Groundwater Recharge Analysis and Strategic Management for Sustainable Water Resources in the Bahuda Watershed, Chittoor District, India

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Abstract: ***Groundwater serves as a critical source of fresh water for drinking, agriculture, and industry, especially in regions with limited surface water availability. This research addresses groundwater recharge and management practices which can be advocated in the Bahuda watershed of Chittoor District. In the course of the years, groundwater recharge was estimated based on the water table fluctuation method and some empirical formulae with relative emphasis placed in appreciating the recharge potential based on rainfall. Furthermore, the Soil Water Assessment Tool (SWAT), a widely used Hydrological model tool was utilized to analyse various recharge components through a water balance model, helping to map the spatial and temporal variations in recharge patterns across the watershed. This understanding formed a basis for the formulation of strategies that seek optimal restoration of surface and groundwater resources. Some of the expected strategies include construction of rainwater harvesting systems, improvement of soil moisture, and alteration of land use practices.***

Keywords: SWAT, QSWAT, QGIS, NE, SW, ET, PET, LULC, DEM, ICAR-AICRP, HRUs, UPIRI, SCS, CN

1.Introduction

Groundwater serves as a critical source of fresh water for drinking, agriculture, and industry, it is vital to maintain the sustainable management of water resources due to climate change and the growing demand of water. Understanding groundwater recharge dynamics is significant for an accurate analysis of water resources in areas like Bahuda Watershed located in Chittoor District, Andhra Pradesh which is semi-arid. The Bahuda River, originating from the scenic Horsley Hills, a renowned hill station in the region, the river traverses the landscape through Vayalpad, eventually entering the neighbouring Kadapa District. Here, it merges with the Pennar River, which is one of the major river systems in Southern India. The latitude and longitude coordinates of the study area encompassing the Bahuda River range from 13°27' to 13°49' North and 78°30' to 78°49' east, respectively. The total area of the watershed is approximately 550 square kilometres, while the river itself spans an impressive 84.02 kilometres in length. Apart from this the watershed is also important because of its cycling precipitation and diversity in hydrogeology, which provides water for irrigation, households and industries. At the same time, there are some evident decreasing trends in the groundwater levels of the area which surely calls for detailed research work for an efficient water resource management. The title of the study is "Groundwater Recharge Analysis and Strategic Management for Sustainable Water Resources in the Bahuda Watershed, Chittoor District" and its main goal is to determine the groundwater recharge processes and formulate recommendations for appropriate management of the resources. The study has three main objectives:

- To assess the groundwater recharge through rainfall over the years in Bahuda watershed
- To study the various recharge components by using the water balance model
- To recommend suitable management strategies for restoration of the surface and groundwater resources

2.Methodology

2.1 Framework of methodology

The methodology for this study employs a comprehensive approach that includes analyzing rainfall data, estimating recharge, modeling hydrology, and providing strategic recommendations for sustainable groundwater management in the Bahuda Watershed. Groundwater recharge is evaluated through empirical formulas and the water table fluctuation method, utilizing rainfall data from 2000 to 2021. Furthermore, the QSWAT model is used to examine recharge components such as surface runoff and groundwater recharge, incorporating inputs like precipitation, temperature, Digital Elevation Map (DEM), Land Use and Land Cover (LULC), and soil data from 2001 to 2023. The results from these methods serve as a foundation for suggesting targeted strategies aimed at improving groundwater recharge and ensuring sustainable resource management in the face of changing climate conditions**.** The Methodological Framework for Groundwater Recharge Analysis and Strategic Management are shown in Fig.1

