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HYDROGEOLOGICAL ANALYSIS OF GROUNDWATER RECHARGE IN SEMI-ARID REGIONS: A CASE STUDY OF A WATERSHED FROM RAJASTHAN

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Abstract

Despite the fact that groundwater recharge in dry locations is essential for the maintenance of water supplies, it is frequently hindered by low precipitation, high evaporation rates, and difficult hydrogeological conditions. The purpose of this study is to investigate the hydrogeological processes that have an effect on groundwater recharge in dry areas, with a particular emphasis on natural and artificial charge mechanisms. Important aspects such as the permeability of the soil, the properties of the aquifer, and the fluctuation of the climate are investigated. In order to identify possible recharge zones and quantify recharge rates, the research makes use of a variety of methodologies including hydrological modelling, and field studies. It is important to pay special attention to the role that wadis, ephemeral streams, and infiltration from flash floods play in the process. In addition, the impact of human activities, such as urbanisation and water extraction, is analysed in order to gain a better understanding of the influence that these activities have on the dynamics of recharge. The preliminary findings emphasise the significance of using localised recharge augmentation strategies, such as managed aquifer recharge (MAR) systems and rainfall collecting, in order to boost the availability of water. Arid regions are characterised by their distinct hydrogeological and climatic circumstances, and the study highlights the importance of developing sustainable groundwater management techniques that are customised to these settings. This study makes a contribution to a better knowledge of the dynamics of groundwater recharge and provides insights that may be put into action by policymakers and water resource managers who are working to alleviate water shortages in dry regions.

Keywords: *Hydrogeology, Groundwater, Recharge, Semi-Arid, Rajasthan, India.*

Introduction

In dry and semi-arid regions, where surface water is sparse and the climate is characterised by low and variable rainfall, coupled with high evaporation rates, groundwater serves as an essential resource. This is because groundwater is extracted from the ground and stored below in the aquifers. As a result of the fact that domestic, agricultural, and industrial activities are supported by groundwater in many regions, the sustainable management of groundwater gains a priority. However, the replenishment of groundwater, also known as recharge, in dry places is restricted by both natural and artificial reasons, which presents considerable problems to the management of water resources. To address the issue of water scarcity and to ensure that water will be available for the long term, it is vital to have a solid understanding of the hydrogeological processes that regulate the groundwater recharge in dry regions. These locations are subject to a complex interaction of meteorological factors, soil and aquifer features, and surface water dynamics, all of which have an impact on the mechanisms that are responsible for recharge. There are a number of features that play an important part in permitting recharging during irregular rainfall episodes. These features include ephemeral streams, wadis, and flood plains (Athavale, Murti, and Chand,1980). Furthermore, groundwater depletion is frequently made worse by excessive extraction, changes in land use, and insufficient management, which further complicates the processes of groundwater recharge. The hydrogeological analysis of groundwater recharge in dry settings is the primary topic of this study. The objectives of this research are to evaluate the elements that influence recharge and to propose solutions that may be used to increase groundwater availability. This research studies both natural and anthropogenic recharge methods by including field-based observations, GIS tools, and hydrological modeling into its methodology(Bredenkamp ,1988)**.** The ultimate objective is to produce insights that can be put into action regarding sustainable groundwater management methods for dry regions. Particular attention will be paid to the significance of customised recharge improvement strategies, such as managed aquifer recharge (MAR) and rainfall collection.

In the next sections of this research, the most important hydrogeological processes that have an effect on recharge, as well as the methodologies that are used for analysis and the tactics that dry regions might employ to maximise recharging are investigated. The findings of this study are anticipated to provide a contribution to a better knowledge of the dynamics of groundwater and to aid decision-making on the management of water resources in regions that are experiencing severe water stress. In dry places, groundwater recharge is very episodic, and it frequently takes place as a result of severe rainfall events that cause surface runoff(Fayer, 2000). In spite of the fact that they occur seldom, these occurrences are extremely important for the replenishment of aquifers. This is especially true in regions that have natural recharge channels, like water infiltration through wadis or alluvial deposits. It is important to note that the efficiency of these natural recharge processes is highly reliant on the hydrogeological characteristics of the surrounding area. These variables include the permeability of the soil, the transmissivity of the aquifer, and the existence of restricting layers. Evaluating the possibility for recharging in a region requires first and foremost an understanding of these factors. Chand, R. (1980). Artificial recharge methods have become more popular as a feasible alternative to augment groundwater supplies. These approaches are in addition to natural recharge methodologies. Techniques including as percolation tanks, recharge wells, and the redirection of floods into recharging zones have been applied in a number of dry places, and the results have been encouraging. However, the effectiveness of these interventions is contingent on a comprehensive understanding of the hydrogeology of the region as well as the careful design of recharge systems to minimise problems such as the pollution of aquifers or the wasteful use of water **(**Flerchinger, Hanson, and Wight, 1996)**.** In addition, this study acknowledges the involvement of climate change in the process of modifying recharge patterns. It is anticipated that dry regions would see an increase in water stress as a result of rising temperatures, protracted droughts, and increasing unpredictability in precipitation sources. As a result of these changes, it is necessary to implement adaptive methods for the management of groundwater resources. These strategies should include the combination of traditional knowledge and contemporary technology in order to improve recharge and maximise water utilisation. The research sheds insight on potential solutions to the problem of water shortage in arid regions by focusing on the interaction between natural and artificial recharge methods (Gandolfi, Facchi, and Maggi, 2006). The study is especially pertinent for decision-makers, managers of water resources, and other stakeholders who are involved in managing the rising demand for water in arid and semi-arid countries. The purpose of this project is to establish a framework for sustainable groundwater management in locations where water is a limiting factor for economic growth and human well-being. This will be accomplished through a mix of hydrogeological analysis and strategies for recharge optimisation (Garatuza-Payan et al. ,1998).

