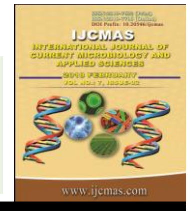
Int.J.Curr.Microbiol.App.Sci (2018) *7*(2): 2552-2565

International Journal of Current Microbiology and Applied Sciences
***ISSN: 2319-7706* Volume 7 Number 02 (2018)**
Journal homepage: http://www.ijcmas.com



Original Research Article https://doi.org/10.20546/ijcmas.2018.702.311

Assessment of Groundwater Recharge in a Small Ravine Watershed in Semi-arid Region of India

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Keywords

Ground water recharge, Water table fluctuation, HYDRUS-1D

Article Info

Accepted:
24 January 2018
Available Online:
10 February 2018

A B S T R A C T

The water availability is limited, however demand of water is increasing many fold due to expansion of agriculture, growing population, rapid industrialization and economic development in India. Available water resources need to be managed properly to meet increasing demands of water. In this study, different hydrological processes as surface runoff, evapotranspiration and soil moisture were modeled to assess the groundwater recharge in a small watershed located in semi-arid region of Rajasthan, India. The daily potential and actual groundwater recharge in the watershed were estimated using HYDRUS-1D, an unsaturated flow model and Water Table Fluctuation (WTF) method, respectively. It was observed that the mean cumulative potential groundwater recharge in the watershed was found to be 3.24 cm (6.91 per cent of average annual precipitation of the region). The average actual recharge estimated by WTF method was found to be 8.3 per cent of average annual precipitation which was comparable with the HYDRUS-1D model.

Introduction

Groundwater is the most preferred source of water in India due to its widespread availability and low capital cost. The total annual replenishable groundwater resources of India have been estimated as 447 Billion Cubic Meter (BCM). Out of which, 36 BCM is turn into natural discharge. The yearly groundwater availability in India is 411 BCM. According to the assessment of dynamic groundwater resources of India, the stage of groundwater development in the India is 62 per cent (MoWR, 2013). Out of total extracted groundwater, the highest (89%) is used in irrigation followed by domestic (9%) and industrial (2%) sectors (Suhag, 2016). Population growth and economic development are putting unprecedented pressure on water resources especially in arid and semi-arid regions of India. Around 1800 million people are likely to face “absolute” water scarcity by 2025 (FAO, 2017). The rising dependence on groundwater as a consistent source of water has resulted in indiscriminate withdrawal in various parts of the country without due regard to the recharging capacities of aquifers and other environmental factors. National Water Policy (2012) states that for the sustainable development and management of the countries precious groundwater resources, scientific efforts from local, research institutions and Government are required in participatory mode. To deal with groundwater management problems, one must quantify and analyze the different components of hydrologic processes occurring within the watershed.

Groundwater recharge is the process for replenishment of groundwater storage. The amount and timing of groundwater recharge are controlled by hydrogeological and climatic factors and have long been of scientific and practical interest (Smerdon *et al.,* 2010). The prime factors affecting groundwater recharge are rainfall, soil type, vegetation characteristics etc. Recharge increases with increase in rainfall (Bredenkamp *et al.,* 1988) and the soils having more clay content produce less recharge (Athavale *et al.,* 1980). Vegetation influences recharge through transpiration and interception. The deep rooted trees remove more water than shallow rooted grasses. The groundwater recharge is usually less in the region having vegetation with longer growing season or deeper roots (Nulsen *et al.,* 1987). Arid and semi-arid regions are categorized by the extreme climate, the deep water table, loosing streams; seasonal recharge and moisture storage in vadose zone are distinctive features of the aquifers in arid and semi-arid regions. Uncontrolled groundwater extractions cause the decline in water table and deteriorating groundwater quality. Groundwater recharge assessment is usually be difficult, particularly in arid and semi-arid regions where water tables are typically deep and recharge is predominately generated from topological depressions such as lakes and streams (Scanlon *et al.,* 2002). Under Indian circumstances, the recharge in arid and semi-arid regions varies from 4-20 per cent (Rangarajan *et al.,* 2000). Assessment of groundwater recharge is important for estimating water resource availability and assessing aquifer vulnerability to pollutants (Scanlon *et al.,* 2002). The common methods for assessment of groundwater recharge are water table fluctuation method, water budget method, rainfall infiltration method, tracer technique and hydrological modeling (Hendricks *et al.,* 1997; Sharma, 1989; Simmers, 2017). Among all these, hydrological models are advanced tool to estimate groundwater recharge and related hydrological processes at field, watershed and regional scales. The numerous hydrological modeling tools for groundwater recharge have been developed in the last decades, these includes, DAISY (Hansen *et al.,* 1990), TOUGH2 (Pruess, 1991), SHAW (Flerchinger *et al.,* 1996), SWAP (Van Dam *et al.,* 1997), HYDRUS-1D (Simunek *et al.,* 1998), UNSATH (Fayer, 2000), and COUP (Jansson *et al.,* 2001). The use of groundwater hydrological models is appealing due to their ability in simplification of important nonlinear interactions between recharge, discharge, evapotranspiration and changes in groundwater storage (Sanford, 2002). Among these, water movement through the unsaturated zone is one of the most important, as it controls recharge to the aquifer system on one side, and evapotranspiration rates and water stress of vegetation on the other side (Gandolfi *et al.,* 2006). In the present study HYDRUS-1D model and water table fluctuation method were used to assess the potential recharge and actual groundwater recharge in a small ravine watershed respectively.