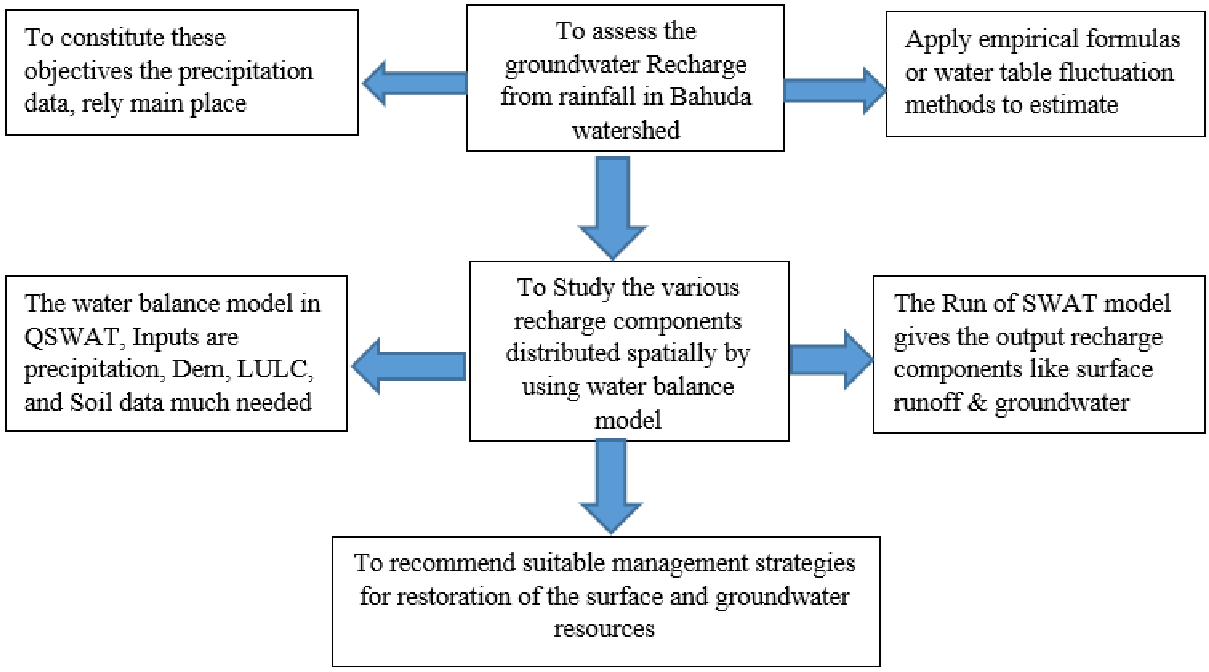

Figure 1: Methodological Framework for Groundwater Recharge Analysis and Strategic Management

2.2 Estimation of groundwater recharge

The estimation of groundwater recharge was conducted using two methods empirical formulae and the water table fluctuation method. The empirical formulae yielded theoretical estimates based on rainfall patterns, these methods offered quick assessments of recharge potential but relied heavily on assumptions tailored to specific regional conditions, whereas the water table fluctuation method provided field-based recharge estimates by examining changes in groundwater levels in response to seasonal rainfall.

2.2.1 Estimation of groundwater recharge by using empirical formulae

Natural groundwater recharge from rainfall was estimated by using the following empirical formulae [1].

- Chaturvedi formula (1936)

Based on water level fluctuation and rainfall amount in Ganga-Yamuna doab, Chaturvedi in 1936 derived an empirical relationship to arrive at the recharge as a function of annual precipitation [2].

$$Rg = 2\ (P-15)^{0.4} \quad (1)$$

Where, Rg is net recharge, in inches, P is annual rainfall, in inches. This formula is useful for preliminary estimates of recharge due to rainfall. This formula later modified by Uttar Pradesh Irrigation Research Institute (UPIRI).

- U.P.I.R.I. Formula (1954)

The formula given by Uttar Pradesh Irrigation Research Institute, the UPIRI formula adjusted the rainfall threshold to 14 inches and applied a square root factor instead of the power of 0.4. This modification aimed to provide a better fit for the recharge characteristics observed in the region [2].

$$R_g = 1.35\ (P-14)^{0.5} \quad (2)$$

Where Rg is net recharge, in inches, P is annual rainfall, in inches.

- Bhattacharjee formula (1954)

Bhattacharjee developed an alternative empirical relationship in 1954 to estimate recharge due to rainfall. The formula is based on studies conducted under the Indian Council of Agricultural Research & All India Coordinated Research Project (ICAR-AICRP) on Groundwater Utilization. This formula is particularly useful for regions where rainfall exceeds a threshold value of 38 cm. It reflects the contribution of excess rainfall above this limit to groundwater recharge. It is particularly valuable for areas with moderate to high rainfall, where recharge estimation is more complex due to runoff and evapotranspiration losses [2].

$$R = 3.47\ (P-38)^{0.4} \quad (3)$$

Where, R is groundwater recharge in cm and P is precipitation in cm

- Krishna Rao formula (1970)

Krishna Rao gave the following empirical relationship in 1970 to determine the groundwater recharge in limited climatological homogeneous areas of Karnataka state [2].

$$R_r = K\ (P-X) \quad (4)$$

Where, R_r is groundwater recharge in mm, P is precipitation in mm and K is recharge coefficient. Following relation holds good for different parts of Karnataka.