Materials and Methods

General characteristics of study area

The present research site may be found in the semi-arid region of the Indian state of Rajasthan. The location is located at latitude of 25^0 36' N and a longitude of $76^0$15' E. The watershed in question encompasses a total area of 682.5 hectares and empties into the Mej River close to the point where the Mej and Chambal rivers meet. Approximately 20% of the watershed area remains relatively stable, while the remaining 80%—particularly in the downstream region—is extensively affected by gully networks. The watershed has a dry semi-arid climate, with an average rainfall of 750 mm, with 90 % of that rainfall occurring between the middle of June and the middle of September. With a typical maximum temperature of 42^0C in May, summers are quite hot. In January, the lowest temperature ever recorded was 6.9^0C. Black soils of recent alluvial origin are found in the watershed. These soils are classified as members of the hyperthermia family of Chromusterts and Pellusterts, which are considered to be members of the Vertisols order. These soils often have a clay loam or silty clay loam texture, depending on the kind of soil. Ravines are quite prevalent across the watershed, which also has a drainage density that is extremely high. Bredenkamp, D. B. (1988).

Groundwater recharge estimation methods

The HYDRUS-1D and water table fluctuation (WTF) methodologies are utilised in this investigation to estimate the potential and actual groundwater recharge, respectively. These are the two approaches that are utilised the most frequently. (Gee and Hillel ,1988)

HYDRUS-1D model

Simunek et al. (2013) used the HYDRUS-1D version 4.17 model to evaluate the potential groundwater recharge from watershed and daily bottom fluxes, as well as cumulative bottom fluxes. This was done in order to determine the potential groundwater recharge. The HYDRUS-1D model is a software program that is used to simulate the movement of water, heat, and solutes in one-dimensional medium that is subject to increasing saturation levels (Hansen et al.,1990). For the purpose of computationally solving the Richard's equation for variably saturated water flow and the advection-dispersion type equations for heat and solute transport, this model is a finite element model (Pruess, 1991). The flow equation includes a sink component in order to take into account the water that is taken up by the roots of plants. The Richards equation, which describes the flow of water in a soil that is homogeneous or uniform, is defined as follows:

$$\frac{\partial \theta(h)}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - S(h,t) \quad (1)$$

Eq. (1) The Richard's model is a partial differential equation that is of the second order, parabolic, nonlinear, and partial differential (Hendrickx, Kruseman, and Rushton, 1997). Affected by the beginning conditions as well as the boundary conditions:

Initial condition:

$$h(z,0) = h_0(z) < 0, \quad 0 \le z \le \infty, \quad t = 0 \quad (2a)$$

$$- K(h)\left(\frac{\partial h}{\partial z}+1\right)\Big|_{z=0} = q_0(t) \quad (2b)$$

Boundary conditions:

$$\frac{\partial h}{\partial z}(L,t) = 0 \quad (3a)$$

Or

$$h(L,t) = h_L(t)$$

$$h = h_t > 0, \quad z \geq 0, \qquad t > 0 \quad (3b)$$

In this equation, h represents the hydraulic head (L), K (h) represents the hydraulic conductivity of the soil (LT-1), z represents the soil depth (L), S (h, t) represents the sink (root water uptake rate) in space and time, and h0 describes the initial potential and ht represents the boundary condition potential, respectively. The following equation, which was provided by Feddes et al. (1978), was utilised in order to represent the sink term, which refers to the root water uptake rate:

$$S(h) = \lambda(z)\,\alpha(h)\,T_p \quad (4)$$

Where λ(z) is the relative root distribution function, Tp is the potential transpiration rate, and α(h) is a water stress response function that does not have any dimensions ($0 \leq \alpha \leq 1$) in order to take into consideration decreases in absorption that are caused by drought stress.

Three soil layers were collected at 15, 30, and 45 cm from the ground surface for mass balancing, and a depth of 300 cm was considered for the simulation of water movement. Between 2002 and 2008, the recharging rate was independently simulated every day. For a given year, the total simulation period was the time it took for the first and last rainfall events to occur. We used a maximum time step of 0.01, a starting time step of 0.001, and a final time step of 0.00001. Using a vertical soil profile that was 300 cm deep, the starting and ending conditions were defined. There are three 100-centimeter-thick strata that make up the entire soil profile (Jansson and Karlberg, 2001). On the day the simulation began, the initial circumstances were chosen as the soil profile pressure head. We assumed a pressure head of -1000 cm on top of the soil profile and -100 cm below it in the research region. For the sake of this investigation, we will assume that surface runoff constitutes the upper boundary condition and free drainage the lower.

The hydraulic parameters of the soil were ascertained by use of the HYDRUS-1D-integrated Van Genuchten (1980) model. Using bulk density and sand, silt, clay percentage as input data, the following water flow parameters were estimated for three different soil layers: saturated water content (θb), residual water content (θf), inverse of the air entry value (α), pore size distribution index (n), saturated hydraulic conductivity (Ks), and pore connectivity parameter. A core cutter was employed to ascertain the bulk density, whereas the International pipette technique was employed to ascertain the particle size distribution.