Materials and Methods

General characteristics of study area

The present study area is located in the semi-arid region of Rajasthan. The latitude and longitude of the area are 25^{o} 36$^{'}$ N and 76^{o}15$^{'}$ E respectively. This watershed covers an area of 682.5 ha and drains into Mej River near confluence point of Mej and Chambal. Nearly 0% area of watershed area are table lands with multidirectional slopes (2-10%) and remaining 80% area are under gully network spread specially downstream site of the watershed area. The climate of watershed is dry semi-arid with 750 mm average rainfall, 90% of which received in during mid-June to mid-September. Summers are hot with 42.04^{0}C of mean maximum temperature in May. The minimum temperature is 6.91^{0}C recorded in January. The soils of the watershed are black soils of recent alluvial origin, which belong to hyperthermia family of Chromusterts and Pellusterts under the order Vertisols. The textures of these soils are generally clay loam or silty clay loam. The watershed is severely infested with ravines and having very high drainage density.

Groundwater recharge estimation methods

In this study, two most commonly methods namely, HYDRUS-1D and water table fluctuation (WTF) are used to estimate the potential and actual groundwater recharge, respectively.

HYDRUS-1D model

The potential groundwater recharge from watershed and daily bottom fluxes as well as cumulative bottom fluxes were assessed using the HYDRUS-1D version 4.17 model (Simunek *et al.,* 2013) The HYDRUS-1D model is a software package for simulating water flow, heat and solute movement in one-dimensional variably saturated media. It is a finite element model which numerically solves the Richard's equation for variably saturated water flow and advection-dispersion type equations for heat and solute transport.

To account for water uptake by plant roots, the flow equation incorporates a sink term. The Richards equation for water flow in a homogeneous or uniform soil is defined as:

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

Eq. (1) is a second order, parabolic, nonlinear, partial differential equation known as Richard's model. Subjected to the initial and boundary conditions:

Initial condition:

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

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

Boundary conditions:

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

Or

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

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

Where h = hydraulic head [L]; K (h) = hydraulic conductivity of soil [LT^{-1}], z = soil depth [L]; S (h, t) = sink (root water uptake rate) in space and time, and h_0 and h_t are the initial and boundary condition potentials, respectively. The sink term (root water uptake rate) was modelled using the following equation given by Feddes *et al.,* (1978):

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

Where $\lambda(z)$ is the relative root distribution function, T_p is the potential transpiration rate, and $\alpha(h)$ is a dimensionless water stress response function ($0 \leq \alpha \leq 1$) to account for reductions in uptake due to drought stress.

For the simulation of water movement, the depth of soil profile was considered as 300 cm and three soil layers at 15, 30 and 45 cm from the ground surface were taken for mass balance. The recharge rate was simulated on daily basis for each year independently during the period 2002–2008. The total simulation period was the period between occurrence of first and last rainfall event in that particular year. The initial and final time steps were taken as 0.001 and 0.00001 respectively and the maximum time step was 0.01. Initial and boundary conditions were specified on a 300 cm deep vertical soil profile. The whole soil profile was discretized into 3 layers of 100 cm each. Initial conditions were selected as pressure head in the soil profile on the day of start of simulation. The pressure head in the study area was taken as -1000 cm at the surface and -100 cm at the bottom of the soil profile. In the present study, the upper boundary condition was taken as the atmospheric boundary condition with surface runoff and the lower boundary condition was taken as the free drainage.

