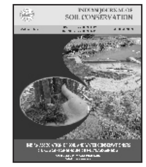
Vol. 47, No. 3, pp 222-230, 2019
Indian Journal of Soil Conservation
Online URL : http://indianjournals.com/ijor.aspx?target=ijor:ijsc&type=home



Comprehensive water balance based water budget for contingent planning in Ur river basin of Bundelkhand region

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ARTICLE INFO

Article history:
Received : December, 2018
Revised : November, 2019
Accepted : December, 2019

Key words:
GIS
Rainfall
River basin
Seasons
Water balance components

ABSTRACT

This study employed field measurements and established techniques to estimate various water budget components in Ur river basin. The spatial information pertaining to the topography, land use and soil type were extracted using the Arc 9.3 GIS software which helped to quantify many of the water balance components. The water budgeting of the Ur river basin was done on a seasonal time scale for two seasons namely *i.e.* monsoon season (June to October) and non-monsoon season (November-May). The result showed the accuracy of un-accounted water during the estimation of the water budget components, and seemed to be satisfactory as it was limited to 6.94% of the seasonal rainfall, considering the complexities in estimation of all the major water balance components. The water budgeting study indicates that about 69.85 MCM of water flows down the stream (storage in tanks included in this value) in monsoon season. This study will help to gain a better understanding of the hydrologic processes occurring in the river basin for contingent planning of available water resources to different sectors.

1. INTRODUCTION

Quantifying components of water balance for a watershed is vital towards understanding the dominant hydrologic processes occurring in a basin. Watersheds dominated by precipitation and evaporation exhibit a high degree of variability in rainfall distribution and vegetation types on hydrologic modeling. Thus, these basins present a distinctive set of problems for hydrologists which include: spatial and temporal variation of precipitation; a water balance dominated by evapotranspiration (ET); spatially varying plant types associated with changes in soil and effective precipitation; soil water added from ground water; and, intermittent stream-flow which lasts only a few months in the monsoon season. Accounting for variability in effective precipitation and estimating ET from plants, which are water-stressed for most of the year, make an accurate accounting of the water balance a difficult task. Increases in agricultural production will depend heavily on existing water resources (Oweis *et al.,* 2000; Wallace, 2000; Hatfield *et al.,* 2001; Kijne *et al.,* 2003). In agricultural system, the actual ET of crops is one of the most useful indicators for optimizing crop production (Jana *et al.,* 2016). Agricultural productivity in rainfed areas oscillates between 0.5 to 2 t ha^{-1} with average of 1 t ha^{-1} (Rockström *et al.,* 2010; Wani *et al.,* 2011[a]; Wani *et al.,* 2011[b]). Irrigated land, which covers 40% of total agricultural area, significantly contributes in satisfying 55% of total food requirement of the country (GoI, 2012), but on the other hand, it consumes almost 70% of fresh water resources and has left limited scope for expanding irrigated area further (CWC, 2005). Thus, achieving food security of the country in future is largely dependent on rainfed agriculture (Wani *et al.,*2009; Wani *et al.,* 2012). It is realized that despite several constraints and limitations of rainfed areas, huge untapped potential exists for enhancing crop yield through improved land, water, nutrient and other natural resource management (Wani *et al.,*2012; Rockström *et al.,* 2007). The objectives of this comprehensive analysis of water balance was to assess the sources of errors in the water balance and to gain a better understanding of the hydrologic processes occurring in a watershed for contingent planning of available water resources to different sectors.

2. MATERIALS AND METHODS

The Ur river basin, a tributary of the river Dhasan, was selected as study area for carrying out the comprehensive water balance analysis of a basin. The study area represents the typical topography and geology of the Bundelkhand region. Ur river basin is situated in Tikamgarh district of Madhya Pradesh (Fig. 1) and lies on the Bundelkhand Plateau between the Jamni, a tributary of the Betwa and the Dhasan rivers. It extends between latitudes 24°35′N and 25°05′N and between 78°50′E and 79°10′E longitudes. The total geographical area (TGA) of Ur river basin is 990.37 sq km. The maximum length of the basin is about 119 km from north to south with a width of about 80 km. The Ur river flows from south to north direction. Ur river basin is bounded by Chhatarpur district in the east, Lalitpur district in the west, Jhansi district in the north and Sagar district in the south.