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Where,

Rr = 0.20 (P-400)--Where annual rainfall between 400 – 600 mm
Rr =0.25 (P-400)--Where annual rainfall between 600–1000 mm
Rr= 0.35 (P-600)--Where annual rainfall greater than 2000 mm

- Amritsar formula (1973)

Using regression analysis for certain doabs in Punjab, the Irrigation and Power Research Institute, Amritsar, developed the following formula in 1973 [2].

$$R_r = 2.5 (P – 16) 0.5 \quad (5)$$

Where, R_r and P are measured in inches. R_r is groundwater recharge and P is Precipitation

- Kumar and Seethapathi formula (2002)

Kumar and Seethapathi (2002) proposed the following relationship for estimation of recharge from rainfall in Upper Ganga canal command area [2].

$$R_g = 0.63 (P-15.28) 0.76 \quad (6)$$

Where R_g is groundwater recharge from rainfall in monsoon season in inches and P is mean rainfall in monsoon season in inches.

2.2.2 Estimation of groundwater by using water table fluctuation method

The water table fluctuation (WTF) method is a useful approach for estimating groundwater recharge during different monsoon seasons. In the Bahuda watershed, recharge is evaluated separately for the south-west (SW) monsoon June to September and the north-east (NE) monsoon October to December. During the SW monsoon, the heavy rainfall results in significant infiltration, leading to a marked increase in the water table. Recharge is determined by measuring the rise in the water table and considering the aquifer's specific yield. Although the NE monsoon is less intense, it still provides additional rainfall and recharge, which is essential for sustaining groundwater levels. And the formula for water table fluctuation method is

$$R_g=Aw*\Delta L*S_y \quad (7)$$

Where R_g is groundwater recharge, Aw is area of watershed (m2), S_y is specific yield and ΔL is water table difference (m). A constant specific yield (S_y) was taken as 0.025, based on Groundwater Estimation Committee Report.

2.3 Recharge estimation using the Soil and Water Assessment Tool (SWAT)

The Soil and Water Assessment Tool (SWAT) model is a medium to large-scale river basin model that was developed to predict the impact of land management practices such as land-use and cover changes, reservoir management, and groundwater withdrawals in complex watersheds with varying soils, land-use and management conditions over long periods of time [3]. Basic input information required for modelling a river basin in SWAT include a digital elevation model, soil, land-use and climate data. SWAT uses the topographic data to divide a river basin into multiple sub-basins, which are further subdivided into hydrologic response units (HRUs) that consist of homogeneous land-use, management and soil characteristics [4]. The hydrologic cycle that takes place in a basin is explained by the water balance in the basin. The water balance equation that represents the hydrologic cycle simulated in SWAT [3].And the Schematic representation of the hydrologic cycle are shown in Fig: 2

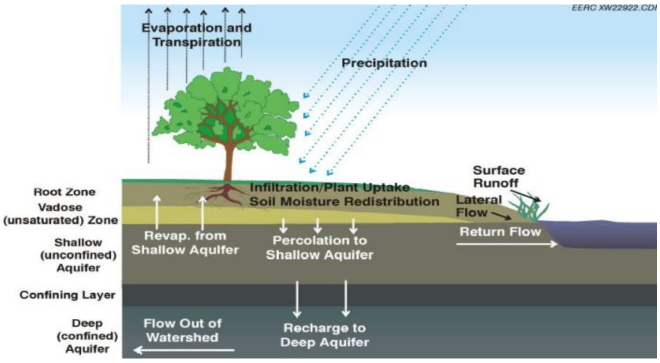

Fig: 2 Schematic representation of the hydrologic cycle

$$SWt = SW + \sum_{i=1}^{t}(R_{it} - Q_i - ET_i - P_i - QR_i) \quad (8)$$

Where,
SWt = Soil water content at time step
SW = Final soil water content
R = Daily amounts (in mm) of precipitation
Q = Amount of runoff
ET = Amount of Evapotranspiration
P = Percolation
QR = Groundwater flow

In SWAT, the majority of hydrologic processes occur at the HRU level, where the water balance is simulated before runoff is directed to the sub basin reaches and subsequently to the basin channel. The key hydrologic components modelled in SWAT, as shown in the water balance equation, include precipitation, surface runoff, evapotranspiration, infiltration, groundwater flow, and soil water content.

