereas the discharge is 97.65 MCM, with a yearly deficit of 36.5 MCM (Ghani et al., 2019).

As per Haq et al. (2024), in Balochistan, the number of tube wells increased from about 5,000 in 1980 to over 40,000 in 2015, where in Quetta, the tube wells increased from 880 to above 2000 during the period. At present, there are 20 tube wells in per km^2 of the city (Kakar et al., 2019). The presence of illegal tube wells has also emerged to be an acute menace in the city, where as per Khan and Malik (2023), nearly 24,000 illegal tube wells have been drilled in and around Quetta, thereby stressing the available groundwater resources. As per the Pakistan Bureau of Statistics (PBS), Quetta's population has ascended from 0.26 million in 1975 to approximately 2.5 million in 2023. In response to the increasing population and groundwater extraction, the groundwater level in Quetta has declined from 91 m (300 ft) in 2010 to 180 m (600 ft) in 2021 at a rate of 7.62 m/year (25 ft/year) (Khan and Malik, 2023). Apart from the population rise and climate change, the land use changes also impact the groundwater replenishment, where the increasing imperviousness and high impact development hydrologically hampers the groundwater recharge process.

Different studies have been conducted in the past to investigate the groundwater recharge and extraction in Quetta employing various approaches. Ghani et al. (2019) employed a hydrogeological model named MODFLOW to assess the behavior of underlying aquifers under stress in Quetta during 1995−2014. As per the study, the groundwater extraction in Quetta increased from 0.146 MCM to 0.26 MCM during the study period, with the water table dropped by 0.91 m/year. According to the MODFLOW's water budget calculations, there was an annual deficit of 0.21 MCM during the research period, since the average yearly recharge was 0.168 MCM and the annual extraction was 0.382 MCM. Further, it was found that 20% of total precipitation contributes to groundwater in Quetta. Aftab et al. (2018) also investigated the groundwater recharge and extraction in the major river basins and valleys of Balochistan and found that the water table in Quetta valley is declining at a rate of 1 to 4 m/year. Alam (2010) used Visual MODFLOW to assess the groundwater recharge and extraction in Quetta. He concluded that 13% of annual precipitation reaches to groundwater. Further, the annual groundwater abstraction in Quetta rose from about 0.87 MCM in 1964 to 3.25 MCM in 2007 and is expected to reach 6.54 MCM by 2030.

In contrast to the application of computer models used in previous studies for groundwater recharge assessment, which requires large hydrogeological data for the model calibration and validation which might not be available for all locales and time periods. Therefore, in such cases, the simple hydrologic water balance may get the job done by a detailed quantitative assessment of water balance of the study area. This study was conducted to evaluate the long-term monthly and annual groundwater recharge from rainfall in Quetta using the Water Balance Approach. For this purpose, the daily climate data comprising of rainfall, temperature, relative humidity, and wind speed was acquired from the Pakistan Meteorological Department (PMD) for the period 1990−2023. The outcomes of this study are expected to help in understanding the overall monthly and annual water balance of Quetta city and to capture the monthly and yearly groundwater recharge dynamics that would serve to devise a well-integrated groundwater management strategy and to optimize the groundwater extraction for a long-term and sustainable management of water resources.

STUDY AREA

Quetta (Fig. 2) is the capital of Balochistan province of Pakistan, with the total area of approximately 2,674 km^2 and population of about 2.5 million. Based on the areal coverage, it is the 10^{th} largest city of Pakistan. Geographically, the Quetta Valley, which is an elongated depression is situated between the Murdar Ghar Mountain on the east and Chiltan Mountain on the west. In the north, the Takatu mountain peak overshadows the area, while in the south, it is divided into two narrow valleys by the intervening hillocks of Landi. Its eastern branch taking a slight eastward bend joins in the south with the Spezand-Ismail Khan valley. The western branch terminates at Lak Pass. In the west of

Quetta town, the valley has a gap extending from Samungli to Balleli through which it joins the Karanga Lora valley in the west. The valley has been carved along a down fold into the softer sediment of Ghazij and Siwaliks.

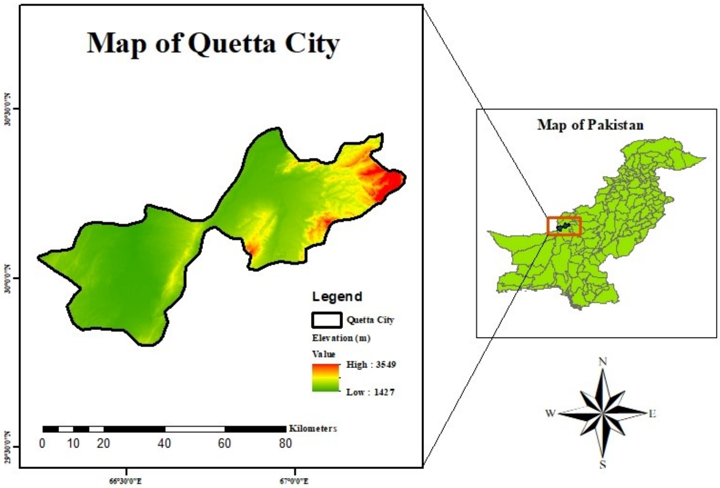

Figure 2: Description of study area

Climatologically, based on the Koeppan climate classification system, Quetta has a cold semi-arid climate with significant air temperature fluctuations round the year, where the mean monthly temperature ranges from lowest in January (4.8 °C) to highest in July (29.2 °C), with the mean annual temperature as 17.2 °C. In summer, the maximum temperature in Quetta often climbs to 37 °C in July, whereas in winter, the minimum temperature normally drops to below -1°C in December and January. For precipitation, Quetta receives approximately 65−70% of its annual precipitation from the Western Disturbances during December to March, while meager precipitation is received in summer due to the weak intrusion of Southwest Monsoon system into northeastern Balochistan, with the mean annual precipitation of city as 300.2 mm. Due to high altitude and low air temperature in winter, Quetta receives generous snowfall during late November to early March (as shown in the Fig. 3), which also contributes to groundwater replenishment. Based on the Sentinel LULC classification, 0.05% of Quetta's land area comprises of waterbodies, 1.8 % as cropland, 8% as built area, 7.5% as barren land, and 82.5% as Rangeland as shown in the Fig. 4. Based on the FAO Soil classification, the study area was classified into two dominant soil textures as I-Rc-Y-kc and Yk36-2/3a as shown in the Fig. 5.