Water budgeting analysis for the Ur river basin was carried out in order to decide strategies for development and management of water resources for agricultural planning on seasonal basis using (Eq. 1);

$$P + GW_{in} - Q_{dsro} - Q_b - E_t - ET_f - ET_c - D_{dom} - D_{liv} - GW_{out} = \Delta S_s + \Delta S_g + U_w \quad \ldots(1)$$

Where, P indicates rainfall, GW_{in} indicates ground water inflow, Q_{dsro} indicates direct surface runoff, Q_b incatesbase flow, E_t indicates evaporation from tanks, ET_f indicates evapotranspiration from forest, ET_c indicates evapotranspiration from cropped areas, D_{dom} indicates domestic usage, D_{liv} indicates livestock needs, GW_{out} indicates ground water outflow, ΔS_s indicates change in surface water storages, ΔS_g indicates change in ground water storage, and U_w indicates un-accounted water.

The different components of inflow and outflow of the Eq. 1 showing water balance for water budgeting were estimated separately for preparing water budget for planning of agricultural activities in the river basin.

Inflow and Outflow in the System

Inflows represent the water income and it includes precipitation, surface water inflows and groundwater inflows.

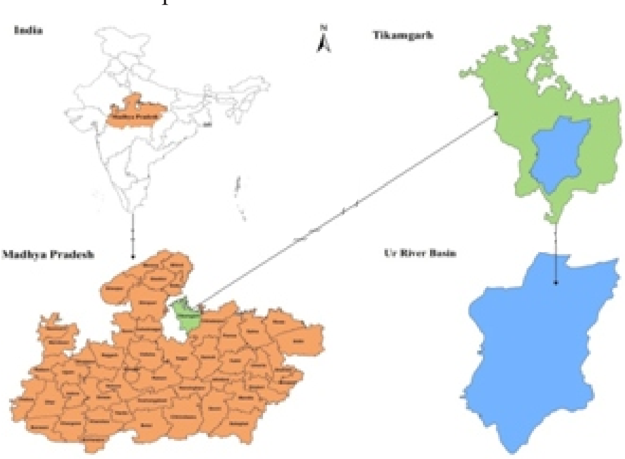

Fig. 1. Location map of study area

Components of Water Balance

a) Precipitation in the basin

Precipitation was computed with the help of Theisen mean method (Thiessen, 1911) using Eq. 2.

$$P_s = \frac{\sum_{i=1}^{n} A_i P_i}{\sum_{i=1}^{n} A_i} \quad \ldots(2)$$

Where, P_s represents mean areal seasonal rainfall, A_i represents area belonging to i^{th} rain gauge station and P_i represents precipitation at i^{th} rain gauge station.

b) Evaporation from water bodies

Evaporation from water bodies was computed using pan coefficient approach with the help of Eq. 3 and 4.

$$Ev_{tank} = EV_{pan} * K_p \quad \ldots(3)$$

Where, Ev_{tank} indicates actual evaporation from tank (mm), Ev_{pan} indicates evaporation from pan (mm), and K_p indicates pan coefficient.

$$VEV_{tank} = ½\,(WSA_{sm} + WSA_{em})EV_{tank} \quad \ldots(4)$$

Where, VEV_{tank} represents volume of actual evaporation from tank (m^3), WSA_{sm} represents water spread area at the start of the month (m^2) and WSA_{em} represents water spread area at the end of the month (m^2).

c) Evapotranspiration from crops

The FAO Penman-Monteith formula (Eq. 5) was used to estimate reference evapotranspiration (ET_o) on daily basis (Cai *et al.,* 2007; Singh *et al.,* 2019).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34\, u_2)} \quad \ldots(5)$$

Where, ET_o indicates reference evapotranspiration (mm day^{-1}), R_n indicates net radiation at the crop surface (MJ $m^{-2} day^{-1}$), G indicates soil heat flux density (MJ $m^{-2} day^{-1}$), T indicates mean daily air temperature at 2 m height (°C), u_2 indicates wind speed at 2 m height (m s^{-1}), e_s represents saturation vapor pressure (kPa), e_a indicates actual vapor pressure (kPa), e_s - e_a indicates saturation vapor pressure deficit (kPa), Δ indicates slope vapor pressure curve (kPa $°C^{-1}$), and γ indicates psychrometric constant (kPa $°C^{-1}$).