2.3.1 Precipitation

Precipitation plays a vital role in the water balance of a watershed, serving as the main source of water entering the hydrological cycle. It affects important processes like infiltration, runoff, evapotranspiration, and groundwater recharge. In the SWAT model, precipitation data is essential for simulating hydrological processes, as it directly influences runoff, stream flow, and the overall water balance. The importance of accurate, observed precipitation data lies in its ability to reflect the real-world variability in rainfall patterns, including aspects like intensity, duration, and frequency. Utilizing observed data improves the model's accuracy in replicating stream hydrographs, making predictions more dependable and aligned with actual watershed dynamics. This underscores the importance of using precise precipitation inputs for effective hydrological modelling [3].

2.3.2 Surface runoff

Surface runoff happens when the amount of water from precipitation surpasses the soil's ability to absorb it, leading to the filling of surface depressions. In the SWAT model, there are two methods to estimate surface runoff: the SCS curve number procedure and the Green-Ampt infiltration method [3]. The Soil Conservation Service (SCS) curve number method takes into account factors like land use, soil permeability, and previous soil moisture conditions, adjusting curve numbers based on soil moisture levels higher when the soil is nearly saturated and lower when it approaches the wilting point. On the other hand, the Green-Ampt method uses detailed sub-daily precipitation data to determine infiltration based on soil characteristics, but this method was not suitable for this study due to data constraints. Therefore, the SCS curve number method was chosen, as it provides a practical way to estimate runoff across various land uses and soil types**.** The equation underlying the SCS curve number is shown below [5].

$$\mathbf{Q_{surf}} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)} \tag{9}$$

Where,
$\mathbf{Q_{surf}}$ is the accumulated runoff or rainfall excess (mm)
R_{day} is the amount of precipitation on a given day (mm)
I_a is the initial abstraction
S is the retention parameter (mm)

The retention parameter (S) varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content. In SWAT, the retention parameter relates to the curve number for the day (CN) and is defined as [3].

$$\mathbf{S} = 25.4\left(\frac{1000}{CN} - 10\right) \tag{10}$$

Where CN is the curve number for the day. The initial abstractions Ia, is commonly approximated as 0.2S and the previous equation (9) becomes:

$$Q_{Surf} = \frac{(R_{day} - 0.2s)^2}{(R_{day} + 0.8s)} \tag{11}$$

It can be inferred from (11) that runoff will only happen when R_{day} exceeds I_a. You can find tables of typical curve numbers for different soil types and land covers suitable for a land slope of 5% from the SCS Engineering Division [6]. In SWAT, runoff is calculated individually for each HRU and then combined to determine the total runoff for each sub-basin. This sub-basin runoff is subsequently routed to calculate the total runoff for the entire basin.

2.3.3 Evapotranspiration

Evapotranspiration (ET) is the combined process of evaporation and plant transpiration, which is essential for the water cycle as it removes water from a basin. In the SWAT model, soil evaporation and plant transpiration are calculated separately. Potential evapotranspiration (PET) indicates the maximum rate of ET under ideal conditions with plenty of water available, and in SWAT, it is estimated using three methods: Hargreaves, Priestly-Taylor, and Penman-Monteith. For this study the Hargreaves takes place the data given to the model are precipitation and temperature [3]. The equation of the Hargreaves as shown below (12)

$$ET = 0.0023 * R_a * (T_{avg} + 17.8) * (T_{max} - T_{min})^{0.5} \tag{12}$$

Where:
ET = Evapotranspiration (mm/day)
Ra = Extra-terrestrial radiation (MJ/m²/day)
$Tavg$, $Tmax$, $Tmin$ are Temperature values (°C).