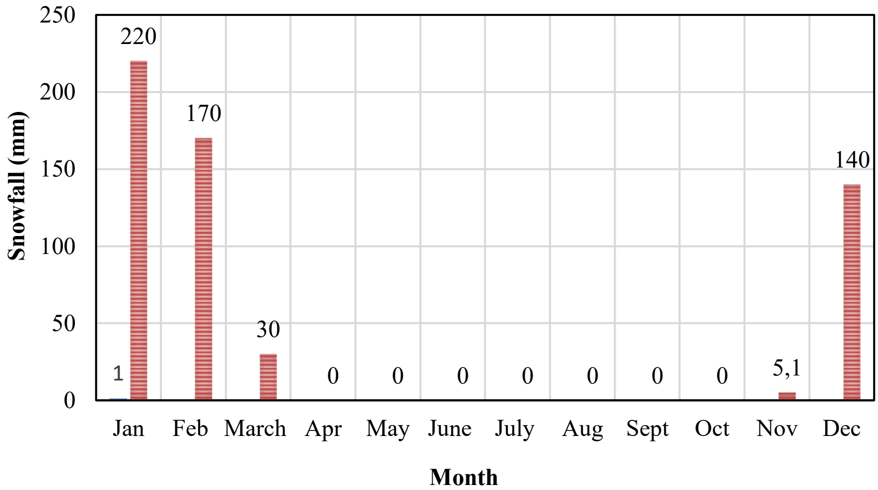

Figure 3: Mean monthly snowfall (mm) in Quetta.

Stratigraphically, the rocks of Quetta valley belongs to the Shirinab formation of Permian to early Jurassic age, with the Chiltan limestone being very thick bedded and massive influenced the formation of flexures and fractures in the area. Geologically, the major geologic formations in Quetta are Jurassic and Triassic rock, Jurassic metamorphic and sedimentary rock, Cretaceous sedimentary rock, Neogene sedimentary rock, Paleogene sedimentary rock, and Quantenary sediments as shown in the Fig. 6.

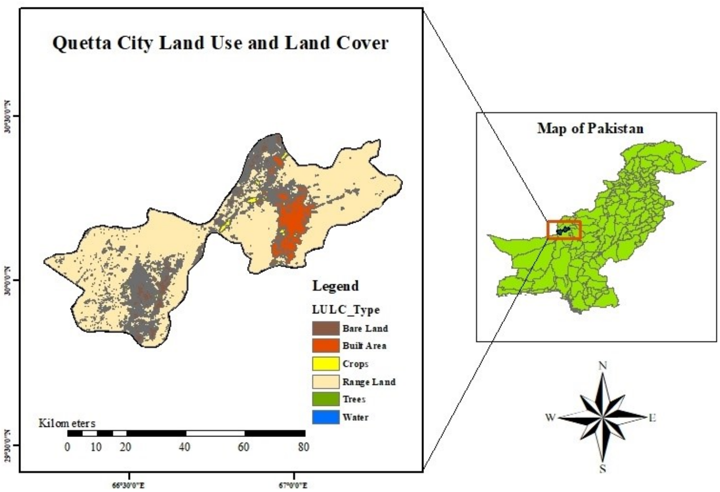

Figure 4: LULC Description of Quetta.

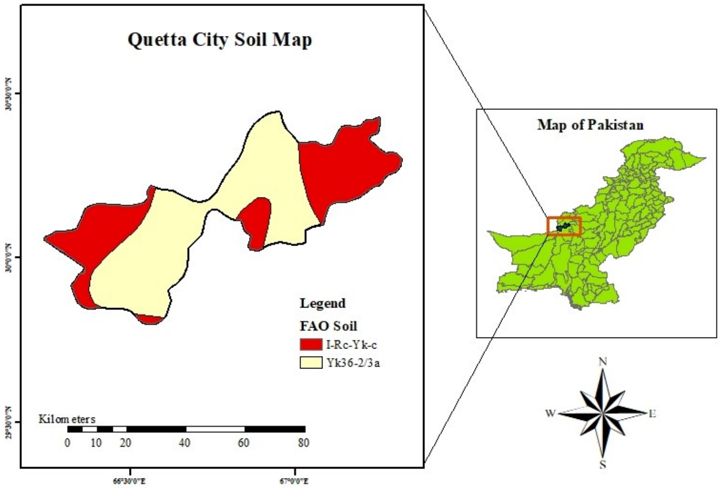

Figure 5: FAO soil classification of Quetta.

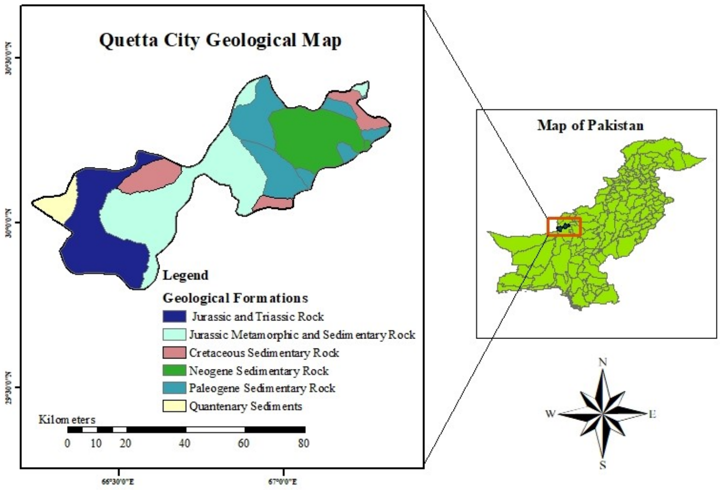

Figure 6: Geological profile of Quetta.