d) Evapotranspiration from forest

The actual ET from non-crop areas (forest) was estimated using Eq. 6 and 7 based on FAO Penman-Monteith method.

$$ET_f = PET \times D_f \quad \ldots(6)$$

Where, ET_f represents actual evapotranspiration from non-crop area (mm), PET indicates potential ET from non-crop area (mm), and D_f indicates coefficient of evaporation for forest area in watershed.

$$VET_f = A_f \times ET_f \quad \ldots (7)$$

Where, VET_f indicates volume of ET from forested areas (m^3), and A_f indicates area under forests (m^2).

e) Surface water outflow or runoff

SCS curve number method (USDA, 1972) given in Eq. 8 was used to calculate daily surface runoff (Singh *et al.,* 2017).

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \; for P > I_a \quad ; \text{and } Q = 0, for\ P \le I_a \quad \ldots (8)$$

$$S = \frac{25400}{CN} - 254$$

Where, Q indicates direct surface runoff (mm), S indicates potential retention (mm), CN indicates curve number and I_a indicates initial abstraction which is 0.2S for general soils.

f) Ground water flow

Rate of ground water flow can be estimated by using Eq. 9 and 10 based on Darcy's law.

$$Q = TiL \quad \ldots (9)$$

Where, T indicates transmissivity ($m^2 day^{-1}$), i indicates hydraulic gradient, L indicates length of reach, Q indicates rate of flow ($m^3 day^{-1}$).

$$i = h / L \quad \ldots (10)$$

Where, i represents hydraulic gradient, h represents difference in groundwater levels between the observation well inside the watershed and observation well downstream for the particular reach (m), and L represents reach length (m).

g) Change in ground water storage

Water Table Fluctuation (WTF) based Eq. 11 was used for calculation of the change in groundwater storage.

$$\Delta GW_s = S_y \times A \times \Delta GWL \quad \ldots (11)$$

Where, ΔGW_s indicates change in ground water level (m), S_y indicates specific yield, A indicates area of the aquifer (m^2), and ΔGWL indicates change in groundwater before and after season.

3. RESULTS AND DISCUSSION

Geographical Distribution of Study Area

The distribution of area under various blocks of Tikamgarh district falling in Ur river basin is represented graphically in Fig. 2. The Jatara block covers an area of 324.94 km^2, which is about 33% of total basin area followed by Tikamgarh block, which covers 315.97 km^2 (32%); Baldevgarh covers 272.65 km^2 (27%) and Palera covers a very small portion of watershed of about 8% of the total basin area as given in Table 1.

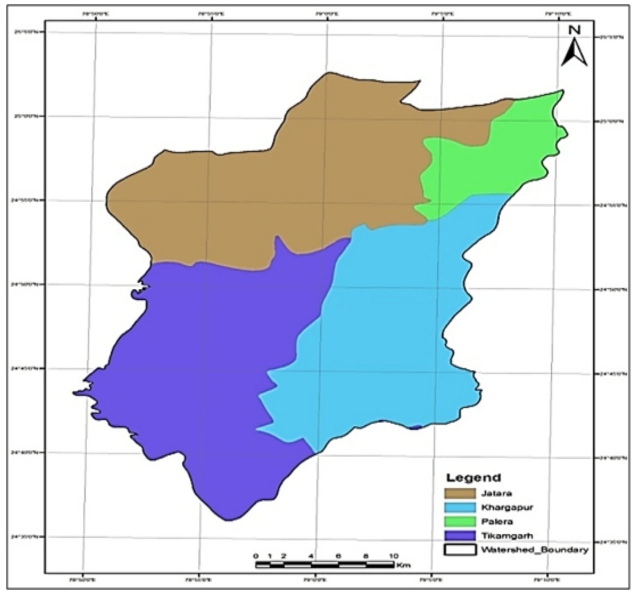

Fig. 2. Areal distribution of different blocks of Ur river basin

Table: 1
Distribution of area of various blocks in the watershed

Block Name	Area of block falling in watershed (km^2)	Area of watershed (%)
Tikamgarh	315.97	31.90
Palera	76.81	7.75
Baldevgarh	272.65	27.52
Jatara	324.94	32.80

Topography of the Study Area

The topography of Ur river basin is undulating, and comprises of very high hills along the ridge line with the elevation varying between 200 m to 400 m above mean sea level (AMSL) as shown in Fig. 3. The elevation gradually decreases from the southern part of the basin towards the north. Therefore, Ur river also flows in a north-easterly direction till its confluence with Dhasan river.