The soil hydraulic properties were determined using Van Genuchten (1980) model which is incorporated in HYDRUS-1D. The different water flow parameters namely, saturated water content (θ_s), residual water content (θ_r), inverse of the air entry value (α), pore size distribution index (n) saturated hydraulic conductivity (K_s) and pore connectivity parameter for three different soil layers were estimated using bulk density and sand, silt, clay percentage as input data. The bulk density was determined by core cutter method and for particle size distribution International pipette method was used. The particle size distribution and bulk density of soil are presented in the Table 1 and the water flow parameters are given in the Table 2.

The daily rainfall and reference evapotranspiration were used as time variable input data. The reference evapotranspiration was estimated using Penman monteith model incorporated in HYDRUS-1D. The daily maximum and minimum temperature, average humidity, wind speed and sunshine hour data were used as input in Penman montieth model. The absolute value of the minimum allowed pressure head at the soil surface *i.e.,* hCritA was taken as 100000 centimetre. In the present study the small grain crops in vegetative period was taken for recharge rate estimation and root water uptake was modelled by using method proposed by Feddes *et al.,* (1978). The average root depth for small grain crops was taken as 60 cm. The values of Feddes parameters were taken from the data base suggested by Wesseling, (1991) and Taylor, (1972) on the basis of their studies. The values of Feddes parameter are presented in the Table 3.

Water Table Fluctuation (WTF) method

The actual groundwater recharge in the entire watershed, which actually reaches on water table, was assessed using water table fluctuation (WTF). The details of WTF method can be seen elsewhere (Scanlon *et al.,* 2002): The WTF is defined as:

$$\text{Actual groundwater recharge} = \text{Specific yield of aquifer} \times \text{Water level rise} \quad (5)$$

Where, the water level rise in all the observation wells located in the watershed was measured manually during period 2002-2008 and the specific yield was determined by using the formula suggested by Shukla *et al.*, (2006):

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

The recharge rate estimated using HYDRUS-1D model was used to estimate the specific yield of an aquifer.

Results and Discussion

Estimation of potential groundwater recharge

The potential groundwater recharge from the watershed was estimated using the HYDRUS-1D model. The model was used to simulate the cumulative bottom flux (potential groundwater recharge), bottom flux, cumulative root water uptake, cumulative evaporation, and soil water storage for small grain crops under three different soils in the watershed.

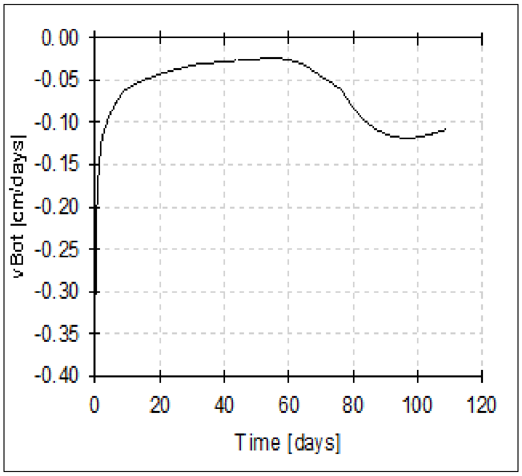
The results of HYDRUS-1D for the year 2008 under silt loam, silty clay loam and clay loam soils are presented in Figures 1, 2 and 3, respectively. The potential groundwater recharge (cumulative bottom flux) in the under silt loam, silty clay loam and clay loam soils were 6.86 cm, 3.76 cm and 1.16 cm, respectively. The cumulative root water uptake under silt loam, silty clay loam and clay loam soils were 39.22 cm, 38.50 cm and 36.03 cm, respectively (Figs 1, 2 and 3).

Figures 4 and 5 showed the comparison of potential groundwater recharge (cumulative bottom flux) and cumulative root water uptake for all three soil types during the period 2002-2008. It can be seen that the maximum and minimum cumulative bottom fluxes were 10 and 0.8 cm respectively, which were found under silt loam and clay loam soils, respectively.

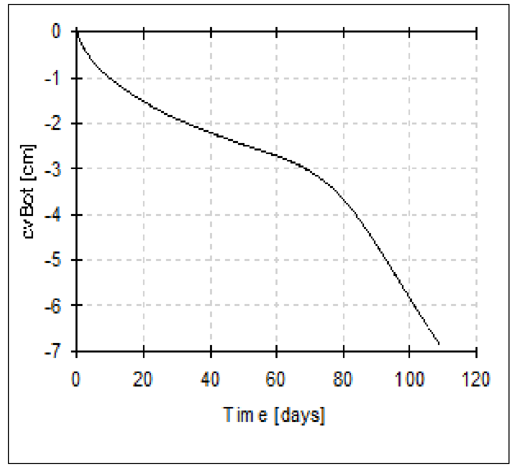
The average annual potential groundwater recharge under silt loam, silty clay loam and clay loam soil were 5.01, 3.46 and 1.26 cm. Result of analysis indicated that on an average annual potential groundwater recharge (cumulative bottom flux) from the watershed was to be estimated 3.24 cm. The cumulative root water uptake under different soil types during entire simulation period varied from 16.85 to 39.22 cm with an average of 26.93 cm. The lowest and highest root water uptake was found in clay loam and silt loam soils, respectively. The cumulative bottom flux as well as cumulative root water uptake was higher in silt loam soils and lower in clay loam soils. In case of silty clay loam soil, the cumulative bottom flux for soybean crop was less than silt loam soil, however more than clay loam soil. These results could be due to the variation in the soil texture.