METHODOLOGY

Water Balance Equation

The water balance equation was employed to estimate the monthly and annual groundwater recharge in Quetta. By assuming ΔS=0, Equation 10 was modified as:

$$P = ET + R + DP \quad (11)$$

$$DP = P - ET - R \quad (12)$$

The above Equation 12 was used for groundwater recharge calculation by solving the daily precipitation, runoff, and ET of the study area for the period 1990−2023.

Reference Evapotranspiration

To compute ET_o for water balance evaluation, the FAO PM equation was used. This method is suggested to be the most reliable method and has been used in numerous past studies. The FAO PM Equation is shown as under (Ma et al., 2023):

$$ETo = \frac{0.408\Delta(R-S)+\gamma\frac{900}{T+273}v(e_s-e_a)}{\Delta+\gamma(1+0.34v)} \quad (13)$$

To compute ET_o using FAO PM Equation, a computer model CROPWAT 8.0 was used in this study.

Runoff Computation

As discussed earlier, excess rainfall is the fraction of gross rainfall (P) left after initial abstraction and is quantitatively equivalent to the direct runoff (surface runoff). In this research, to calculate overland flow from rainfall for the water balance evaluation, the Natural Resource Conservation Services (NRCS, 1972) Curve Number method was employed.

NRCS CN Method

NRCS proposed the CN approach in 1972 using records of rainfall and runoff spanning many years for agricultural watersheds across USA. It is used to analyze rainfall and runoff on a daily scale. The NRCS states that surface runoff is produced when the initial abstraction (I_a) is less than the gross rainfall depth (P), as described below (Moglen et al., 2022).

For $P \leq I_a$

$$R = 0 \quad (14)$$

For $P > I_a$

$$R = \frac{(P - I_a)^2}{P - I_a + S} \quad (15)$$

Where R is the runoff depth (mm or inch), P is the total rainfall (mm or inch), and S is the maximum potential soil water retention (mm or inch).

Initial Abstraction (I_a)

NRCS relates I_a as a percent of Maximum Potential Retention (S) due to its hydrologic correlation with the watershed's soil and land cover characteristics. By using regression analysis based on observed rainfall and runoff data from smaller drainage basins in USA, the following average approximate relationship was proposed by NRCS for I_a (Moglen et al., 2022):

$$I_a = 0.2S \quad (16)$$

and

$$S\ (mm) = \frac{25{,}400}{CN} - 254 \quad (17)$$

Where CN is the curve number.

Curve Number (CN)

A watershed's potential for runoff is indicated by the empirical hydrologic parameter known as CN, which takes into account the watershed's hydrologic characteristics, antecedent moisture condition, hydrologic soil group, location of the water table, and land use and treatment practices. A greater CN value denotes limited infiltration and strong runoff potential. The value of CN normally varies from 30 to 100, where a higher CN shows higher runoff potential of watershed. Since CN is an event-based parameter, it cannot be utilized for a single annual rainfall value, as doing so would ignore the importance of an initial abstraction threshold and the influence of inital soil moisture (Wang & Chu, 2023).

Antecedent Moisture Condition (AMC)

AMC is the soil moisture prior to the given rainfall and it significantly impacts the watershed's response to rainfall. For instance, a wet soil generates higher runoff than dry soil from the same rainfall depth. Based on the initial soil moisture content, NRCS defined three (03) antecedent moisture conditions as AMC-I, which indicates dry soil having low initial moisture content before rainfall. AMC-II depicts fair moisture condition, while AMC-III shows high soil moisture or heavy precipitation in preceding days prior to the given rainfall. In addition, high water table (i.e., waterlogged conditions) also create AMC-III and results in higher runoff. CN significantly varies with AMC apart from the other watershed characteristics, with higher CN for wet soil and lower CN for dry soil. To select the true representative AMC for a watershed, NRCS considers 5-day prior rainfall (i.e. cumulative rainfall of preceding 5 days before given rainfall) as described in Table 2 below (Sharma et al., 2022):

Table 2: Description of NRCS AMCs. Source: (Schwab et al., 1992)

AMC	Description	5-Day Prior Rainfall (mm)	
		Dormant Season	Growing Season
I	Optimum soil conditions range from wilting point to the lower plastic limit.	Less than 13	Less than 36
II	Moderate soil moisture.	13−28	36−53
III	Five days before the specific storm, there may have been low temperatures and either heavy or little rainfall.	Above 28	Above 53

Hydrologic Soil Group

The Hydrologic Soil Group defines the infiltration capability of a soil texture. Hydrologically, the soil having high infiltration rate will tend to take large rainwater into storage and thus produce smaller runoff. NRCS defines four (04) hydrologic soil groups as described in the Table 3 below (Ramadan et al., 2020):

Table 3: Description of NRCS Hydrologic Soil Groups. Source: (Schwab et al., 1992)

Hydrologic Soil Group	Description	Rate of Infiltration (mm/h)
A	Lowest Runoff: Sand, loamy sand or sandy loam types of soils.	8.0−12.0
B	Moderately Low Runoff: Silt loam or loam.	4.0−8.0
C	Moderately High Runoff: Sandy clay loam.	1.0−4.0
D	Highest Runoff: Clay loam, silty clay loam, sandy clay, silty clay or clay.	0.0−1.0

Hydrologic Condition

The watershed's hydrologic condition significantly affects runoff. As per NRCS, hydrologic condition accounts the factors that govern infiltration and runoff including vegetation density, amount of year-round vegetal cover, amount of grass or closed-seeded legumes in rotations, percent of residue cover on the land surface, and degree of surface roughness. As per NRCS, the watershed hydrologic condition is classed as "good", "fair", or “poor”, where a “good” hydrologic condition will allow more infiltration to occur and thus less runoff. A well-established root system, large surface covered areas, long stand of vegetation, large quantities of organic matter, humus and peat soil, presence of wetlands, swamps, small ponds, etc. make the conditions very conductive for infiltration. On the contrary, “poor” hydrologic condition results in meagre infiltration and higher runoff. For example, lack of vegetative cover, soil compaction, and urbanization results in poor hydrologic condition.