Land Use of Ur River Basin

Land use of Ur river basin was prepared by supervised classification method with maximum likelihood algorithm using LANDSAT ETM+ imagery in GIS environment and it was found that the most dominant, being 59% of the basin area, is under agriculture *viz., rabi* crop (24.85%), *kharif* crop (10.54%) and area under double crop (23.23%) as shown in Fig. 4. The scrub land is next in land use covering an area of 131.18 km^2. Scrubs and sparse forests are the next dominant land use with a coverage of 13.25% followed by

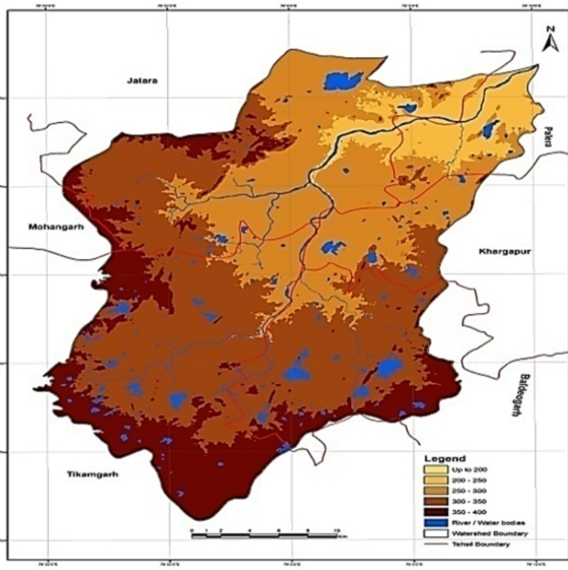

Fig. 3. Areal distribution of topography of Ur river basin

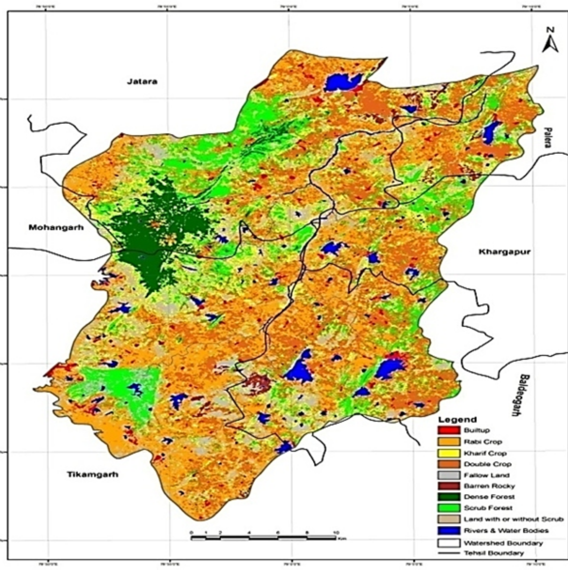

Fig. 4. Land use map of Ur river basin

dense forests (10.0%) described in Fig. 5. The area covered by the settlement is 19.98 km^2, whereas dense forest occupies an area of 44.56 km^2. The river and water bodies cover area of 34.47 km^2, fallow land covers 69.25 km^2 area, and barren land covers 110.54 km^2 area of the basin as shown in Fig. 4. The agricultural area is spread all around the basin, possibly because of large number of tanks that provide irrigation and domestic demands. Tanks are also well distributed in the basin and the Madan Sagar tank, which is a very large tank with its canal system, is located towards the north-west corner of the basin.

Soils of Ur River Basin

The major portion of the basin is covered by sandy loam soil, which is about 635.46 km^2 and covers 68.05% of the total basin area (Fig. 6). Normally, high infiltration rate of this type of soil requires more frequent irrigation for the successful growth of plants. From Fig. 7 it is revealed that the second most dominant soil type in the basin is sandy clay loam, which covers 266.38 km^2 and about 28.53% of the total basin area followed by silt clay loam, which covers 31.98 km^2 (3.42 %) of the total basin area.