Table 1 shows the soil's bulk density and particle size distribution, whereas Table 2 gives the water flow characteristics. Time variables were supplied using daily rainfall and reference evapotranspiration (Lerner, Issar, and Simmers,1990). A Penman-Monteith model, which is part of HYDRUS-1D, was used to estimate the reference evapotranspiration. The Penman-Montieth model was fed data on daylight hours, average humidity, wind speed, maximum and lowest temperatures, and days with no precipitation. As an absolute figure, 100,000 centimetres was chosen as the lowest allowable pressure head at the soil surface, hCritA. To estimate the recharge rate and simulate root water absorption, this study used small grain crops in their vegetative state and followed the approach described by Feddes et al. (1978). We assumed a root depth of 60 cm for small grain crops on average. Wesseling (1991) and Taylor and Ashcroft (1972) proposed a database where the values of the Feddes parameters could be found based on their research. You can see the values of the Feddes parameter in Table 3.

Water Table Fluctuation (WTF) method

Utilising water table fluctuation (WTF), we were able to gauge the whole watershed's groundwater recharge, which ultimately reaches the water table. Scanlon et al. (2002) provides further information about the WTF method: What the Fuck Means is:

$$\text{Actual groundwate r recharge} = \text{Specific yield of aquifer} \quad \text{Water level rise} \qquad (5)$$

Whereas, from 2002 to 2008, the specific yield was calculated using the method proposed by (or Shukla and Jaber, 2006) and the water level rise was monitored manually in all of the watershed monitoring wells (2006):

$$\text{Specific yield} = \frac{\text{Potential recharge rate}}{\text{change in water table}} \qquad (6)$$

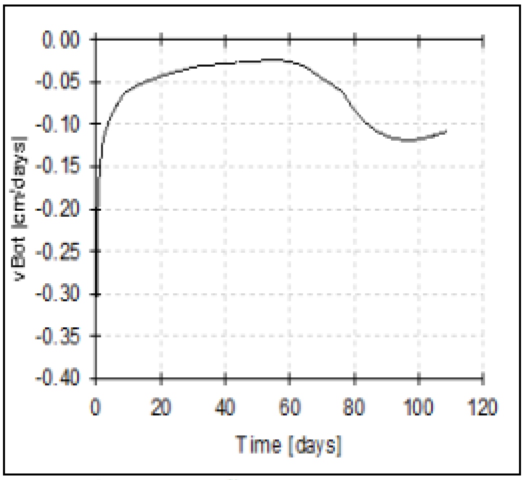
An aquifer's specific yield was determined using the recharge rate predicted by the HYDRUS1D model.

Results and Discussion

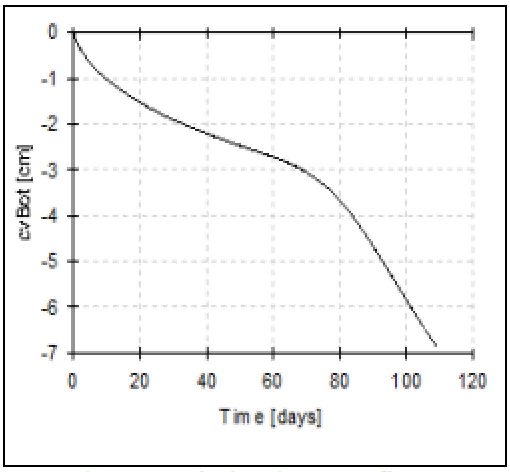
Estimation of potential groundwater recharge

In order to assess the potential groundwater recharge from the watershed, the HYDRUS1D model was used. Small grain crops grown on three distinct soil types in the watershed were modelled to determine their cumulative bottom flux, root water intake, evaporation, and soil water storage, as well as their cumulative bottom flux and potential groundwater recharge. The 2008 HYDRUS-1D findings for silt loam, silty clay loam, and clay loam soils are shown in Figures 1, 2, and 3, correspondingly. Soils characterised by silty clay loam (6.86 cm), clay loam (1.16 cm), and under silt loam (6.86 cm) have different potential groundwater recharge (cumulative bottom flux). According to Figures 1, 2, and 3, the cumulative root water uptake under silt loam soil was 39.22 cm, silty clay loam soil was 38.50 cm, and clay loam soil was 36.03 cm. Figures 4 and 5 compared the three soil types' cumulative root water absorption and potential groundwater recharge (cumulative bottom flow) from 2002 to 2008. The total bottom fluxes were 10 cm at their highest and 0.8 cm at their lowest for silt loam and clay loam soils, respectively. The average yearly potential recharge of groundwater under silt loam, clay loam, and silty clay loam soils was 5.01 cm, 3.46

