

Simple water balance model and crop water demand at different spatial and temporal scales in Periya Pallam catchment of upper Bhavani basin, Tamilnadu

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ABSTRACT

Reduction in agricultural water use and increasing the sustainability of water resources can be achieved by studying the water balance of the area and crop water demand. In this paper, by using a simple water balance model, Evapotranspiration, Rainfall, Runoff, Water Demand and Water Requirement different crops are estimated. The crop water requirement and crop water demand for different crops grown in the Periya Pallam Catchment of Upper Bhavani Basin, Tamilnadu, was estimated. Water balance estimation of the area reveals that out of the annual rainfall, runoff is estimated to be 129 mm, effective rainfall is 252 mm, and deep percolation is about 67 mm. The demand for water for agriculture in the study area is about 61 million cubic meters (MCM), but only 19 MCM of water is available through precipitation in the form of effective rainfall. Hence, the remaining 43 MCM of water is supplied through groundwater and other sources. The results will pave the way for sustainable crop water use planning and would achieve water security in the basin.

Introduction

Water scarcity is a principal constraint in crop production (Bhutiani and Ahamad, 2019). Agricultural activity governs the use of freshwater and 70% of withdrawals from water resources globally (FAO, 2002). Scarcity of water leads to drought which have a severe effect on people and also on agricultural activity (Pereira *et al.*, 2007). The need of the hour is sustainable use of agricultural water which can be done by studying the water balance of the area and crop water demand. Studying water balance is a necessary prerequisite to improve crop-water usage and reduce losses due to evaporation and surface runoff. Hydrology scientists are interested in simulating hydrological behavior over a large domain. Thornthwaite (1948) and Thornthwaite and Mather

(1957) first developed water balance models in the 1940s and 1950s. The water balance analysis tells how much amount of precipitation, evapotranspiration, groundwater recharge, and soil storage percentage is for the understanding of the hydrological cycle (Lijuan *et al.*, 2008). Chabi *et al.* (2019) expressed that understanding water balance will help in minimizing the short, medium, and long term water shortages which is due to climate change. It will help in managing or mitigating face the water requirements of local use. Crop water requirement refers to the quantity of water required to recompense for the evapotranspiration from field crop (Allen *et al.*, 1998). A precise estimate of crop evapotranspiration aids in the effective management of water resources (Cai *et al.*, 2007;

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Lovelli *et al.*, 2008). Crop water demand is the product of crop water requirement and planting area. Several studies in evaluating crop water demand have been conducted globally, including in India (Pandey *et al.*, 2008; Rao and Poonia 2011). The information on irrigation strategies for local crop production was extracted as a result of these studies.

This study is taken up in the Periya Pallam Catchment of Upper Bhavani Basin with the following objectives. (i) To study the various components of the water balance estimation for delineated Upper Bhavani Basin (ii) To the crop-water requirement of major crops in the basin and estimate the time series water demand for the basin. The present study focuses on the water demand for agriculture in the future, changes in the cropping pattern, and measures to reduce the supply-demand gap to achieve sustainability. The results derived from the study will pave the way for sustainable crop water use planning and would achieve water security in the basin.

Material and Methods

Study Area

The Bhavani basin is the sub-basin in the Cauvery basin spread over in Karnataka, Kerala, and Tamil Nadu, with the majority of the catchment laying in Tamil Nadu. The main river courses through Coimbatore, Nilgiris, and Erode districts of Tamil Nadu. About 90% of the river's water is used for irrigation. The study area is limited to the upper Bhavani basin, which includes Periya Pallam Catchment of Coimbatore district. Figure 1 shows the exact location of the study area in the Bhavani basin. There are three sub-catchment in the Periya Pallam Catchment area, and the boundaries of the sub-catchment are shown in figure 2. The major crops grown in the priority area include Sugarcane, Banana, vegetables, etc.

Simple Water Balance Model

The most commonly used crop-water balance model is given by equation 1 as follow as:

$$ET = P + I - S - D - R \text{ -----(1)}$$

where ET is evapotranspiration, P is precipitation, I is irrigation, S is change in soil water storage, D is deep drainage, and R is runoff.

Estimation of Water Balance Components

Water balance is an important technique to bring out the relationship between precipitation and

potential evapotranspiration and plays a significant role in water resources and agriculture development in a basin.