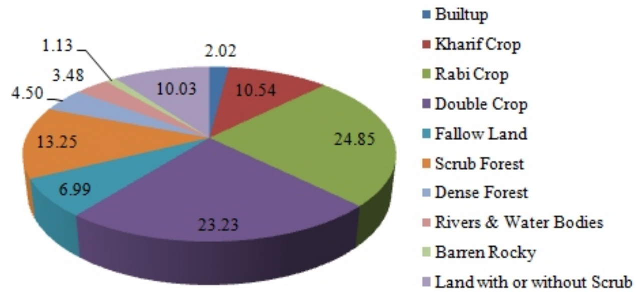

Fig. 5. Distribution of various land use classes in Ur river basin

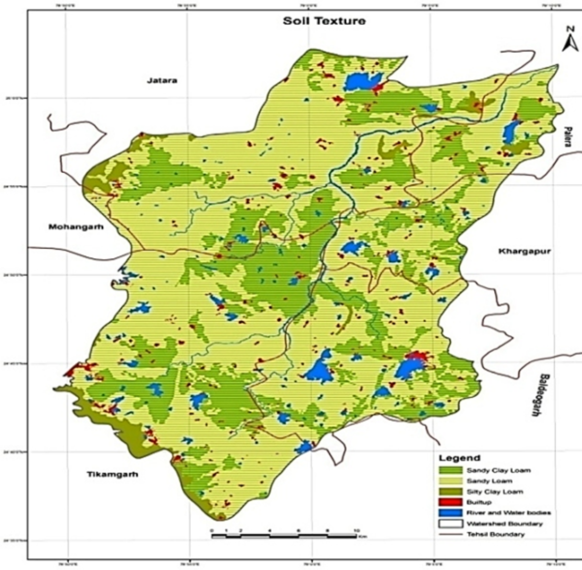

Fig. 6. Soil map of Ur river basin

Seasonal Distribution of Rainfall in Ur River Basin

The mean areal rainfall was computed based on the Thiessen's polygon method. The rain gauge stations at Tikamgarh, Jatara, Baldevgarh and Palera influence the rainfall pattern in the basin, as shown in Fig. 8, and spatio-temporal distribution of monthly average rainfall (June - October) in the basin is shown in Fig. 9 (a-e).

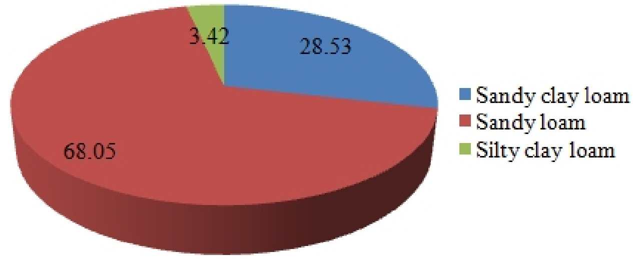

Fig. 7. Area (percent) under various soil types in Ur river basin

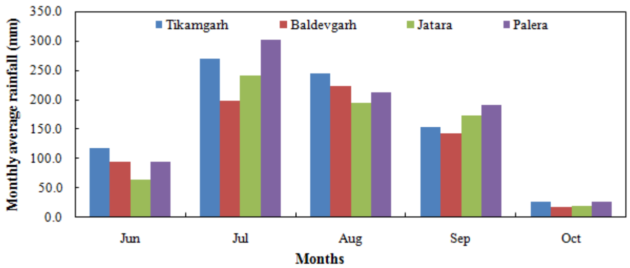

Fig. 8. Monthly average rainfall at influencing rain gauge stations in Ur river basin