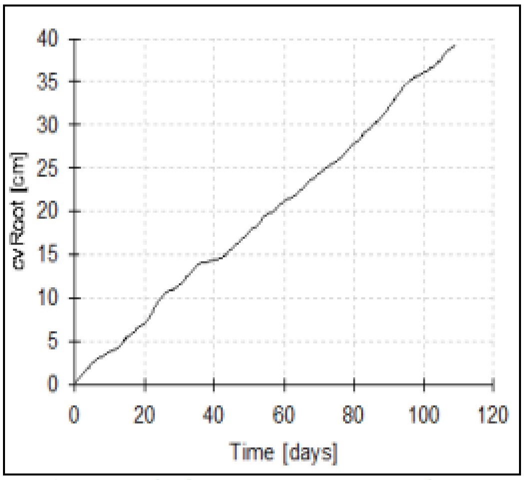
cm, and 1.26 cm, respectively. Based on the investigation, it was projected that the watershed may potentially replenish the groundwater by 3.24 cm per year (the cumulative bottom flux). Fayer, M. J. (2000). Throughout the whole simulation period, the cumulative root water intake under various soil types ranged from 16.85 to 39.22 cm, with an average of 26.93 cm. Soils with clay loam had the most root water absorption, whereas soils with silt loam had the lowest. Soils with silt loam were shown to have a greater cumulative bottom flux and root water absorption than soils with clay loam. Wight, J. R. (1996). The cumulative bottom flux for the soybean crop was higher on clay loam soil than on silt loam soil, but lower on silty clay loam soil (Nulsen and Baxter,1987). Soil texture variation might be the cause of these results. In Table 4, we can see the cumulative bottom flux and root water intake as a fraction of the region's total rainfall during the monsoon season. Gandolfi, C., Facchi, A. and Maggi, D. (2006).The cumulative recharge flow ranged from 4.6% to 10.8% of yearly rainfall, as seen in Table 4. The average yearly cumulative bottom flux under silt loam soil was 10.83%, under silty clay loam soil it was 7.08%, and under clay loam soil it was 2.81% of the rainfall during the monsoon season. The watershed's cumulative bottom flow during the monsoon season amounted to 6.91% of the total yearly rainfall. Findings from the HYDRUS-1D model were consistent with those from previous studies that calculated recharge rates in semiarid areas, such as Scanlon et al. (2010), Patle et al. (2016), and (Rangarajan and Athavale, 2000). According to Scanlon et al. (2010), the recharge rates in the rain-fed Rajasthan region were 10–16% while in the thinly vegetated dune region they were 2-3.