The Table 4 shows the cumulative root water uptake and cumulative bottom flux as the percentage of cumulative monsoon season rainfall of the region. From Table 4, it can be seen that the cumulative recharge flux varied from 4.6 to 10.8% of annual rainfall. The average annual cumulative bottom flux under silt loam, silty clay loam and clay loam soil were found to be 10.83, 7.08, and 2.81% of monsoon season rainfall, respectively. The average annual cumulative bottom flux from the watershed was 6.91% of monsoon season rainfall. The results of the HYDRUS-1D model were comparable with the results reported by Scanlon *et al.*, (2010), Patle *et al.*, (2006) and Rangarajan *et al.*, (2000), those who had estimated recharge rates in the semi-arid regions. Scanlon *et al.*, (2010) reported that the recharge rates from sparsely vegetated dune region and the rain fed region of Rajasthan were 2-3 and 10-16%, respectively.

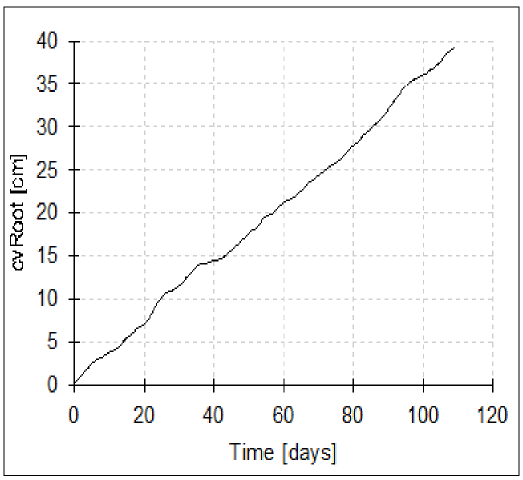
Fig.1 Simulated results of HYDRUS-1D model under silt loam soil for the Year 2008