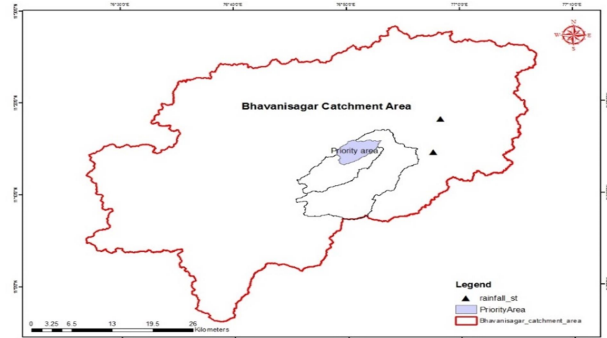


Figure 1: Location of Rain gauge stations in the study area

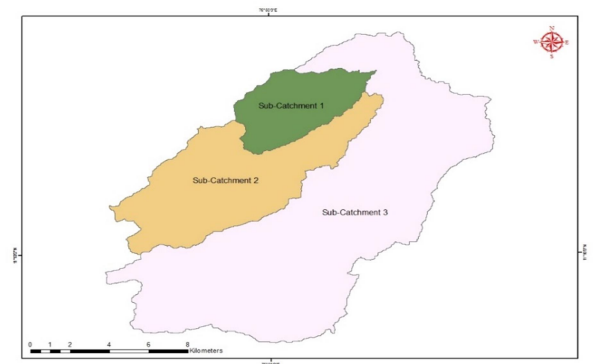


Figure 2: Sub-Catchment in the Periya Pallam Catchment

Rainfall

Precipitation is input to the hydrologic cycle, which is estimated in all water budget calculations. The available rainfall recording stations nearby the priority area is Mettupalayam and Tholampalayam (figure 1). Since the Tholampalayam station is more close to the priority area, Tholampalayam station data is used for the study. The temporal changes in rainfall were studied over a period of 11 years (2007-2017).

Runoff

Surface runoff is calculated by the curve number method (CN), developed by the Soil Conservation Service (SCS) in 1954. The curve number for each land use/land cover class is given. The hydrologic soil group of each land use depends upon the soil texture. Based on the soil texture in the study area, the hydrologic soil group is assigned. The weighted curve number for the entire area is calculated based on equation 2 as follow as:

$$\text{WeightedCN} = \frac{\sum \text{CN} * A}{A_{\text{total}}} \quad \text{-----2}$$

Where CN is the curve number of each land use, and A is the area of each land use, and A_{total} is a total area. Based on the weighted CN and rainfall, the potential maximum retention (S) is calculated using equation 3:

$$\text{CN} = \frac{25400}{254 + S} \quad \text{-----3}$$

Then the depth of runoff (Q) is calculated using the SCS-CN method (equation 4):

$$Q = \frac{(P - 0.3S)^2}{P + 0.7S} \quad \text{-----4}$$

Effective Rainfall

The quantity of rainfall effectively be used by plants is effective rainfall in agricultural production. Runoff (Q) and Deep Percolation (DP) are the ways of water loss that make the entire rainwater unavailable for plants. Infiltration of rainwater is based on soil type, slope, crop canopy, storm intensity, and the initial soil moisture. Effective rainfall is calculated using equation 5 and 6.

$$P_{\text{eff}} = (0.6 * P_{\text{month}}) - 10 \text{ for } P_{\text{month}} \leq 70 \text{ mm} \quad \text{-----5}$$

$$P_{\text{eff}} = (0.7 * P_{\text{month}}) - 24 \text{ for } P_{\text{month}} > 70 \text{ mm} \quad \text{-----6}$$

Infiltration and Deep Percolation

The vertical entry of water into the soil is called infiltration, and the amount of water percolating and recharging the groundwater is called deep percolation. The difference between rainfall and effective rainfall is the sum of runoff, infiltration, and deep percolation. Excluding the runoff and infiltration, a deep percolation component is obtained. It is assumed that 30% of water entering into the soil deep percolates. Thus, the infiltration and deep percolation are calculated.

Evapotranspiration

The reference crop (ET_o) represents the water use of a standard crop in that environment. In this study, the Hargreaves equation is used for the estimation of ET_o. When solar radiation data, relative humidity data, and/or wind speed data are missing, instead of estimating those data, ET_o can be estimated using the Hargreaves ET_o equation 7.

$$ET_0 = 0.0023 (T_{\text{mean}} + 17.8) (T_{\text{max}} - T_{\text{min}})^{0.5} R_a \quad \text{-----7}$$

Where T_{max} and T_{min} are maximum and minimum temperature; T_{mean} is the mean temperature; R_a is the extraterrestrial radiation. The maximum and minimum temperature is used, and the average temperature over 2006 to 2016 is used to find the evapotranspiration.