The NRCS defines "Fair" hydrologic condition as 50–75% of ground cover and not heavily grazed, while "Good" hydrologic condition is greater than 75% of ground cover and little or only seldom grazed. Conversely, a "poor" hydrologic situation is defined as having less than 50% of the ground covered or being severely grazed without any mulch (Eslami et al., 2023).

Land Treatment or Conservation Practice

Land treatment, commonly referred to as conservation practice, is mostly applied to agricultural land uses and comprises management methods like crop rotation or grazing control as well as structural techniques like vegetative measures and contouring or terracing. Land treatment defines the way the watershed surface is used with consideration to the soil and water conservation practices, i.e., to what extent any generated runoff may be enhanced or conserved within the area. The practice also helps to maintain soil structure at the surface, which enhances infiltration and reduces runoff. The CN values suggested by NRCS for average moisture condition are shown in the Table 4 as under (Mehta et al., 2023):

Table 4: Runoff CN values for Hydrologic Soil-Cover Complexes for AMC-II and I_a=0.2S. Source: (Schwab et al., 1992)

Land Use Description	Land Treatment or Practice	Hydrologic Condition	Hydrologic Soil Group			
			A	B	C	D
Fallow	Straight rows	Poor	77	86	91	94
Row Crops	Straight rows	Poor	72	81	88	91
	Straight rows	Good	67	78	85	89
	Contoured	Poor	70	79	81	88
	Contoured	Good	65	75	82	86
	Contoured and terraced	Poor	66	74	80	82
	Contoured and terraced	Good	62	71	78	81
Small grains	Straight rows	Poor	65	76	84	88
	Straight rows	Good	63	75	83	87
	Contoured	Good	61	73	81	84
	Contoured and terraced	Poor	61	72	79	82

	Contoured and terraced	Good	59	70	78	81
Close seeded legumes or rotational meadows	Straight rows	Poor	66	77	85	89
		Good	58	72	81	85
	Contoured	Poor	64	75	83	85
		Good	55	69	78	83
	Contoured and terraced	Poor	63	73	80	83
	Contoured and terraced	Good	51	67	76	80
Pasture or range	Terraced	Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
		Fair	25	59	75	83
		Good	06	35	70	79
Non- cultivated agricultural land pasture or range	No treatment	Poor	68	79	86	89
		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
		Fair	25	59	75	83
		Good	06	35	70	79
Forestland-grass or orchards -evergreen or deciduous brush		Poor	55	73	82	86
		Fair	44	65	76	82
		Good	32	58	72	79
Commercial, built-up, and industrial areas (85% impervious)			89	92	94	95
Streets and Roads						
a) Paved with curbs			98	98	98	98
and storm sewers			76	85	89	91
b) Gravel			83	89	92	93
c) Paved with open ditches						

For dry or wet soil conditions, CN can be computed using the following relationships:

$$CN(I) = \frac{4.2CN(II)}{10-0.058CN(II)} \quad (18)$$

and

$$CN(III) = \frac{23CN(II)}{10+0.13CN(II)} \quad (19)$$

Weighted-Area CN

Due to different land use in the study area, a weighted-area CN was estimated by considering "**Fair**" hydrologic condition for assessment of runoff and the daily water balance. The equation used for CN is shown as under:

$$CN_{weighted} = \frac{\sum_1^n (A \ X \ CN)}{\sum_1^n A} \tag{20}$$

RESULTS AND DISCUSSION

Weighted-Area CN

On the basis of land use and hydrologic soil group of the study area, the weighted CN (II) was found to be 82, whereas under AMC-I and AMC-III conditions, CN was found to be 63 and 94 respectively as shown in the Table 5 below:

Table 5: Computed Weighted-area CN for Quetta under different hydrologic conditions.

LULC	Areal Coverage (km^2)	Percent Coverage (%)	Hydrologic Soil Group	CN (II)	Weighted-Area CN		
					AMC I	AMC II	AMC III
Barren Land	263.30	7.52	D (Clay Loam)	85	63	82	94
Built Area	280.10	8.0		95			
Crops	65.80	1.90		77			
Rangeland	2890.1	82.55		80			
Water	1.81	0.05		100			

Daily Water Balance Evaluation of Quetta

Water balance equation was applied to evaluate the daily water balance of Quetta and subsequently the monthly and annual groundwater recharge for the period 1990-2023. The results obtained from the analysis are shown in the Table 6 as under:

Table 6: Computed mean monthly water balance of Quetta for the period 1990-2023.