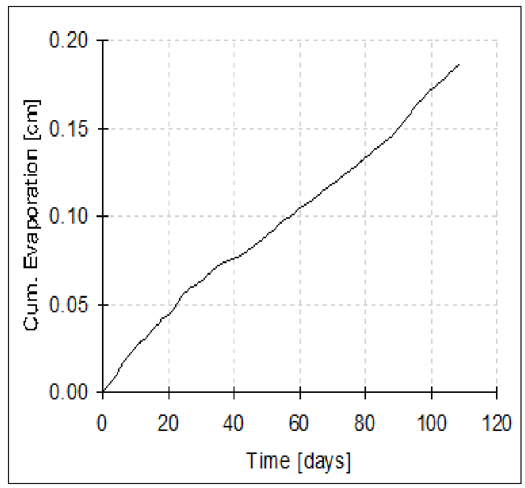
a) Bottom flux



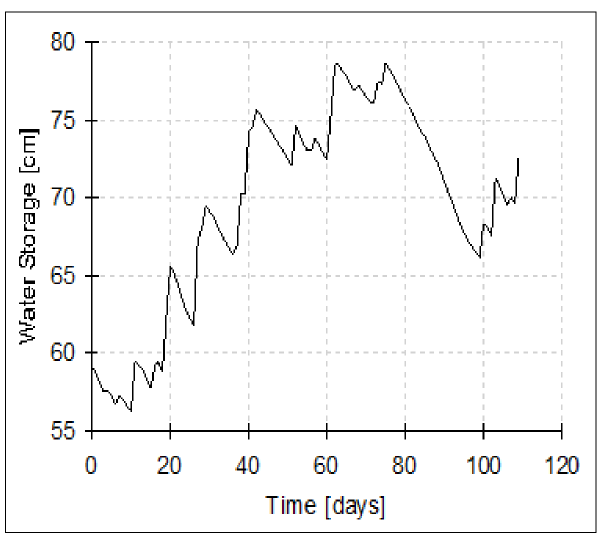
b) Cumulative bottom flux



c) Cumulative root water uptake

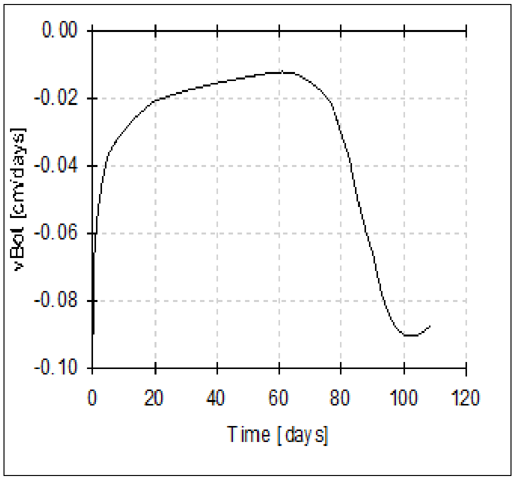


d) Cumulative evaporation

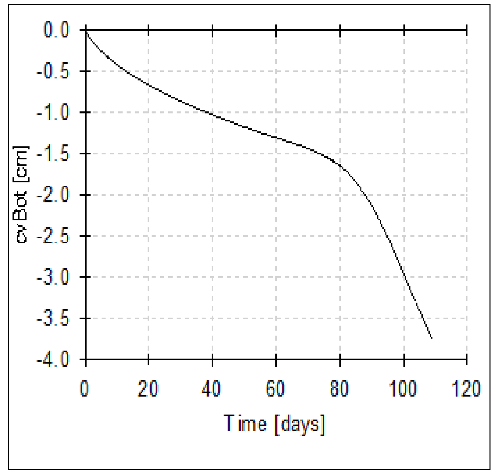


e) Soil water storage

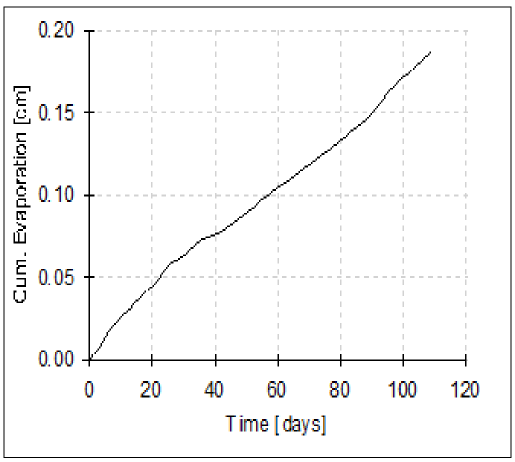
Fig.2 The simulated results of HYDRUS-1D model under silty clay Loam soil for the Year 2008