Crop Evapotranspiration

The crop evapotranspiration is estimates as the product of reference evapotranspiration and crop coefficient. It is given by equation 8:

$$ET_c = ET_0 * K_c \quad \text{-----8}$$

Where: ET_c = actual crop evapotranspiration rate; K_c = crop coefficient; ET_o = evapotranspiration calculated using the Hargreaves' Method. The crop coefficients for major crops grown in the study area at different stages are taken from Allen *et al.* (1998), and the crop evapotranspiration is estimated.

Time series water demand for the study area

Water Demand (Agriculture) includes water requirements for the crop along with field preparation and other activities. The crop evapotranspiration is multiplied by the area grown given the total volume of water required or evaporative demand. The crop-grown areas for Banana, Paddy, Millets, Green gram, Groundnut, Gingelly (Sesame), Sunflower, and Sugarcane are taken from the Handbook of Karamadai block. The effective rainfall throughout the growing period for different crops is multiplied with crop grown area to estimate the total volume of the water available for the crop. The difference between the evaporative demand and effective rainfall gives the demand for the priority area.

Results and Discussion

Water Balance Components

The analysis of rainfall data showed that average annual rainfall recorded at Tholampalayam station was 604 mm. The temporal changes in rainfall over a period of 11 years (2007-2017) revealed that out of the eleven years of observation, five years recorded more than the normal rainfall and the remaining six years recorded less than the normal rainfall (figure 3). It was also found that maximum rainfall was recorded in the year 2011 and the lowest rainfall was recorded in the year 2016. The priority area receives about 7% of its rainfall in

Winter (January and February); 27% rainfall in Summer (March to May); 16% of its rainfall in Southwest Monsoon (June to September), and the majority of the contribution is from Northeast monsoon (October to December) accounting for 50% (figure 4). The considerable rainfall from northeast monsoon during October to December, has great significance in agriculture and allied sectors in these regions. Proper understanding of the seasonal prediction of northeast monsoon rainfall have considerable application value for decision making in agriculture and water resource sectors of these regions (Samui *et al.*, 2013). Lijuan *et al.* (2008) indicated that the water balance analysis is useful for understanding the hydrological processes in the Xitiaoxi catchment.

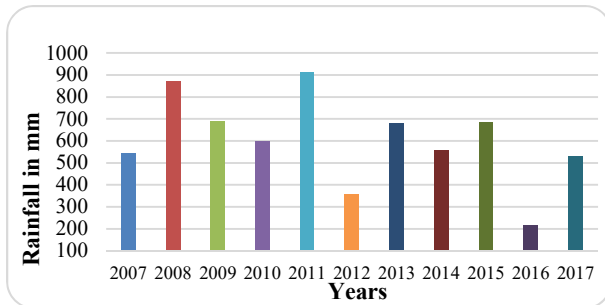


Figure 3: Annual rainfall variation in the priority area

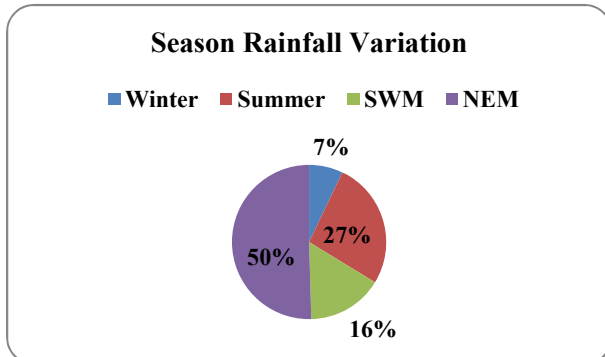


Figure 4: Seasonal rainfall variation in the priority area

Runoff

Surface runoff is computed using the runoff CN method, in which the weighted curve number for the Upper Bhavani Basin (UBB) is about 68. The potential maximum retention is about 119 mm. The low value of weighted CN indicates the availability of good forest cover. The quantity of runoff

generated from the UBB on a monthly basis is presented in Table 1. Similarly, the curve number for three sub-catchments and the entire Periya Pallam catchment is calculated as 71, 75, 72, and 72, respectively. The greater curve numbers represent a greater proportion of surface runoff (Stuebe and Johnston, 1990; Schulze *et al.*, 1992). Since the CN number of Periya Pallam catchment and Sub-Catchment 3 are the same, the runoff in depth units is the same (Table 2). It differs by the volume of runoff generated. Around 27 Mm³ of water is generated as runoff from the Periya Pallam catchment and 17 Mm³ of runoff from Sub-Catchment 3. The quantity of runoff generated from the three sub-catchments and the entire Periya Pallam catchment on a monthly basis is presented in Table 2 - 5. Providing an accurate runoff generation within a basin is an important factor in developing a strategic runoff harvesting plan to overcome water scarce problem (Saravanan *et al.*, 2015).