Actual evapotranspiration (AET) refers to the amount of water that is removed from a surface through evaporation and transpiration processes. AET matches potential evapotranspiration (PET) when there is sufficient water available. The SWAT model calculates AET after determining the total PET. It first accounts for the evaporation of rainfall that is intercepted by plant canopies, and then it estimates the maximum transpiration and sublimation or soil evaporation using a method similar. If snow is present in the hydrologic response unit (HRU), sublimation occurs; evaporation from the soil only takes place when there is no snow [7].

2.3.4 Groundwater

Estimating groundwater recharge in the SWAT model can be done using various methods, including the water balance method, percolation method, and aquifer simulation. In the case of the Bahuda watershed, where only rainfall and temperature data are accessible, the water balance method stands out as the most appropriate choice due to its simplicity and low data requirements. This method determines recharge by calculating the difference between precipitation and the combined effects of surface runoff, evapotranspiration, and soil storage, making it particularly useful in regions with limited data. By utilizing rainfall as the main input and temperature data to estimate evapotranspiration, the water balance method yields reliable recharge estimates that are influenced by climatic conditions. Its easy implementation and broad applicability in watershed studies provide valuable insights into recharge potential, even in areas where detailed subsurface data is unavailable. The equation for groundwater recharge are shown below [3].

$$R = P - ET - Q - \Delta S \tag{13}$$

Where,
R = Groundwater recharge (mm)
P = Precipitation (mm)
ET = Evapotranspiration (mm) (estimated using Hargreaves)
Q = Surface runoff (mm) (estimated using the SCS Curve Number Method)
ΔS = Change in soil moisture storage (mm)

3.Results and Discussions

3.1 Estimation of Groundwater Recharge by using Empirical Formulae

After identifying the relevant rain gauge station, calculations were performed to estimate the natural groundwater recharge from rainfall in the study area. Six empirical methods, developed by Chaturvedi, UPRI, Bhattacharjee, Krishna Rao, Kumar et al., and the Amritsar formulae, were employed for this analysis. These approaches were used to evaluate 22 years of rainfall data, offering a thorough assessment of recharge rates across different climatic and geological conditions**.** Rainfall variability in the Bahuda watershed over the past 22 years has had a significant impact on estimating groundwater recharge. Annual rainfall varied from 1245 mm in 2021 to 421.23 mm in 2018 shown in Table 1, underscoring the climatic fluctuations in this semiarid region. Several empirical formulas, including those by Krishna Rao and Chaturvedi, were employed to estimate recharge, revealing notable differences due to varying assumptions. Krishna Rao's formula yielded conservative estimates, with a minimum recharge of 4.33 mm recorded in 2018, while Amritsar's formula indicated the highest recharge at 365.06 mm in 2021 shown in (Table 1). Despite the differences in absolute values, all methods consistently demonstrated that recharge was higher during wet years and lower during dry years, indicating a strong correlation with rainfall and a reliable means of identifying recharge trends.

Table: 1 Determination of Ground water recharge in Bahuda watershed (mm)

Years	Rainfall (mm)	Chaturvedi (mm)	U.P.I.R.I (mm)	Bhattacharjee (mm)	Amritsar (mm)	Kumar (mm)	Krishna Rao(mm)
2000	706.88	140.98	127.52	139.99	218.41	109.44	76.73
2001	902.20	170.11	159.07	168.84	280.55	157.36	125.55
2002	449.60	75.59	65.97	75.40	82.81	31.33	9.92
2003	598.00	119.82	105.93	119.05	174.40	79.65	39.60
2004	608.86	122.17	108.26	121.37	179.25	82.75	52.20
2005	1023.80	185.00	175.87	183.58	313.07	184.91	155.95
2006	512.56	98.08	85.24	97.57	129.82	53.54	22.51
2007	966.71	178.24	168.19	176.89	298.24	172.15	141.68
2008	767.40	150.92	138.07	149.83	239.39	124.89	91.85
2009	540.18	105.85	92.44	105.24	145.73	62.35	28.04
2010	760.16	149.79	136.85	148.70	236.99	123.08	90.05
2011	642.93	129.18	115.33	128.31	193.78	92.31	60.73
2012	624.30	125.43	111.53	124.59	185.99	87.13	56.08
2013	568.00	112.89	99.16	112.20	160.17	70.84	42.00
2014	431.50	66.87	59.27	66.84	63.12	24.04	6.30
2015	1087.56	192.13	184.08	190.65	328.85	198.85	171.90
2016	444.43	73.26	64.13	73.11	77.70	29.31	8.89
2017	744.25	147.24	134.13	146.18	231.59	119.05	86.06
2018	421.63	61.30	55.29	61.39	49.18	19.76	4.33
2019	564.70	112.09	98.38	111.41	158.52	69.85	32.94
2020	1153.15	199.08	192.15	197.54	344.32	212.87	188.30
2021	1245.93	208.31	203.01	206.69	365.06	232.20	211.48