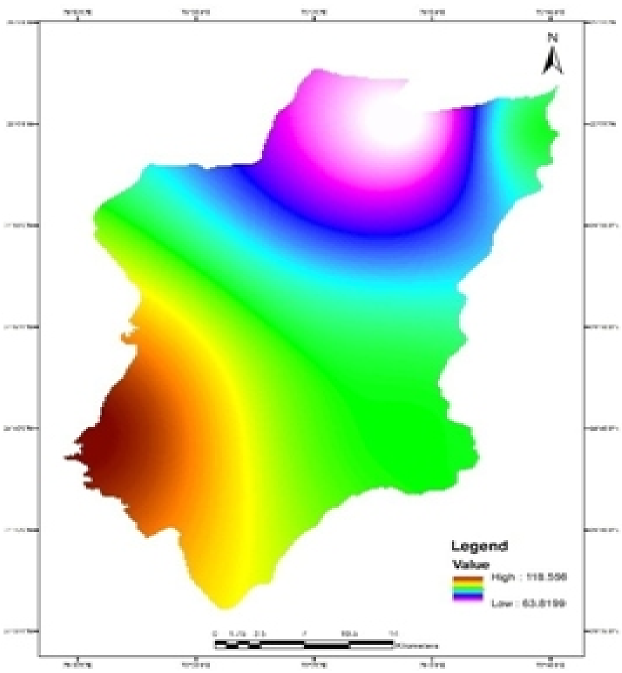

Fig. 9a. Average rainfall for month of June (mm)

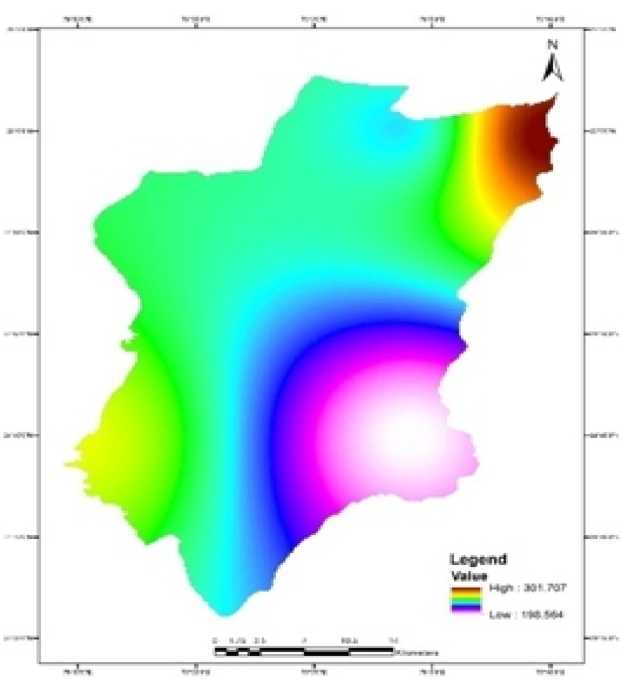

Fig. 9b. Average rainfall for month of July (mm)

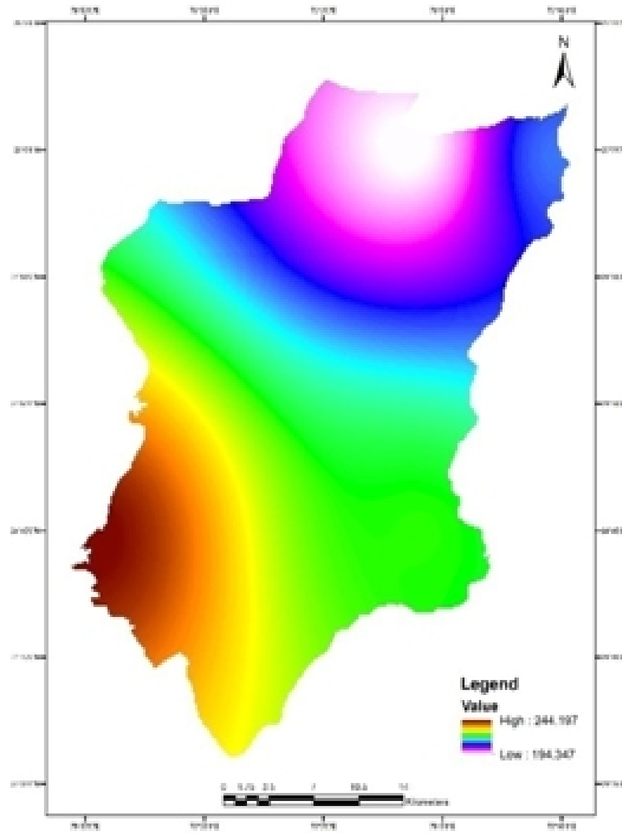

Fig. 9c. Average rainfall for month of August (mm)