The quantity of effective rainfall that can effectively be used by plants is calculated by USDA Method, and it is presented in Table 1-5. It was found that from average annual rainfall of 604 mm, 250 mm of rainfall is available for the plants in the form of effective rainfall. The residual quantity of effective rainfall and runoff from rainfall infiltrates into the soil. From the entire UBB, 172 and 73 mm of total rainfall infiltrates into the soil (Table 1). Around one-third of the total rainfall infiltrates in UBB. In the Periya Pallam catchment, the total rainwater that infiltrates into the soil is around 158 mm. The deep percolation component estimated from this study is around 67 mm. The good clay content in the soils of the priority area is the causing factor for this lesser deep percolation (10% of total rainfall). It also has a greater advantage that the water harvesting potential in the priority area and also effective replenishment of soil water in the effective plant root zone (Table 2). The average monthly evapotranspiration for the study area is shown in figure 5. The evapotranspiration is maximum during the month of March, April, and May, which is around 6 mm/day. The estimation of evapotranspiration is of great importance for agricultural, hydrological and climatic studies, as it constitutes a major part of the hydrological cycle (Sobrinho *et al.*, 2005).

Table 1: Monthly water balance estimation for the Upper Bhavani Basin

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rainfall (mm)	3.2	39.7	45.0	48.8	66.9	18.2	14.2	28.4	35.0	159.1	106.7	38.8	603.9
Runoff (mm)	0.0	0.1	0.6	1.3	6.4	3.1	4.8	0.5	0.0	62.5	26.4	0.1	105.8
Eff Rainfall (mm)	0.0	13.8	17.0	19.3	30.2	0.9	0.0	7.0	11.0	85.4	54.0	13.3	251.9
ET ₀ (mm)	4.6	5.4	6.1	6.4	6.2	5.3	4.8	5.1	5.2	4.8	4.2	4.1	62.2
Infiltration (mm)	2.2	18.0	19.1	19.8	21.3	9.9	6.6	14.6	16.8	7.8	18.4	17.8	172.3
DP (mm)	1.0	7.7	8.2	8.5	9.1	4.3	2.8	6.3	7.2	3.3	7.9	7.6	73.9

Table 2: Monthly water balance estimation for the Periya Pallam catchment

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rainfall (mm)	3.2	39.7	45.0	48.8	66.9	18.2	14.2	28.4	35.0	159.1	106.7	38.8	603.9
Runoff (mm)	0.0	0.9	2.1	3.1	10.2	1.5	2.9	0.0	0.3	73.4	33.8	0.8	129.0
Eff Rainfall (mm)	0.0	13.8	17.0	19.3	30.2	0.9	0.0	7.0	11.0	85.4	54.0	13.3	251.9
ET ₀ (mm)	4.6	5.4	6.1	6.4	6.2	5.3	4.8	5.1	5.2	4.8	4.2	4.1	62.2
Infiltration (mm)	2.2	17.5	18.1	18.5	18.6	11.0	7.9	14.9	16.6	0.1	13.2	17.3	156.1
DP (mm)	1.0	7.5	7.8	7.9	8.0	4.7	3.4	6.4	7.1	0.1	5.7	7.4	66.9

Note: Rainfall above 5 mm is expected to generate runoff as per the SCS-CN method

Table 3: Monthly water balance estimation for the Sub-Catchment 1.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rainfall (mm)	3.2	39.7	45.0	48.8	66.9	18.2	14.2	28.4	35.0	159.1	106.7	38.8	603.9
Runoff (mm)	0.0	0.7	1.6	2.6	9.2	1.8	3.3	0.1	0.1	70.7	31.9	0.5	122.5
Eff Rainfall (mm)	0.0	13.8	17.0	19.3	30.2	0.9	0.0	7.0	11.0	85.4	54.0	13.3	251.9
ET ₀ (mm)	4.6	5.4	6.1	6.4	6.2	5.3	4.8	5.1	5.2	4.8	4.2	4.1	62.2
Infiltration (mm)	2.2	17.7	18.4	18.9	19.3	10.8	7.6	14.9	16.7	2.1	14.6	17.5	160.7
DP (mm)	1.0	7.6	7.9	8.1	8.3	4.6	3.3	6.4	7.2	0.9	6.2	7.5	68.9