3.2 Estimation of groundwater recharge by using water table fluctuation method

Understanding groundwater recharge is crucial for effective resource management, especially in areas like the Bahuda watershed. In this region, aquifer replenishment usually happens about a month after rainfall, which highlights the importance of considering the time delays in recharge processes. To improve accuracy, the hydrological year is split into South-west (SW) June to September and North-east (NE) October to December monsoon periods, capturing the seasonal variations in recharge. By using the water table fluctuation method for each monsoon season separately, this approach offers a better insight into recharge patterns that are affected by different rainfall intensities and distributions. Between 2000 and 2021, recharge estimates showed considerable variability, closely tied to rainfall amounts. For example, in 2020, the SW monsoon brought 581.79 mm of rain, resulting in a recharge volume of 65.39 million cubic meters (mm^3), while the NE monsoon, with 487.05 mm of rain, contributed 53.40 mm^3 shown in Table 2. Conversely, in drier years like 2001, lower rainfall during both monsoon periods led to decreased recharge volumes. These seasonal observations underscore the importance of analysing recharge specific to each monsoon in order to create sustainable groundwater management strategies for the region.

Table: 2 Groundwater recharge by water table fluctuation method (season wise)

Year	Weighted Rainfall (mm)		Average Fluctuation (m)		Recharge vol, mm^3	
	SW	NE	SW	NE	SW	NE
2000	382.70	147.30	0.39	0.15	42.79	16.60
2001	354.62	435.87	0.36	0.44	39.62	48.92
2002	193.25	175.20	0.20	0.17	22.60	18.68
2003	383.67	188.13	0.39	0.19	43.24	20.97
2004	360.31	80.99	0.35	0.08	38.36	8.79
2005	465.06	477.10	0.45	0.48	49.48	53.54
2006	340.14	177.55	0.34	0.17	37.71	19.21
2007	455.85	391.11	0.46	0.39	51.01	42.67
2008	267.99	323.28	0.30	0.32	32.76	35.18
2009	361.74	178.28	0.37	0.17	40.39	19.32
2010	457.38	386.34	0.45	0.36	49.19	39.41
2011	329.98	217.34	0.32	0.23	35.21	24.87
2012	263.65	213.21	0.28	0.21	31.16	23.60
2013	327.45	135.11	0.35	0.14	38.43	15.74
2014	235.49	120.89	0.24	0.12	26.87	13.03
2015	256.06	716.54	0.26	0.72	28.73	79.14
2016	237.92	180.55	0.24	0.13	26.24	13.84
2017	422.98	237.90	0.43	0.24	47.26	26.07
2018	270.91	88.02	0.26	0.08	28.69	9.13
2019	342.05	171.41	0.35	0.17	38.13	18.73
2020	581.79	487.05	0.59	0.48	65.40	53.40
2021	551.31	587.37	0.53	0.57	58.61	63.22

The average fluctuation of the water table in the Bahuda watershed closely aligns with seasonal rainfall patterns, showcasing how the aquifer responds dynamically to precipitation. During the south-west monsoon, fluctuations varied from 0.20 m in 2001 to 0.59 m in 2020, while the north-east monsoon saw changes from 0.15 m in 2000 to 0.57 m in 2020. Groundwater recharge volumes, calculated with a specific yield of 0.2 and a watershed area of 552.44 km^2, also displayed significant seasonal and inter-annual variability. For instance, in 2003, moderate rainfall led to recharge volumes of 43.23 mm^3 for the south-west monsoon and 20.96 mm^3 for the northeast monsoon, highlighting how rainfall intensity, duration, and distribution affect recharge efficiency. In years with higher rainfall, such as 2020, recharge volumes were consistently greater, while drought years like 2012 saw a decline in recharge, emphasizing the system's vulnerability to rainfall shortages. This highlights the necessity of considering seasonal variations in recharge for effective groundwater resource management. To tackle the variability in recharge rates, implementing strategic measures like enhancing soil moisture retention, building rainwater harvesting systems, and improving aquifer recharge methods is essential.