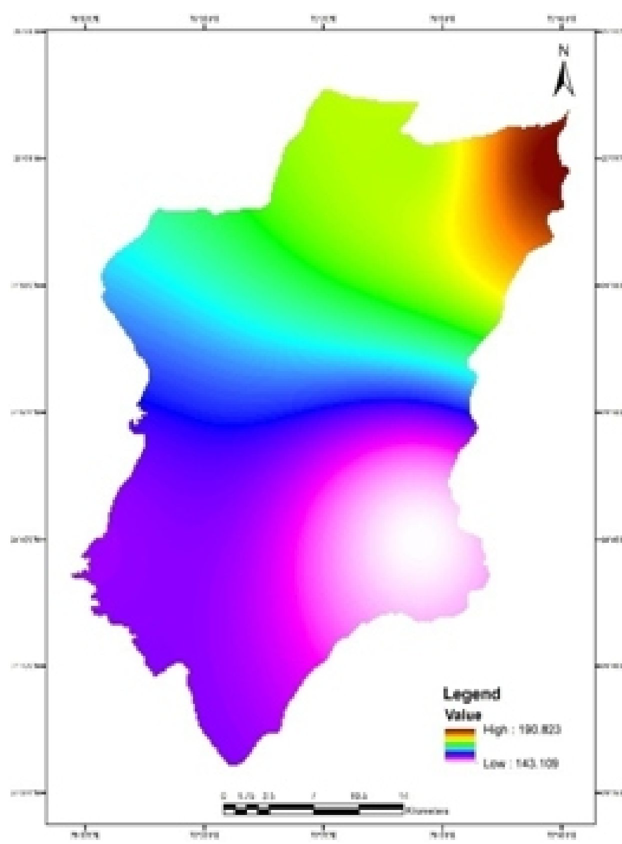

Fig. 9d. Average rainfall for month of September (mm)

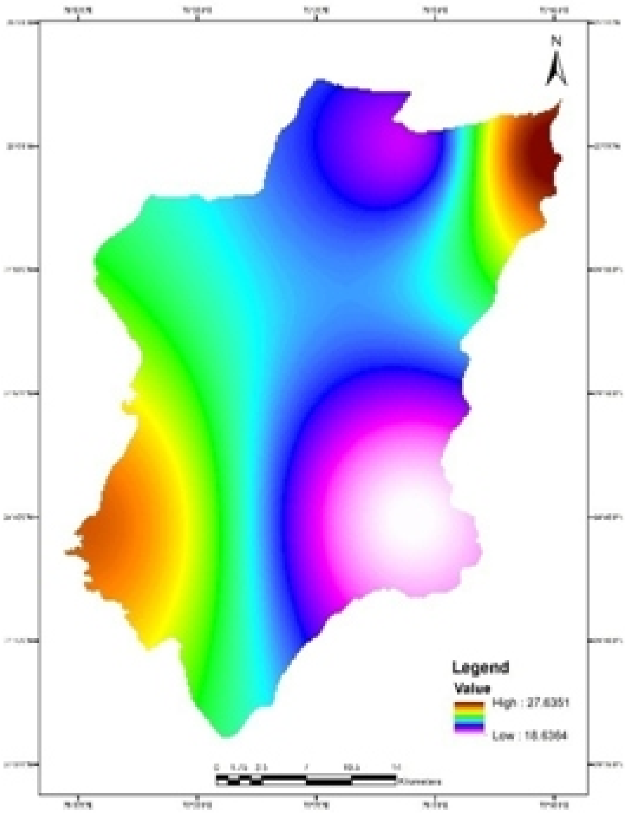

Fig. 9e. Average rainfall for month of October (mm)

Fig. 9f. Thiessen Polygon Map of Ur river basin

Fig. 9(a-e), f: Spatio-temporal distribution of monthly average rainfall (June-October) and Thiessenpolygon map of influencing rain-gauge stations in Ur river basin

It can be observed from Table 2 that the rain gauges at Jatara and Tikamgarh have maximum area of influence followed by Baldevgarh, and the rain gauge at Palera has minimal influence on the rainfall pattern in the basin, which is also shown in Fig. 9f.

Based on the recommendations of FAO, the probability analysis of the normal annual rainfall series was carried out to find the rainfall corresponding to various levels of probability as given in Table 3. The rainfall corresponding to 20% probability of exceedance is taken as wet year, rainfall corresponding to 50% probability of exceedance is taken as normal year, and rainfall corresponding to 80% probability of exceedance is taken as dry year. This analysis helped to understand the rainfall deficit/surplus information for better agricultural planning and management of water resources in the basin area.