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Yearly Total/Mean
Rainfall (mm)	39.54	29.85	35.74	28.25	16.62	16.08	7.62	12.15	5.89	8.36	11.13	11.58	222.79
ET_o (mm/d)	2.8	3.6	5.1	6.8	9	9.1	8.3	7.3	6.6	5.7	4.2	3.1	5.97
Runoff (mm)	11.83	5.56	8.45	8.16	4.89	5.77	1.14	2.95	1.59	2.20	2.51	3.33	58.38
Groundwater Recharge (mm)	21.60	17.67	17.18	11.40	5.90	6.93	3.31	5.55	3.07	4.50	5.32	6.23	108.66

The results obtained from the daily water balance evaluation of Quetta showed a significant contribution of rainfall to groundwater recharge in the city, with the recharge regime closely following the rainfall and ET patterns. On the monthly scale, the analysis revealed that Quetta receives its highest rainfall in January (39.54 mm on average) due to the incursion of Western Disturbances into the region, which brings good amount of snow and rainfall in the city, while lowest rainfall is received in September (5.89 mm on average). Due to high rainfall and low ET, the monthly groundwater recharge was found to be highest in January (21.6 mm on average), while lowest recharge was found in July (3.31 mm on average) due to low rainfall and high ET losses. To assess the percent of rainfall contributing to groundwater recharge, a hydrogeological parameter called Recharge to Precipitation ratio (DP/P) was also estimated. The value of DP/P indicates the relationship between rainfall and groundwater recharge and depends on the climate, soil, land use, and the geologic characteristics of the region. In this study, DP/P was found to have significant monthly variations, ranging from highest in January (0.29) to lowest in September (0.03) as shown in the Fig. 7, with the average DP/P as 0.15.

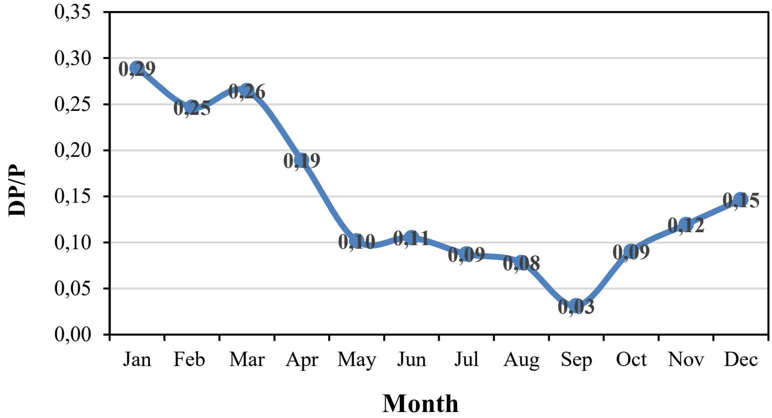

Figure 7: Monthly recharge to precipitation (DP/P) ratio for Quetta.

The computed annual groundwater recharge using the water balance method are shown in the Fig. 8 as under:

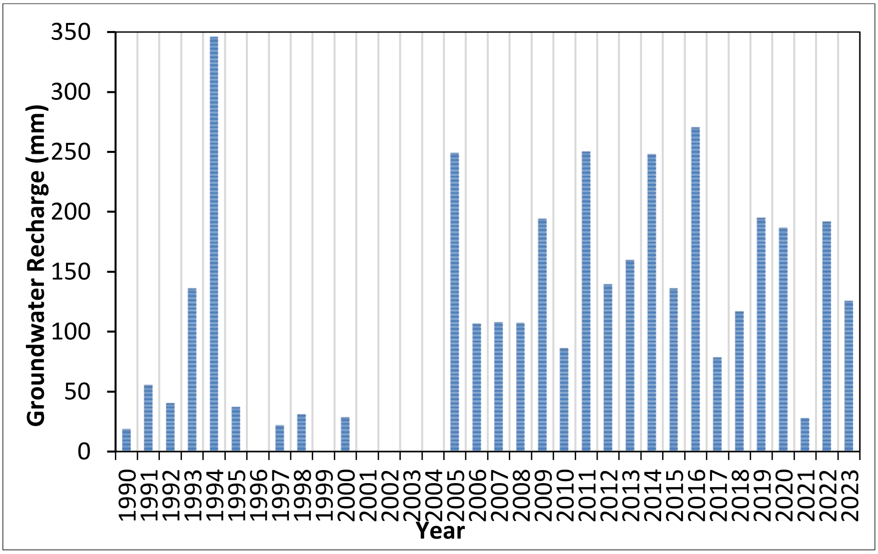

Figure 8: Annual groundwater recharge (mm) in Quetta during 1990-2023.

Based on the analysis, the mean annual groundwater recharge from rainfall was found to be 108.6 mm. Conclusively, rainfall plays a significant role in the groundwater replenishment. Quetta being climatologically located in the arid climatic zone with no reliable surface water resources critically relies on the groundwater resources. The estimates obtained from the above analysis may greatly serve to sustainably manage the available groundwater resources and to optimize the extraction-recharge scenario in the city.

CONCLUSION

This research was conducted to determine the monthly and annual groundwater recharge in Quetta using the water balance approach. On the basis of analysis, the following conclusions were reached:

- The reference evapotranspiration linearly follows the air temperature profile of the city and varies significantly throughout the year, ranging from 2.8 mm/day in January to 9.1 mm/day in July, with the mean daily ET as 5.97 mm/day.
- Like temperature and ET, rainfall also varies throughout the year in Quetta, with highest monthly rainfall occurs in January (39.54 mm), whereas lowest rainfall is received in September (5.89 mm).
- The monthly and annual groundwater recharge assessment showed that the recharge regime in Quetta keenly follows the rainfall and ET trends, with highest monthly recharge was found in January (21.6 mm) due to high precipitation and low evaporation and transpiration losses. In contrast, the lowest monthly groundwater recharge was found in July (3.31 mm) due to low precipitation and high ET, with mean annual groundwater recharge in the city was found to be 108.6 mm.
- The Recharge to Precipitation ratio well indicated the fraction of rainfall contributing to the groundwater recharge. On monthly scale, R/P was found to be ranging from highest 0.29 in January to lowest 0.03 in September. Conclusively, the long-term daily water balance evaluation showed that 15% of rainfall was contributing to the groundwater recharge in Quetta.

Declaration of competing interest

The authors declare that they have no know competing interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

ABAIDIA S., REMINI B. (2020). Ghrib and Boukourdane (Algeria): when the water discharged from the dams feed the alluvial aquifer, Larhyss Journal, No 44, pp. 133-159.