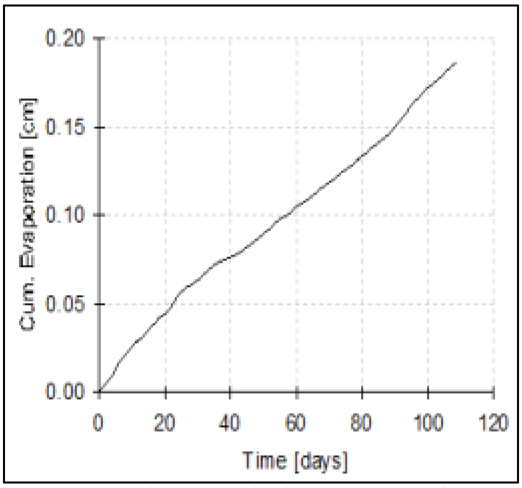
a) Bottom flux



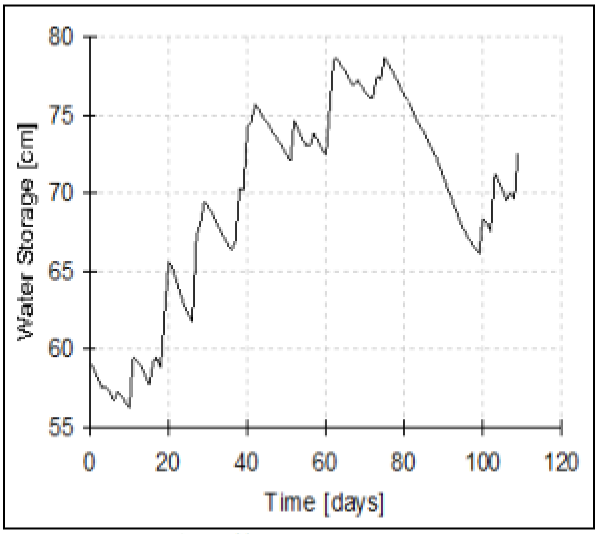
b) Cumulative bottom flux



c) Cumulative root water uptake

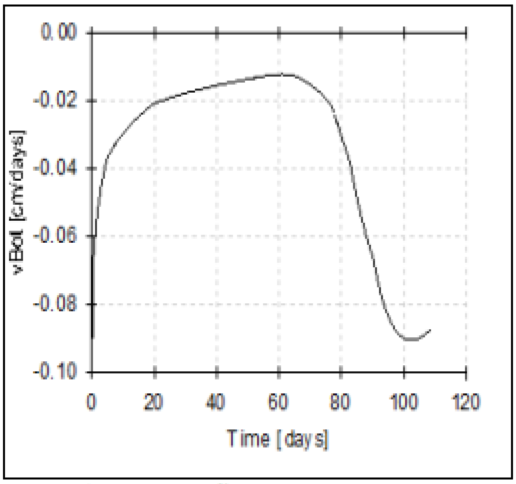


d) Cumulative evaporation

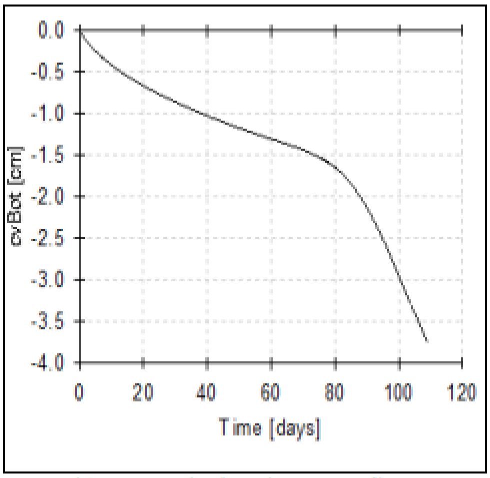


e) Soil water storage

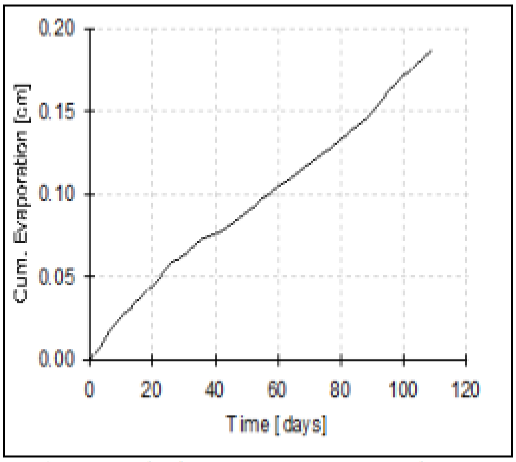
Fig.1 Results from the 2008 HYDRUS-1D model run on silt loam soil



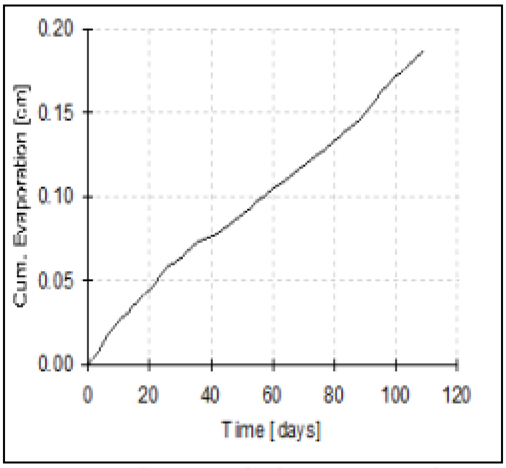
a) Bottom flux



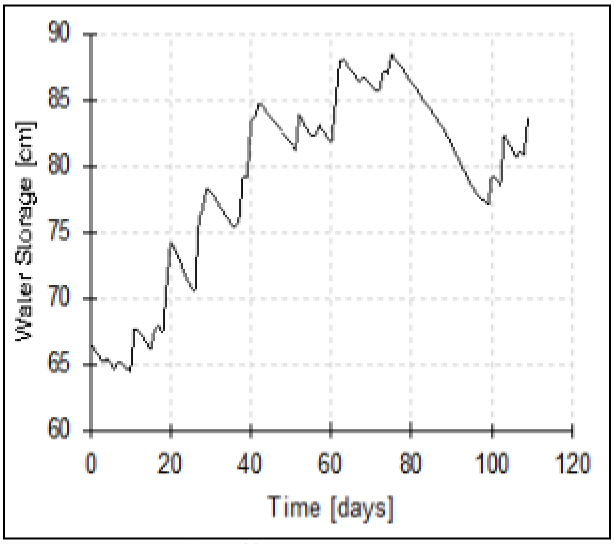
b) Cumulative bottom flux



c) Cumulative root water uptake

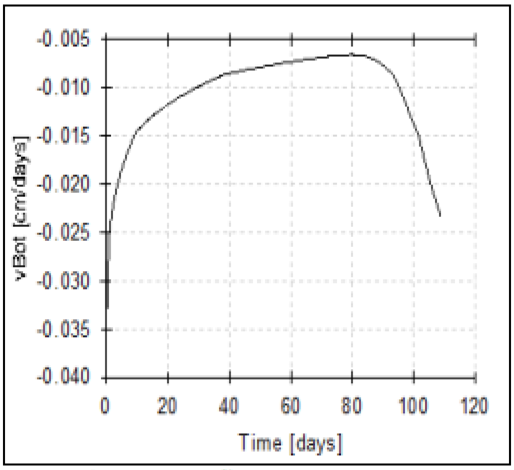


d) Cumulative evaporation

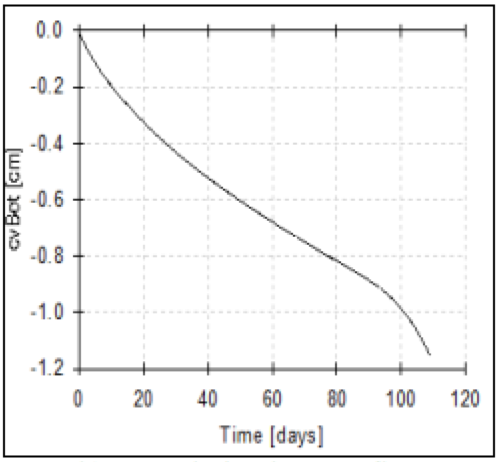


e) Soil water storage

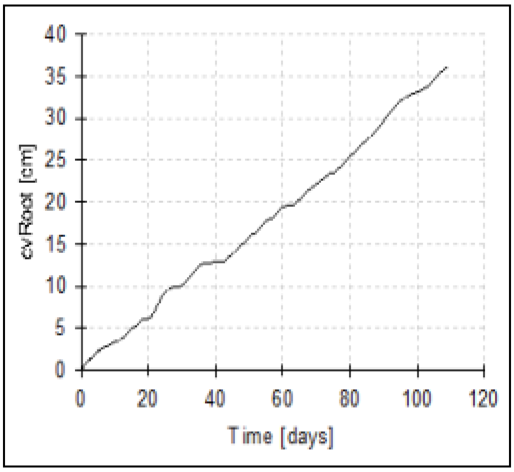
Fig.2 Results from the 2008 HYDRUS-1D model run on silty clay loam soil