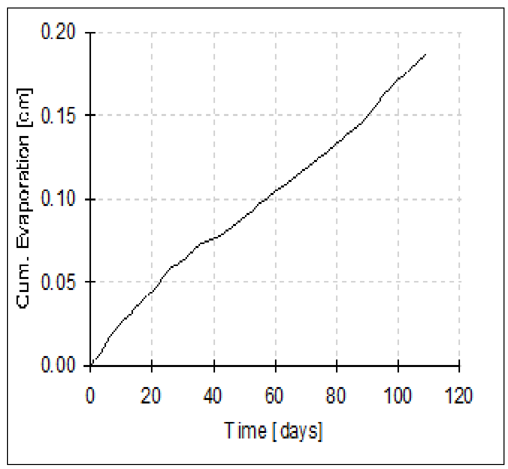
a) Bottom flux



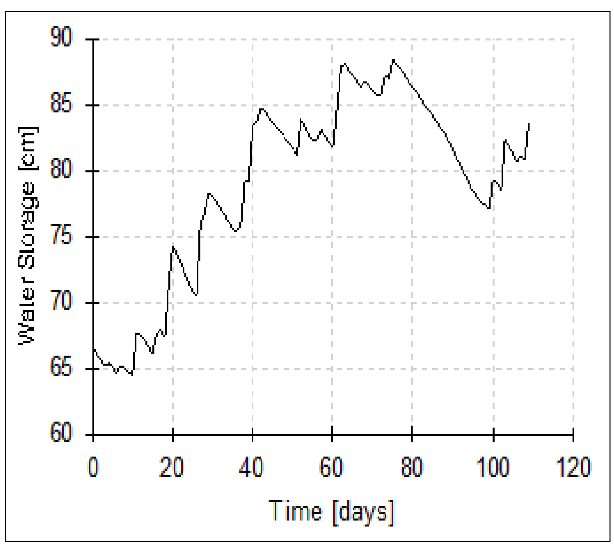
b) Cumulative bottom flux



c) Cumulative root water uptake

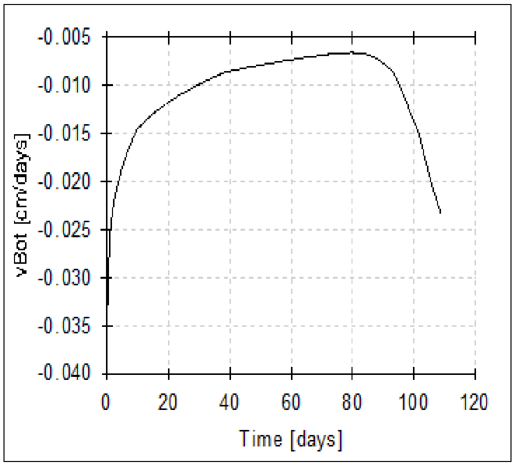


d) Cumulative evaporation

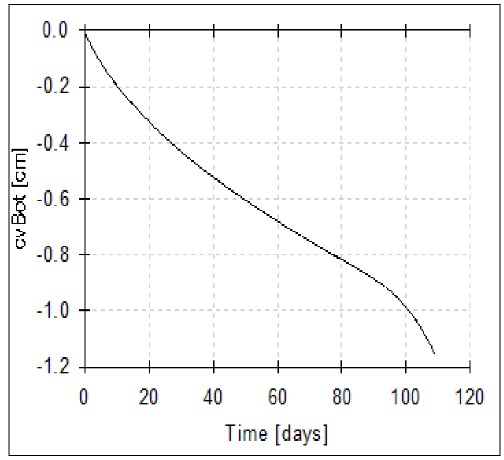


e) Soil water storage

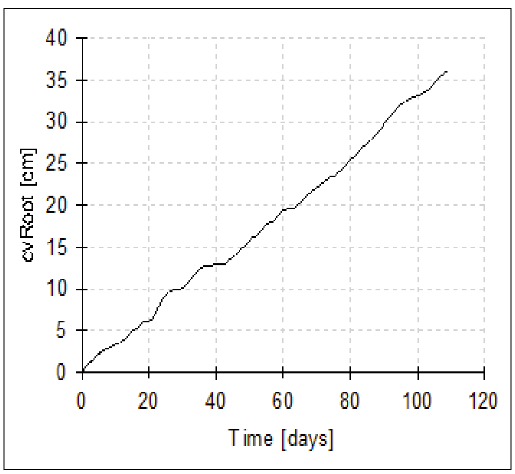
Fig.3 The simulated results of HYDRUS-1D model under clay Loam soil for the Year 2008