Table 4: Monthly water balance estimation for the Sub-Catchment 2

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rainfall (mm)	3.2	39.7	45.0	48.8	66.9	18.2	14.2	28.4	35.0	159.1	106.7	38.8	603.9
Runoff (mm)	0.0	2.1	3.7	5.1	13.7	0.7	1.7	0.1	1.0	81.8	39.8	1.8	151.4
Eff Rainfall (mm)	0.0	13.8	17.0	19.3	30.2	0.9	0.0	7.0	11.0	85.4	54.0	13.3	251.9
ET ₀ (mm)	4.6	5.4	6.1	6.4	6.2	5.3	4.8	5.1	5.2	4.8	4.2	4.1	62.2
Infiltration (mm)	2.2	16.7	17.0	17.1	16.2	11.6	8.7	14.9	16.1	0.0	9.0	16.6	146.1
DP (mm)	1.0	7.1	7.3	7.3	6.9	5.0	3.7	6.4	6.9	0.0	3.9	7.1	62.6

Table 5: Monthly water balance estimation for the Sub-Catchment 3

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rainfall (mm)	3.2	39.7	45.0	48.8	66.9	18.2	14.2	28.4	35.0	159.1	106.7	38.8	603.9
Runoff (mm)	0.0	0.9	2.1	3.1	10.2	1.5	2.9	0.0	0.3	73.4	33.8	0.8	129.0
Eff Rainfall (mm)	0.0	13.8	17.0	19.3	30.2	0.9	0.0	7.0	11.0	85.4	54.0	13.3	251.9
ET ₀ (mm)	4.6	5.4	6.1	6.4	6.2	5.3	4.8	5.1	5.2	4.8	4.2	4.1	62.2
Infiltration (mm)	2.2	17.5	18.1	18.5	18.6	11.0	7.9	14.9	16.6	0.1	13.2	17.3	156.1
DP (mm)	1.0	7.5	7.8	7.9	8.0	4.7	3.4	6.4	7.1	0.1	5.7	7.4	66.9

Table 6: Crop water requirement of different crops grown in the study area

SN	Crop	Plant date	Ini	Dev	Mid	Late	Total Days	Kc			ET _c Calculated (mm)
								Ini	Mid	Late	
1	Green gram	March	20	30	30	20	100	0.40	1.05	0.47	258
2	Sunflower	May	25	35	45	25	130	0.35	1.07	0.35	405
3	Millets	April	20	30	55	35	140	0.30	1.00	0.30	443
4	Groundnut	May	35	35	35	35	140	0.40	1.15	0.60	462
5	Paddy	Dec	30	30	30	30	120	1.05	1.20	0.75	545
6	Gingelly (Sesame)	June	20	30	40	20	110	0.35	1.10	0.25	566
7	Paddy	Dec	30	45	45	30	150	1.05	1.20	0.75	754
8	Banana	March	120	90	120	60	390	0.50	1.10	1.00	1779
9	Sugarcane	Jan	35	60	190	120	405	0.40	1.25	0.75	1901

Table 7: Demand of water requirement for different crops in Karamadai block

Crop	ET _c	Total Area		Volume of Water Required (Mm ³)		Effective Rainfall	Volume of Water Available (Mm ³)		Supply-Demand Gap (Mm ³)	
		mm	2006	2016	2006		2016	mm	2006	2016
Paddy	545	60.32	0.38	0.33	0.00	44.00	0.03	0.00	0.30	0.00
Millets	443	99.81	429.32	0.44	1.90	54.00	0.05	0.23	0.39	1.67
Green gram	258	103.83	139.79	0.27	0.36	67.00	0.07	0.09	0.20	0.27
Groundnut	462	250.21	118.15	1.16	0.55	49.00	0.12	0.06	1.03	0.49
Gingelly (Sesame)	566	20.94	51.15	0.12	0.29	19.00	0.00	0.01	0.11	0.28
Sunflower	405	19.17	1.00	0.08	0.00	49.00	0.01	0.00	0.07	0.00
Sugarcane	1901	287.17	85.66	5.46	1.63	264.00	0.76	0.23	4.70	1.40

The components of the water balance were estimated. It was found that total annual rainfall is around 604 mm; effective rainfall is around 252 mm, and evapotranspiration is around 72 mm. In Periya Pallam, the total available water for the cropping in the form of precipitation is around 52 Mm³. If the entire runoff is effectively harvested, around 27 Mm³ of water can be harvested and used for agriculture and allied activities. Further, about 14 Mm³ of water is recharging the groundwater. With the understanding of available water in a basin, irrigation scheduling, crop rotation, and cropping pattern can be planned.