ADHIKARI R.K., YILMAZ A.G., MAINALI B., DYSON P., IMTEAZ M.A. (2022). Methods of groundwater recharge estimation under climate change: A review, Sustainability, Vol. 23, Issue 14, Paper ID 15619.

ALI RAHMANI S.E., CHIBANE B., HALLOUZ F., BOUTELBA A., AIACHI N. (2017). New modified Green-Ampt models to calculate water flux via unsaturated layers, case of Sidi Slimane River (Algeria), Larhyss Journal, No 32, pp. 93-105.

AZHARUDDIN M., VERMA S., VERMA M.K., PRASAD A. (2022). A synoptic-scale assessment of flood events and ENSO—streamflow variability in Sheonath River Basin, India, Advanced Modelling and Innovations in Water Resources Engineering (AMIWRE) Conference, Springer, Vol. 176, pp. 93-104.

AFTAB S.M., SIDDIQUI R.H., FAROOQUI M.A. (2018). Strategies to Manage Aquifer Recharge in Balochistan, Pakistan: An Overview, IOP Conference Series: Materials Science and Engineering, IOP Publishing, Vol. 414, Issue1, Paper ID 012023.

AHMAD S., JIA H., ASHRAF A., YIN D., CHEN Z., XU C., CHENYANG W., JIA Q., XIAOYUE Z., ISRAR M. (2023). Water resources and their management in Pakistan: A critical analysis on challenges and implications, Water-Energy Nexus, Vol. 6, pp. 137-150.

AHMED N., KASSI A.M., KASI A.K., SOHAIL K., ASIF M., NAEEM A., PANEZAI M. (2022). GIS-Based High-Resolution Geological Map (Scale 1: 50,000): A New Window Into Structural Domains of the Quetta and Surrounding Areas, Journal of Mountain Area Research, Vol. 8, pp. 27-48.

ALAM K. (2010). Evaluation of aquifer system in Quetta valley through geophysical methods and groundwater flow modeling, Doctoral Dissertation, University of Punjab, Pakistan.

ALI M., MUBARAK S. (2017). Effective rainfall calculation methods for field crops: an overview, analysis and new formulation, Asian Research Journal of Agriculture, Vol. 7, Issue 1, pp.1-12.

ALI M., MUBARAK S., ISLAM A., BISWAS P. (2017). Comparative evaluation of various empirical methods for estimating groundwater recharge, Archives of Current Research International, Vol. 11, Issue 1, pp.1-10.

ALI M. H., HASANUZZAMAN M., ISLAM M.A., BISWAS P. (2022). Groundwater recharge estimation at Barind area, Bangladesh for sustainable groundwater management: application of multiple methods, European Journal of Environment and Earth Sciences, Vol. 3, Issue 6, pp. 23-29.

ALLEN R.G., PEREIRA L.S., RAES D., SMITH M. (1998). FAO Irrigation and drainage paper No. 56, Food and Agriculture Organization of the United Nations, Rome.

ALLOCCA V., MANNA F., VITA V.D. (2013). Estimating annual effective infiltration coefficient and groundwater recharge for karst aquifers of the southern Apennines. Hydrological Earth Systems Science, Vol. 10**,** Issue 8, pp. 10127-10159.

ARONIS G., BURDON D.J., ZERIS K. (1961). Development of a karst limestone Spring in Greece, Report from United Nations Educational, Scientific and Cultural Organization (UNESCO), Ground Water Resources, Athens.

ASCHALE T.M., SCIUTO G., PERES D.J., GULLOTTA A., CANCELLIERE A. (2022). Evaluation of reference evapotranspiration estimation methods for the assessment of hydrological impacts of photovoltaic power plants in Mediterranean climates, Water, Vol. 14, Issue 14, Paper ID 2268.

ASSEMIAN A.E., DJE BI DOUTIN S., SAMAKÉ Y., (2021). Consequences of the effects of climate change on water resources in a humic tropical zone of central eastern Côte d'Ivoire, Larhyss Journal, No 45, pp. 95-105.

BAHIR M., EL MOUKHAYAR R., CARREIRA P., SOUHEL A. (2015). Isotopic tools for groundwater management in semi-arid area: case of the wadi Ouazzi basin (Morocco), Larhyss Journal, No 23, pp. 23-39.

BEMMOUSSAT A., ADJIM M., BENSAOULA F. (2017). Use of the Zygos model for the estimation of groundwater recharge in Sikkak watershed (northern west of Algeria), Larhyss Journal, No 30, pp. 105-119.

BONACCI O., ANDRIC I. (2015). Karst spring catchment: An example from Dinaric karst. Environmental Earth Sciences, Vol. 74, pp. 6211-6223.

BORDBAR M., BUSICO G., SIRNA M., TEDESCO D., MASTROCICCO M. (2023). A multi-step approach to evaluate the sustainable use of groundwater resources for human consumption and agriculture, Journal of Environmental Management, Vol. 347, Paper ID 119041.

BOUMIS G., KUMAR M., NIMMO J.R., CLEMENT T.P. (2022). Influence of shallow groundwater evapotranspiration on recharge estimation using the water table fluctuation method. Water Resources Research, Vol. 58, Issue 10, Paper ID e2022WR032073.

CHADEE A., NARRA M., MEHTA D., ANDREW J., AZAMATHULLA H. (2023). Impact of climate change on water resource engineering in Trinidad and Tobago, Larhyss Journal, No 55, pp. 215-229.

CHIBANE B., ALI-RAHMANI S.E. (2015). Hydrological based model to estimate groundwater recharge, real-evapotranspiration and runoff in semi-arid area, Larhyss Journal, No 23, pp. 231-242.