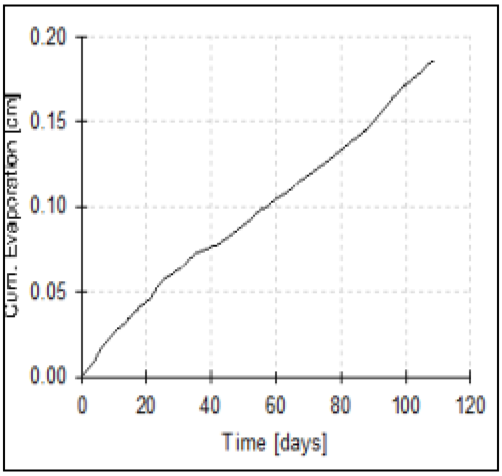
a) Bottom flux



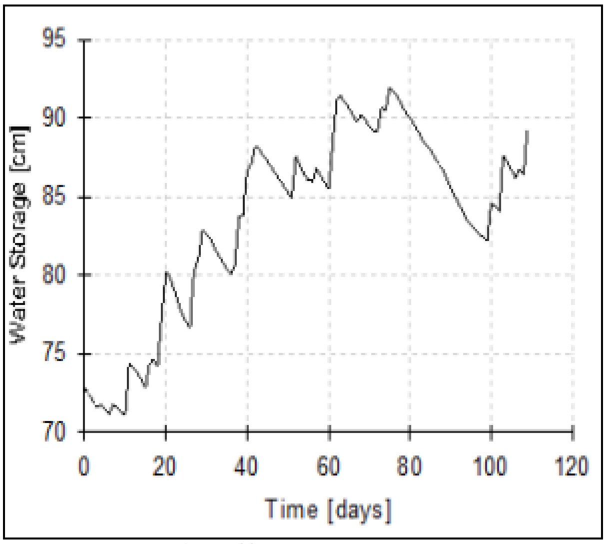
b) Cumulative bottom flux



c) Cumulative root water uptake



d) Cumulative evaporation



e) Soil water storage

Fig.3 The simulated results of HYDRUS-1D model under clay Loam soil for the Year 2008

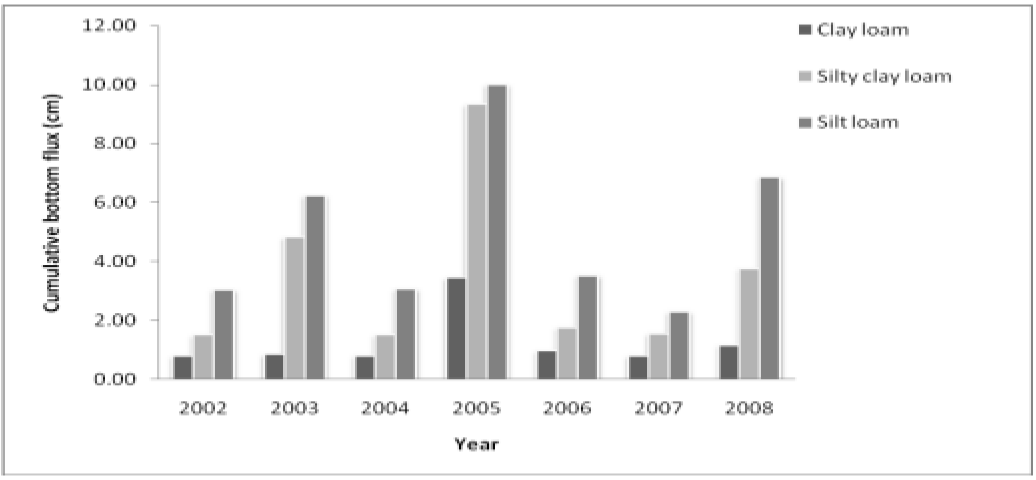


Fig.4 Comparison of cumulative bottom flux for soybean crop under different soils during the period 2002-08

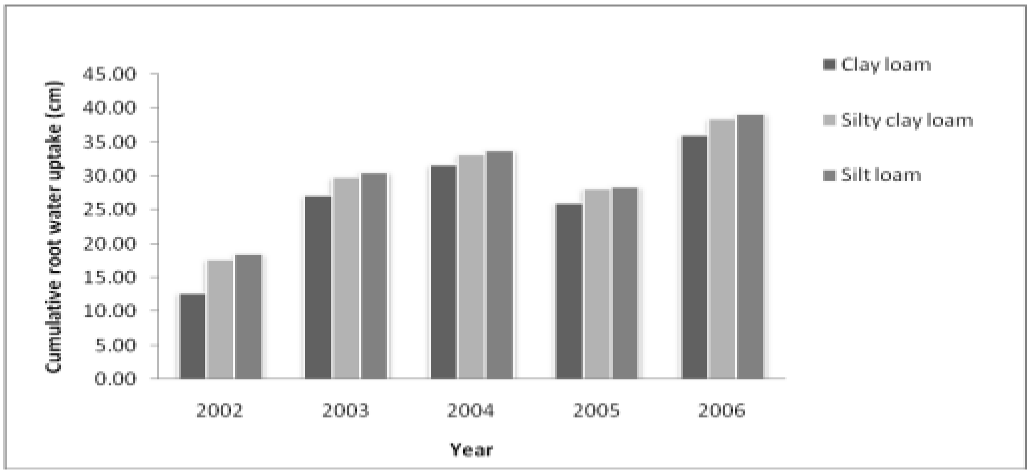


Fig.5 Comparison of cumulative root water uptake under different soils during the period 2002- 08