Crop evapotranspiration

The total water required throughout the growing period is crop evapotranspiration. The crop evapotranspiration for different crops like Banana, Paddy, Millets, Green gram, Gingelly, Sunflower, Sugarcane, and Groundnuts are calculated and presented in Table 6. The green gram was found to be the low water requirement crop, and banana and

sugarcane are high water requirement and annual crops. The water demand for various crops in the Karamadai blocks viz., Paddy, Millets, Green gram, Groundnut, Gingelly (Sesame), Sunflower and Sugarcane are given in Table 7. The results reveal that the total volume of water that is required for meeting the above-mentioned crop water requirement is about 61 Mm³. But only 19 Mm³ of water is supplied through precipitation in the form of effective rainfall. The remaining 43 Mm³ of water should be given through other water resources. There is a great increase in cropping area of Millets, Green gram, Gingelly at the same time, the demand of water requirement is also less compared to other crops. The crop water requirement can be used for the determination of crop pattern suitable for the locality. It can pave way for the improved productivity and hence better national wealth. The following strategies can be adopted to overcome the water-scarce situation and to improve the water use efficiency in the priority

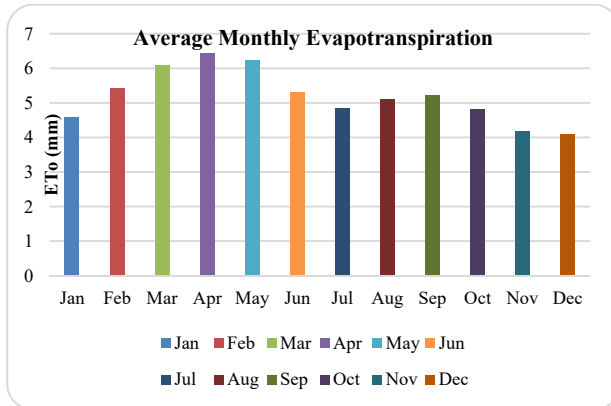


Figure 5: Average monthly evapotranspiration in the priority area

area: (i) opt for alternate cropping pattern instead of going for high water-consuming crops, (ii) Implementation of integrated watershed management programs including *in-situ* soil and moisture conservation programmes to augment the rainwater and to improve the groundwater situation, (iii) Afforestation programmes to increase the percentage of tree cover, (iv) Implementation of micro-irrigation technology for water-saving and yield increase, (v) Large scale adoption of farm ponds to harvest the runoff potential in the priority area.

Conclusion

Water scarcity is becoming a key issue in most of the river basins in India with the majority of the water use is taken up by the agriculture sector of about 80% followed by industrial and domestic sector, it is imperative that in future the contribution of water to agriculture would be reduced and it is shared among the domestic and industrial sectors. Hence, water management plays a key role in the agriculture sector to increase

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productivity and water use efficiency with reduced water availability. The normal rainfall of the priority area is around 604 mm, with the majority of occurrence is in the Northeast monsoon (50%), followed by summer (27%), southwest monsoon (16%), and winter (7%). Water balance estimation of the area reveals that out of the annual rainfall, runoff is estimated to be 129 mm, effective rainfall is 252 mm, and deep percolation is about 67 mm. Runoff is maximum during the months of October and November, wherein the potential of rainwater harvesting is more in the area. The minimum amount of deep percolation of 10% is limiting the groundwater recharge in the study area leading to declining groundwater tables over the years. Further, it was also understood that about 27 MCM of water could be harvested and supplemented for agriculture and allied activities, and about 14 MCM of water can be recharged underground. The demand for water for agriculture in the study area is about 61 MCM, but only 19 MCM of water is available through precipitation in the form of effective rainfall. Therefore, the remaining 43 MCM of water is supplied through groundwater and other sources. Hence, it is highly recommended to go for micro-irrigation to avoid over-exploitation of groundwater in the priority area. And the groundwater depleted zones has to be identified and measures has to be taken to improve the ground water situation through artificial recharge of depleted groundwater aquifers. The water balance model used in this study focus more on the surface component and hence for further water budget modelling consideration of two main components, namely surface water and groundwater resources will enhance the assessments and adequately portray crop water demand.

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