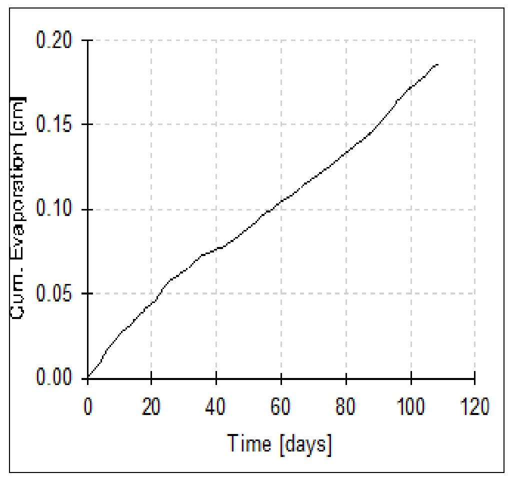
a) Bottom flux



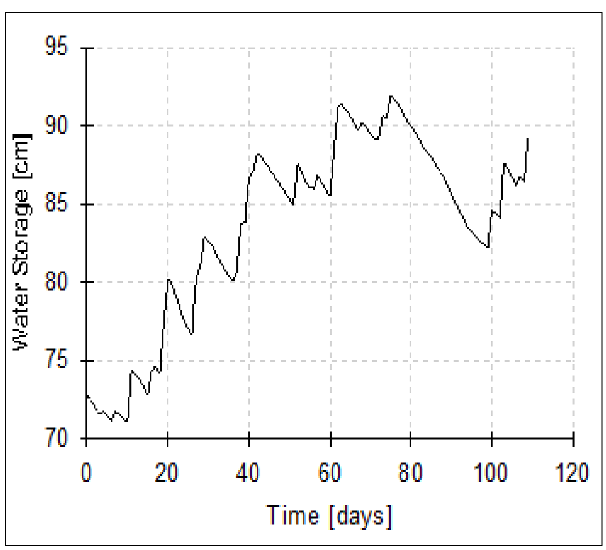
b) Cumulative bottom flux



c) Cumulative root water uptake



d) Cumulative evaporation



e) Soil water storage

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

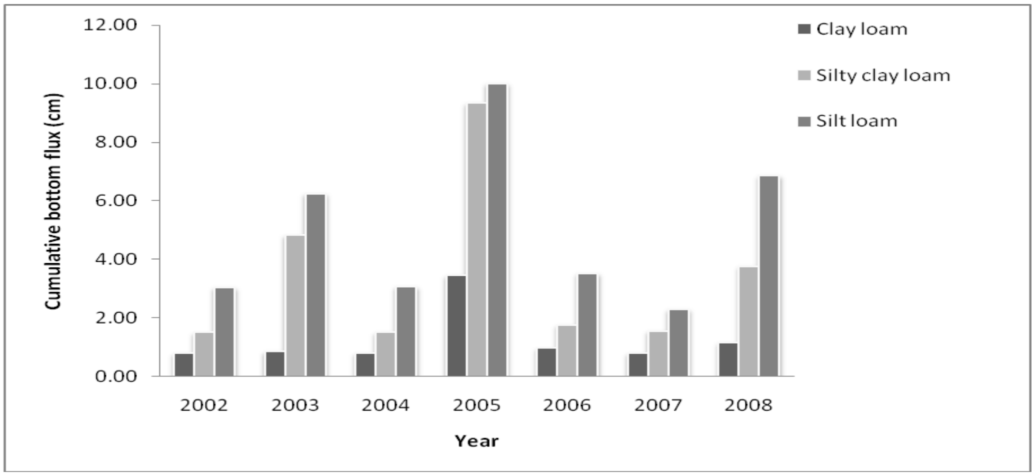


Fig.5 Comparison of cumulative root water uptake under different soils during the period 2002-08

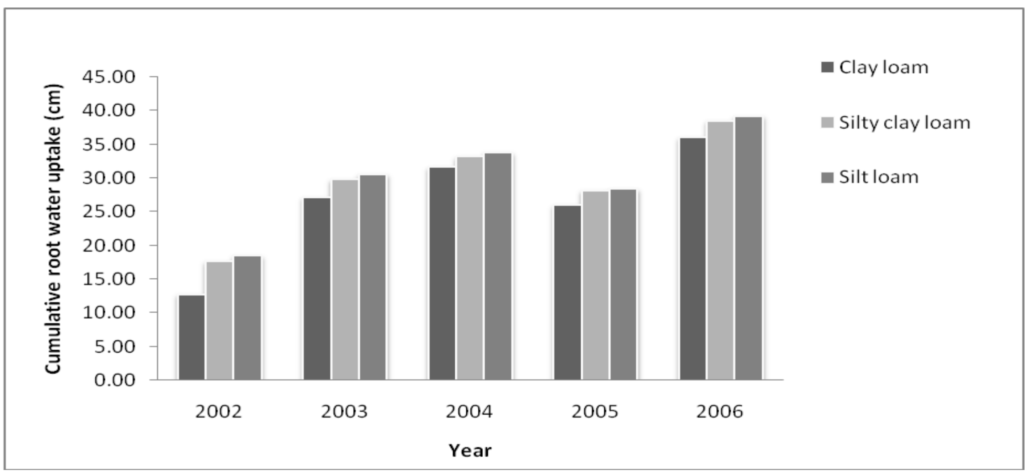


Fig.6 Variations in monsoon season rainfall and actual groundwater recharge in BK watershed during the period 2002-08

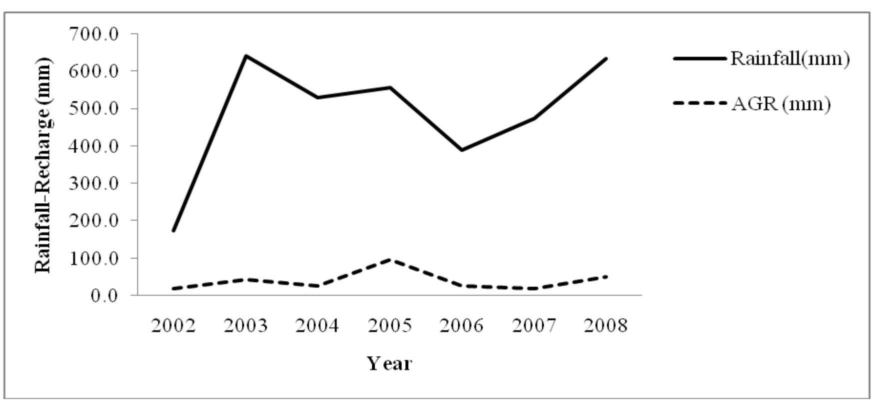


Fig.7 Comparison of potential and actual groundwater recharge from BK watershed during the period 2002-08