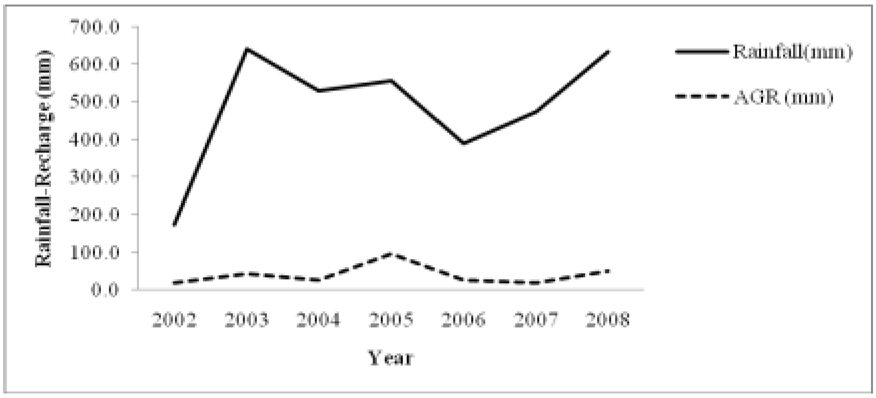


Fig.6 Variations in monsoon season rainfall and actual groundwater recharge in BK watershed during the period 2002-08

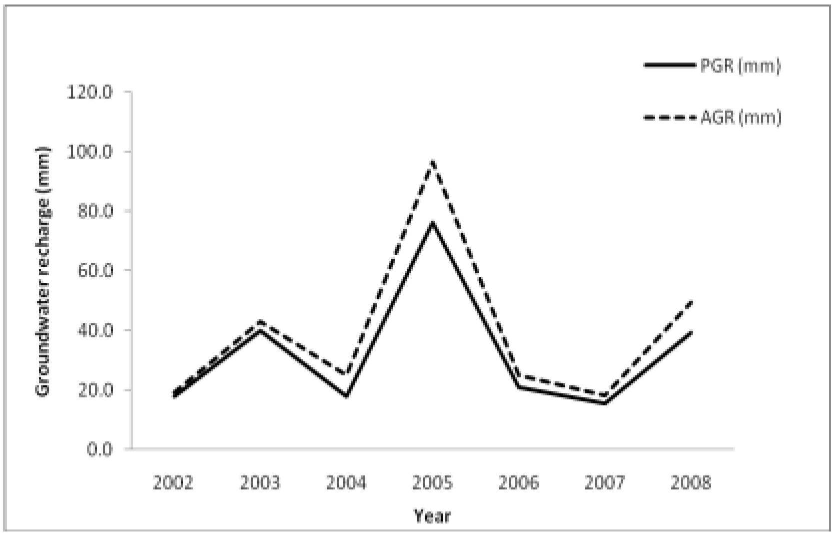


Fig.7 Comparison of potential and actual groundwater recharge from BK watershed during the period 2002-08

Table.1 Particle size distribution and bulk density of soil

Profile depth (cm)	Textural class	Average S and, silt and clay %			Average bulk density (gm/cm^3)
		% Sand	% Silt	% Clay	
0-15	Silt loam	62	20	18	1.5
15-30	Silt loam	66	16	18	1.5
30-45	Silt loam	64	18	18	1.4
0-15	Silty clay loam	54.7	21.3	24	1.6
15-30	Silty clay loam	54	20.7	25.3	1.6
30-45	Silty clay loam	53.3	21.3	25.3	1.6
0-15	Clay loam	39	27	34	1.7
15-30	Clay loam	42	26	32	1.7
30-45	Clay loam	40	26	34	1.7

Table. 2 Water flow parameters obtained from Rosetta model

Textual Class	$\theta r(cm^3/cm^3)$	$\theta s(cm^3/cm^3)$	α(cm-1)	n	Ks (cm/day)	l
Silt loam	0.0561	0.3954	0.0235	1.4112	25.88	0.5
Silt loam	0.0573	0.3988	0.0253	1.4217	31.11	0.5
Silt loam	0.0593	0.4229	0.0228	1.4427	42.51	0.5
Silty clay loam	0.0605	0.3762	0.0219	1.3168	9.95	0.5
Silty clay loam	0.0622	0.3781	0.0217	1.3078	9.36	0.5
Silty clay loam	0.0625	0.3787	0.0214	1.3064	8.92	0.5
Clay loam	0.0682	0.3611	0.0193	1.243	2.62	0.5
Clay loam	0.0656	0.3584	0.0201	1.2428	2.92	0.5
Clay loam	0.0680	0.3611	0.0198	1.2381	2.72	0.5

Table. 3 Fedde's parameter for small grain crop in vegetative period

Feddes parameter	Small grain crop in vegetative period
P0(cm)	-10
$P0_{pt}$(cm)	-25
P2H(cm)	-400
P2L(cm)	-500
P3(cm)	-8000
r2H(cm/day)	0.5
r2L(cm/day)	0.1

Table. 4 Cumulative root water uptake and cumulative bottom flux expressed as the per cent of cumulative rainfall