3.3 Groundwater recharge estimation using soil and water assessment tool (SWAT)

The SWAT model for the Bahuda watershed was developed using Quantum Soil Water Assessment Tool (QSWAT), a Quantum Geographic Information System (QGIS) extension that helps integrate spatial data for hydrological modelling. The watershed was divided into 14 micro-basins based on a Digital Elevation Model (DEM) and stream network, which allows for a detailed analysis of water flow and recharge processes. The Digital Elevation Model (DEM) download from Bhuvan website. Each micro-basin was then broken down into Hydrological Response Units (HRUs), characterized by specific combinations of soil type, slope, land use, and weather conditions. This breakdown captures the spatial diversity of the watershed and enables accurate simulation of processes such as infiltration, surface runoff, evapotranspiration, and groundwater recharge. The thorough model setup offers a solid framework for estimating groundwater recharge and aids in making informed decisions for sustainable watershed management.

The annual precipitation in the Bahuda watershed from 2001 to 2023 shows considerable variability, with amounts ranging from 425 mm in 2002 to 1486 mm in 2021, typical of semi-arid and tropical monsoonal areas. Precipitation is a key driver of important hydrological processes, such as surface flow, groundwater recharge, percolation, and evapotranspiration (ET). Surface flow, which is closely linked to rainfall, varies significantly, from 93.71 mm in drier years like 2012 to 587.86 mm in wetter years like 2021. The moderate runoff compared to precipitation indicates effective infiltration and water retention, as demonstrated in 2018, when 499 mm of rainfall led to only 49.85 mm of runoff. Groundwater flow and percolation also mirror rainfall variability, with groundwater flow peaking at 65.36 mm in 2020 and percolation reaching 243.21 mm in 2023, suggesting favourable conditions for recharge during years with well-distributed rainfall. ET remains relatively stable, ranging from 411.79 mm in 2002 to 619.64 mm in 2023, underscoring the stabilizing effects of vegetation and soil moisture despite fluctuations in rainfall. All these values shown in table 3. In dry years, ET decreases due to limited soil moisture, highlighting the importance of water conservation and sustainable land management to preserve soil and vegetation health and support the hydrological cycle during times of low rainfall.

Table 3: Annual water balance of the Bahuda watershed

Year	Precipitation (mm)	Surface Flow (mm)	Groundwater flow (mm)	Percolation (mm)	ET (mm)
2001	856	280.43	30.89	81.79	484.71
2002	425	43.20	4.68	9.46	411.79
2003	596	118.38	7.52	29.06	433.29
2004	634	102.56	5.64	24.54	502.93
2005	1070	313.43	53.00	164.29	570.07
2006	596	89.09	29.13	20.78	494.29
2007	828	174.57	22.66	92.96	543.00
2008	730	146.79	6.32	34.36	560.21
2009	703	139.57	7.48	37.73	522.43
2010	817	160.43	17.08	74.46	578.29
2011	681	93.71	10.19	27.05	550.64
2012	633	110.81	4.65	4.32	536.93
2013	574	72.92	6.32	19.25	498.07
2014	433	23.25	8.92	12.00	430.79
2015	1068	391.21	15.02	148.96	484.00
2016	453	50.60	22.62	2.35	425.36
2017	916	265.29	43.53	121.97	507.29
2018	499	49.85	3.95	1.44	463.64
2019	725	175.69	18.99	63.76	468.14
2020	1355	587.86	65.36	195.00	557.71
2021	1486	599.14	145.56	218.64	622.93
2022	1120	292.21	215.36	243.21	619.64
2023	764	77.84	54.39	79.01	614.14