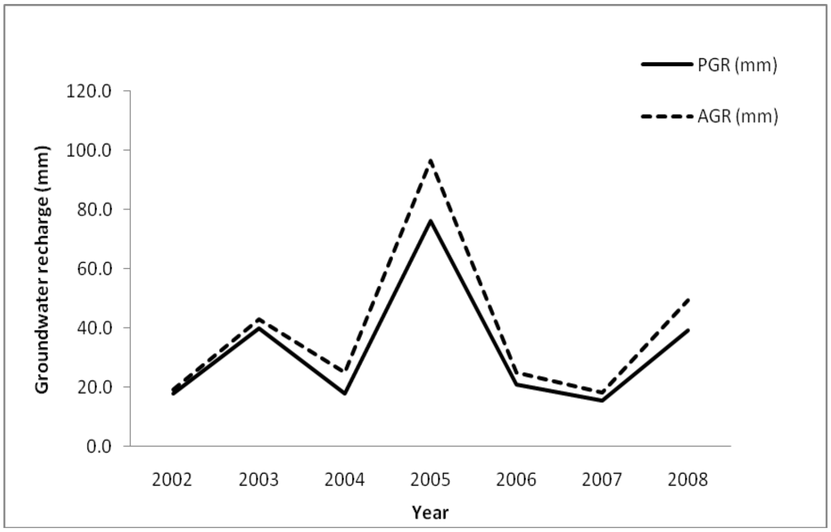


Table.1 Particle size distribution and bulk density of soil

Profile depth (cm)	Textural class	Average Sand, silt and clay per cent			Average bulk density (gram/cm^3)
		Per cent sand	per cent silt	per cent 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

Textural class	θr (cm^3/ cm^3)	θs (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 Feddes 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

Actual Groundwater Recharge (AGR) was estimated by using water table fluctuation (WTF) method during the period 2002-08. Table 5 shows the average values of annual rainfall, depth of water table, change in water table, specific yield, AGR (mm) and AGR as the percentage of rainfall. Analysis of results showed that the mean depth to water table varied from 14.5 to 17.67 m and the average change in water table ranged from 1.23 to 2.04 m.

The specific yield of aquifer varied from 0.013 to 0.066 with an average of 0.03. The minimum and maximum actual groundwater recharge from the watershed was estimated to be 18.23 and 96.35 mm, respectively with a mean of 39.42 mm (8.3% of the monsoon season rainfall).

The annual variation of rainfall and actual groundwater recharge during 2002-2008 is presented in Figure 6. From this figure, it can be observed that the variation in actual recharge follows the variation in rainfall, but with lesser amounts. The peaks of the recharge curve are less marked because; the years having heavy rainfall causes increase surface runoff.

Figure 7 shows the comparison of actual and potential groundwater recharge from watershed. It showed that the potential recharge curve follows the actual recharge curve with the actual recharge values slightly higher than potential recharge. The higher values of actual recharge may be due to ground water recharge from the soil and water conservation techniques as bonding, check dams and ponds in the watershed and irrigation return flow. The effect of these conservation measures were not considered in the HYDRUS-1D model.

For the efficient groundwater water management in semi-arid region of India accurate knowledge of groundwater recharge is indispensable. In this study, Potential recharge and other process of unsaturated zone as root water uptake were simulated using HYDRUS-1D model. The actual ground water recharge was assessed by using water table fluctuation (WTF) method. The cumulative potential recharge in the watershed estimated by HYDRUS-1D model varied from 0.8-10 cm (4.6-10.8% of monsoon season rainfall) with an average of 3.24 cm (6.91%). The highest and lowest potential recharge was found to be for silt loam and clay loam soils, respectively. The actual recharge estimated by WTF method varied between 3.8 and 17.3 % of monsoon season rainfall with an average of 8.3% which was comparable with the HYDRUS-1D model.

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How to cite this article:

Sangita Aba Khatal, Shakir Ali, Murtaza Hasan, Dhirendra Kumar Singh, Anil Kumar Mishra and Mir Asif Iquebal. 2018. Assessment of Groundwater Recharge in a Small Ravine Watershed in Semi-arid Region of India. *Int.J.Curr.Microbiol.App.Sci.* 7(02): 2552-2565.
doi: https://doi.org/10.20546/ijcmas.2018.702.311