Year	Cumulative Bottom Flux			Cumulative Root Water Uptake		
	CL	SCL	SL	CL	SCL	SL
2002	4.61	8.67	17.58	97.29	99.31	99.25
2003	1.33	7.53	9.75	40.90	43.74	44.78
2004	1.52	2.86	5.81	24.14	33.45	35.00
2005	6.21	16.79	18.00	48.87	53.65	55.06
2006	2.49	4.51	9.04	81.21	85.19	86.78
2007	1.68	3.28	4.84	54.85	59.38	59.89
2008	1.82	5.92	10.81	56.81	60.71	61.84
Average	2.81	7.08	10.83	57.72	62.20	63.23

Table. 5 Average values of monsoon rainfall, depth of water table, change in water table, specific yield, AGR (mm) and AGR as the percentage of rainfall during the period 2002-2008

Years	Rainfall (mm)	Mean depth of water table (m)	Average change in water table(m)	Specific yield	AGR (mm)	AGR (%)
2002	173.2	17.63	1.23	0.031	19.33	11.2
2003	640.4	17.97	1.89	0.045	42.99	6.7
2004	528.6	14.5	1.27	0.029	24.85	4.5
2005	555.8	15.9	1.97	0.066	96.35	17.3
2006	389.6	16.71	1.91	0.014	24.88	6.4
2007	474.4	15.88	2.04	0.013	18.23	3.8
2008	634.2	15.69	1.96	0.031	49.33	7.8
Average	485.17	16.33	1.75	0.03	39.42	8.3

Estimation of Actual Groundwater Recharge in the watershed

Using the water table fluctuation (WTF) approach, the actual groundwater recharge (AGR) was assessed from 2002 to 2008. Annual rainfall, water table depth, water table change, specific yield, AGR (mm), and AGR as a proportion of rainfall are all displayed in Table 5. Findings indicated that average changes in water table level ranged from 1.23 to 2.04 mbgl and that average depth to water table varied from 14.5 to 17.67 mbgl . An average of 0.03 was the specific yield of the aquifer, which ranged from 0.013 to 0.066. With an average of 39.42 mm, or 8.3% of the monsoon season's rainfall, the actual groundwater recharge from the watershed ranged from 96.35 mm at its highest point to 18.23 mm at its lowest point. Figure 6 shows the yearly change in rainfall and actual recharging of groundwater from 2002 to 2008. Gee, G. W. and Hillel, D. (1988). It is clear from this graph that, although to a lesser extent, the change in real recharge tracks the change in rainfall. Because more surface runoff occurs in years with excessive rainfall, the recharge curve's peaks are less prominent in such years (Sanford, 2002). The actual and prospective groundwater recharge from the watershed are shown in Figure 7. It shown that real recharge values are somewhat greater than potential recharge values, and that the prospective recharge curve is in line with the actual recharge curve. Svendsen, H. (1990). Bonding, check dams, ponds in the watershed, and irrigation return flow are all examples of water conservation measures that might be contributing to the higher levels of real recharge. This conservation measure's impact was not taken into account by the HYDRUS-1D model. In India's semi-arid regions, precise information about groundwater recharge is crucial for effective management of groundwater resources (Sharma ,1989). This work utilised the HYDRUS-1D model to predict root water intake, potential recharge, and other unsaturated zone processes. In order to determine the true recharge of groundwater, the water table fluctuation (WTF) approach was employed. With an average of 3.24 cm (6.91%), the cumulative potential recharge in the watershed as predicted by the HYDRUS-1D model ranged from 0.8 to 10 cm, or 4.6 to 10.8% of the rainfall over the monsoon season (Suhag, 2016). Among the soil types tested, silt loam had the greatest potential recharge, while clay loam had the lowest. Similar to the HYDRUS-1D model, the WTF technique indicated an average recharge of 8.3% of monsoon season rainfall, with a range of 3.8% to 17.3%. Nulsen, R. A. and Baxter, I. N. (1987).

Conclusion

The unpredictable nature of precipitation and the restricted supply of surface water make groundwater recharging an essential yet complex process in dry places. The complex interplay of hydrogeological variables, weather patterns, and human activities is the subject of this study, which has shed insight on the dynamics of groundwater recharge in various settings. The importance of both natural and artificial recharge pathways in increasing groundwater availability has been highlighted by key studies. Natural channels include infiltration through wadis and ephemeral streams, while artificial interventions include managed aquifer recharge (MAR) systems and rainfall harvesting. In order to pinpoint possible recharging zones and precisely measure recharge rates, the study stresses the need for comprehensive hydrogeological evaluations. Developing targeted methods for optimising recharge processes is made feasible by merging field data, GIS technologies, and hydrological modelling. In addition, the study emphasises how human activities, such excessive extraction and changes in land use, can worsen groundwater depletion and call for sustainable management strategies. The importance of adaptive groundwater management is magnified when seen through the lens of climate change. Water supplies in dry places are already under pressure from rising temperatures, changing rainfall patterns, and extended droughts. Because of this, we need to take preventative actions to ensure groundwater quality, decrease water losses, and increase recharge efficiency. To sum up, groundwater recharge in dry areas can only be achieved by a concerted effort of scientific advancement, government action, and community engagement. Adopting a comprehensive approach that incorporates both natural and man-made recharge mechanisms will help dry regions become more resistant to water shortages and secure the supply of this vital resource for the future. Sustainable development in areas with water scarcity may be achieved by more study into improving recharge processes, investigating alternative water sources, and evaluating the social and economic effects of groundwater management systems.

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