The hydrological components precipitation, runoff, groundwater flow, percolation, and evapotranspiration together illustrate a complete water balance for the watershed. The findings show that a large portion of precipitation goes into percolation and groundwater recharge instead of being lost as surface runoff, which is advantageous for maintaining groundwater levels. For example, in 2020, from a total of 1355 mm of precipitation, only 195 mm was lost as runoff, while 218.64 mm percolated into the soil, demonstrating effective water use and storage. Conversely, in years with low rainfall, like 2018, the limited percolation and high surface flow indicate a decrease in recharge and a greater risk of water scarcity. The groundwater recharge estimation using Soil Water Assessment Tool (SWAT) in Quantum Geographic Information System (QGIS) gives the hydrology parameters which much need for estimation of Groundwater recharge and Soil Water Assessment Tool (SWAT) tool defined that the groundwater recharge in Bahuda Watershed is pretty much low. This variability underscores the importance of implementing effective water management strategies, such as rainwater harvesting and soil moisture conservation, to boost recharge during wet years and address shortages during dry spells.

3.4 Validation of the SWAT Model Using Evapotranspiration Data

The accuracy of the SWAT model was validated by comparing the predicted evapotranspiration (ET) values with observed ET data from 2001 to 2023 (Figure 3). The results indicate a strong correlation, with both datasets exhibiting similar trends. Although observed ET values are somewhat higher in certain years, the overall consistency suggests that the SWAT model effectively simulates evapotranspiration in the Bahuda watershed. This validation reinforces the model's reliability for estimating important hydrological parameters such as groundwater recharge and surface runoff, making it a valuable tool for water resource management.

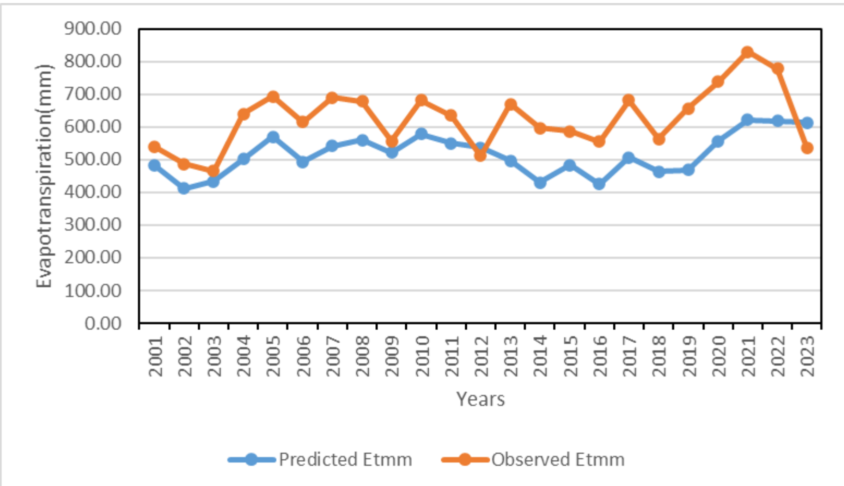

Figure 3: Variations of Observed ET and Predicted ET

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4.Conclusion

Groundwater recharge in the Bahuda watershed is closely linked to both annual and seasonal rainfall patterns. When rainfall is above average, there is a notable increase in recharge, whereas in drier years, recharge diminishes. This underscores the critical role of precipitation in hydrological processes and the necessity of considering rainfall variability in water management strategies. Both empirical methods and the water table fluctuation method effectively captured trends in recharge, with the latter offering more precise field-based assessments. The SWAT model, utilized in QSWAT through QGIS, simulated changes in precipitation, runoff, evapotranspiration, and groundwater recharge. An analysis of the annual water balance revealed that a significant portion of precipitation contributes to recharge, particularly during wet years, while dry years result in lower recharge and heightened risks of water scarcity. The study highlights the importance of sustainable practices such as rainwater harvesting, soil moisture conservation, and optimized land use to improve groundwater recharge and address the impacts of rainfall variability, thereby ensuring long-term water security.

5.Future Scope

The future direction of this study involves enhancing groundwater recharge estimates by incorporating advanced hydrological models and remote sensing methods to achieve better spatial and temporal resolution. Additional research could concentrate on evaluating the effects of climate change scenarios on groundwater recharge and water availability in the Bahuda watershed.

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