COSTANTINI M., COLIN J., DECHARME B. (2023). Projected Climate-Driven Changes of Water Table Depth in the World's Major Groundwater Basins, Earth's Future, Vol. 11, Issue 3, Paper ID e2022EF003068.

DHIWAR B.K., VERMA S., PRASAD A. (2022). Identification of flood vulnerable area for Kharun River Basin by GIS techniques, Advanced Modelling and Innovations in Water Resources Engineering (AMIWRE), Springer, Vol. 176, pp.385-408.

EL MOUKHAYAR R., BAHIR M., CARREIRA P. (2015). Estimation of groundwater recharge in arid region through hydrochemistry and isotope a case study Kourimat basin, Morocco, Larhyss Journal, No 23, pp. 87-104.

ESLAMI Z., ABDOLLAHI K., EBRAHIMI A. (2023). On the Role of Hydrological Losses in Estimating Event Runoff Coefficients Using the NRCS Method, Water Resources Management, Vol. 37, Issue 11, pp. 4233-4252.

FAYE M.D., BIAOU A.C., SORO D.D., LEYE B., KOITA M., YACOUBA H. (2020). Understanding groundwater pollution of Sissili catchment area in Burkina-Faso, Larhyss Journal, No 42, pp. 121-144.

GENEVIEVE L., ROMAIN C., MARIE B. (2020). Water-table fluctuation method for assessing aquifer recharge: application to Canadian aquifers and comparison with other methods, Hydrogeology Journal, Vol. 28, Issue 2, pp. 521-533.

GHANI A., CHAUDARY Z.A., REHMAN H., AZHAR A.H., MASOOD M. (2019). Assessment of sustainable groundwater extraction rate for Quetta city using MODFLOW, Pakistan Journal of Engineering and Applied Sciences, Vol. 24, Issue 1, pp. 1-10.

GUO C., LI J., SUN Y., GAO W., MAO Z., YE S. (2022). Influence of constructed rapid infiltration system on groundwater recharge and quality, Frontiers in Environmental Science, Vol. 10, Paper ID 1022970.

KAKAR N., KAKAR D.M., KHAN A.S., KHAN S.D. (2019). Land subsidence caused by groundwater exploitation in Quetta Valley, Pakistan. International Journal of Economic and Environmental Geology, Vol. 381, pp.10-19.

KAMAGATE B., DAO A., NOUFE D., YAO K.L., FADIKA V., GONE D.L., SAVANE I. (2017). Contribution of Gr4J model for modeling Agneby watershed runoff in southeast of Cote d'Ivoire, Larhyss Journal, No 29, pp. 187-208. (In French)

KESSLER H. (1957). Estimation of subsurface water resources in karstic regions, Toronto Meeting, Institute of Advanced Studies in the Humanities (IASH II), pp. 199-206.

KESSLER M. (1965). Water balance investigations in the karstic regions of Hungary, KIP Articles, Vol. 9, Paper ID 5585.

KEZZAR M.A., SOUAR A. (2024). The water management system in the village of Menades in Algeria between past and present, Larhyss Journal, No 57, pp. 55-79.

KISIKI C.P., AYENEW T., MJEMAH I.C. (2023). Estimation of groundwater recharge variability using a GIS-based distributed water balance model in Makutupora basin, Tanzania, Heliyon, Vol. 9, Issue 4, Paper ID e15117.

KOUASSI A.M., ASSOKO A.V.S., KOUAKOU K.E., DJE K.B., KOUAME K.F., BIEMI J. (2017). Analysis of the hydrological impacts of climate variability in West Africa: case study of the Bandama watershed in Ivory Coast, Larhyss Journal, No 31, pp. 19-40. (In French)

LACHACHE S., DERDOUR A., MAAZOUZI I., AMROUNE A., GUASTALDI E., MERZOUGUI T. (2023). Statistical approach of groundwater quality assessment at Naama region, south-west Algeria, Larhyss Journal, No 55, pp. 125-144.

LATER F., LABADI A.S. (2024). Origin of the alluvial aquifer's groundwater in wadi Biskra (Algeria), Larhyss Journal, No 57, pp. 145-158.

LIAN X., ZHAO W., GENTINE P. (2022). Recent global decline in rainfall interception loss due to altered rainfall regimes, Nature Communications, Vol. 13, Issue 1, Paper ID 7642.

LING Y., PODGORSKI J., SADIQ M., RASHEED H., EQANI S. A. M. A. S., BERG M. (2022). Monitoring and prediction of high fluoride concentrations in groundwater in Pakistan, Science of the Total Environment, Vol. 839, Issue 8, Paper ID 156058.

LOAICIGA H.A., DOH R. (2023). Groundwater for people and the environment: a globally threatened resource, Groundwater, Vol. 62, Issue 3, pp. 332-340.

MA Y., NIU Z., WANG X., SUN D., JIA L. (2023). The Influence of Meteorological Variables on Reference Evapotranspiration Based on the FAO PM Model - A Case Study of the Taohe River Basin, NW China, Water, Vol. 15, Issue 12, Paper ID 2264.

MALAKAR P., BOUMIS G., KUMAR M., CLEMENT P., THAKUR H. P., TASHIE A., RATHORE L.S. (2022). A benchmark data for daily groundwater recharge in the US using the Water Table Fluctuation Method. AGU Fall Meeting Abstracts, Vol. 2022, pp. 55-69.

MEHTA D., HADVANI J., KANTHARIYA D., SONAWALA P. (2023). Effect of land use land cover change on runoff characteristics using curve number: A GIS and remote sensing approach, International Journal of Hydrology Science and Technology, Vol. 16, Issue 1, pp. 1-16.

MEHTA D., PRAJAPATI K., VERMA S., KUMAR V. (2024). Analysis of water distribution network using Epanet: a case study of Variav headwork Surat-India, Larhyss Journal, No 57, pp. 81-100.

MISHRA R.K. (2023). Fresh water availability and its global challenge, British Journal of Multidisciplinary and Advanced Studies, Vol. 4, Issue 3, pp.1-78.

MOGLEN G., SADEQ H, HUGHES L., MEADOWS M., MILLER J., RAMIREZ A.J., TOLLNER E. (2022). NRCS curve number method: comparison of methods for estimating the curve number from rainfall-runoff data, Journal of Hydrologic Engineering, Vol. 27, Issue 10, Paper ID 04022023.

MUSIE W., GONFA G. (2023). Fresh water resource, scarcity, water salinity challenges and possible remedies: A review, Heliyon, Vol. 9, Issue 8, Paper ID e18685.

NEITSCH S.L., ARNOLD J.G., KINIRY J.R., Williams J.R. (2011). Soil and water assessment tool theoretical documentation version 2009, Texas Water Resources Institute.

OUHAMDOUCH S., BAHIR M., CARREIRA P.M., CHAMCHATI H., GOUMIH A. (2016). Climate change impact on water resource in Morocco, case of Essaouira basin, Larhyss Journal, No 27, pp. 221-237. (In French)

QURESHI A.S. (2020). Groundwater governance in Pakistan: From colossal development to neglected management, Water, Vol. 12, Issue 11, Paper ID 3017.

QURESHI H.U., SHAH S.M.H., YASSIN M.A., ABBA S.I., MUSTAFFA Z. (2023). Investigation of Causes and Characteristics of Monsoon Extremes in Pakistan: A Case Study for Summer Monsoon 2022, The Journal of The Institution of Engineers Malaysia, Vol. 83, Issue 2, pp.6−19.

RAFI KHAN D.M.M. (2023). Scarcity of water in Quetta–a way forward, Journal of Positive School Psychology, Vol. 7, Issue 3, pp.1-10.

RAMADAN A.N. A., SADILI A., SUMARDI Z., SOLIHIN R.R. (2020). Determination of Hydrologic Soil Group from Soil Map Unit of Indonesia in Pataruman Water Catchment Area. Journal of Physics, Vol. 1477, Issue 5, Paper ID 052040.

REMINI B. (2018). The Foggaras of the Oasis of Ghardaia (Algeria): the sharing of flood waters, Larhyss Journal, No 36, pp. 157-178.

REMINI B., OULED BELKHIR C. (2019). The ancestral water sharing system of the oasis of Metlili (Algeria): a forgotten hydraulic heritage! Larhyss Journal, No 40, pp. 81-115. (In French)

REMINI B. (2019). The oasis of El Guerrara (Algeria): irrigation and recharge of the aquifers ensured by the floods, Larhyss Journal, No 40, pp. 135-163. (In French)

REMINI B. (2021). Africa, a continent with ignored large water reserves, Larhyss Journal, No 47, pp. 233-244.

REMINI B. (2021). Ahbas N'Bouchen: when the artificial recharge of water table becomes a priority in the M'zab valley, Larhyss Journal, No 45, pp. 183-201.

ROSSI M., DONNINI M. (2018). Estimation of regional scale effective infiltration using an open-source hydrogeological balance model and free/open data, Environmental Modelling & Software, Vol. 104, pp. 153-170.

SCHWAB G.O., FANGMEIER D.D., ELLIOT W.J., FREVERT R.K. (1992). Soil and Water Conservation Engineering, 4th edition, USA.

SCANLON B.R., FAKHREDDINE S., RATEB A., DE GRAAF I., FAMIGLIETTI J., GLEESON T., GRAFTON R.Q., JOBBAGY E., KEBEDE S., KOLUSU S.R. (2023). Global water resources and the role of groundwater in a resilient water future, Nature Reviews Earth & Environment, Vol. 4, Issue 2, pp. 87-101.

SHAIKH A.U.H., QURESHI A.L., JAMALI M.A., ZAIDI A., JAMALI S. (2024). Mapping Groundwater Potential Zones in Quetta Region, Balochistan, Pakistan using Geospatial Techniques, 3rd International Conference on Advances in Civil and Environmental Engineering (ICACEE), pp. 913−921.

SHARMA I., MISHRA S., PANDEY A., KUMRE S. (2022). A modified NRCS-CN method for eliminating abrupt runoff changes induced by the categorical antecedent moisture conditions, Journal of Hydro-environment Research, Vol. 44, pp. 35−52.

SHAH S.M.H., ABBA S.I., YASSIN M.A., LAWAL D.U., ALIYU F., AL-QADAMI E. H.H., QURESHI H.U., ALJUNDI I.H., ASMALY H.A., SAMMEN S.S. (2024) New strategy based on Hammerstein–Wiener and supervised machine learning for identification of treated wastewater salinization in Al-Hassa region, Saudi Arabia, Environmental Sciences Europe, Vol. 36, Issue 1, Paper ID 114.

VERMA S., PRASAD A., VERMA M.K. (2021). Trend analysis and rainfall variability of monthly rainfall in Sheonath River Basin, Chhattisgarh, Recent Trends in Civil Engineering, Select Proceedings of ICRTICE 2019, Springer, Vol. 77, pp.777−790.

VITTECOQ B., LACHASSAGNE P., LANINI S., MARECHAL J.C. (2010). Assessment of water resources in Martinique: spatialized calculation of effective rainfall and validation at the watershed scale, Revue des Sciences de l'Eau, Vol. 23, No 4, pp. 361-373. (In French)

WANG N., CHU X. (2023). A Modified SCS curve number method for temporally varying rainfall excess simulation, Water, Vol. 15, Issue 13, Paper ID 2374.

YUN S.M., JEON H.T., CHEONG J.Y., KIM J., HAMM S.Y. (2023). Combined Analysis of Net Groundwater Recharge Using Water Budget and Climate Change Scenarios, Water, Vol. 15, Issue 3, Paper ID 571.