Table: 2
Area of influence of various rain gauge stations in Ur river basin

Name of rain-gauge station	Area of influence (sq km)	Thiessen's weight
Tikamgarh	313.37	0.317
Baldevgarh	275.63	0.278
Jatara	324.66	0.328
Palera	76.70	0.077

Crop Water Requirement in Ur River Basin

The total crop ET was computed on a daily basis for all the major crops grown and water requirement of *kharif* and *rabi* grown in different blocks of the basin is given in Table 4. Soybean is the principal crop grown during the *kharif* season, and wheat is the predominant *rabi* crop. The water

Table: 3
Rainfall (mm) corresponding to different probability levels in Ur river basin

Name of rain-gauge station	Wet year: 20% probability of exceedance	Normal year: 50% probability of exceedance	Dry year: 80% probability of exceedance
Tikamgarh	1093.46	803.00	677.80
Baldevgarh	933.91	659.00	437.80
Jatara	1136.80	549.00	472.60
Palera	1328.00	715.00	524.05

demands for all the crops during each season were summed up to arrive at the seasonal crop water demand in the basin.

Seasonal Water Requirement for Forests in Ur River Basin

The forested area having deep rooted trees, which comprises of dense forests and open forests, have different water requirement and were therefore analyzed separately as given in Table 5. The basin comprises of dense and open forests all along the hills on the ridge line, and also sparsely on the flat topped hills inside.

Domestic Water Requirement in Ur River Basin

The domestic water consumption was estimated based on the population of four Tehsils namely Jatara, Tikamgarh, Palera and Baldevgarh which lie inside the basin at the rate of 135 litre capita^{-1}day^{-1} as per BIS:1172-1993. There are about 366 villages located in the four blocks falling in the Ur river basin. The domestic water demand in the Ur river basin is given in Table 6.

Livestock Water Requirement in Ur River Basin

The main source of livelihood of the local population other than agriculture is dairy farming, and therefore there is considerable livestock population in the basin. The livestocks water use in the villages inside the study area was calculated at the rate of 40 litre capita^{-1}day^{-1} as given in Table 7.

Ground Water Inflow and Outflow in Ur River Basin

The groundwater outflow from the watershed, which is also of significant importance, was estimated. The groundwater levels were monitored from a network of observation wells located inside and surrounding the basin. The groundwater outflow takes mostly from the downstream portions of the basin both in the monsoon as well as the non-monsoon season. The groundwater outflow from the basin was computed as 0.034 MCM during the monsoon season, and 0.045 MCM during the non-monsoon season. At the upstream reaches of the watershed based on the water table gradients, the ground water inflow is taking place into the basin both during the monsoon season (0.068 MCM) as well as the non-monsoon season (0.081 MCM). The groundwater outflows/inflows are presented in Table 8 and the groundwater table contour map for the pre-monsoon and post-monsoon period of the basin is shown in Fig. 10a and Fig. 10b, respectively.

Water Budget for Ur River Basin

The water budget of the Ur river basin has been carried out on a seasonal time scale for two seasons namely, monsoon season (June to October) and non-monsoon

Table: 4
Seasonal crop water requirement in Ur river basin

Block name	Crop water requirement (MCM)	
	Kharif	*Rabi*
Tikamgarh	12.335	27.654
Jatara	15.536	22.504
Baldevgarh	19.802	24.24
Palera	4.942	6.252
Total	52.615	80.65

Table: 5
Seasonal water requirement for deep rooted trees under forests in Ur river basin

Forest type	Area (sq km)	During monsoon season (MCM)	During non monsoon season (MCM)
Dense forest	45.57	32.80	38.80
Open forest	130.18	93.73	110.83
Total	175.75	126.53	149.63

Table: 6
Domestic water demands in Ur river basin

Station	Population	Water demand (MCM day^{-1})	During monsoon season (MCM)	During non-monsoon season (MCM)
Jatara	195488	0.026	4.011	5.621
Palera	10993	0.001	0.226	0.316
Tikamgarh	59498	0.008	1.221	1.711
Baldevgarh	100021	0.014	2.052	2.876
Total	366000		7.510	10.524

Table: 7
Livestock water demands in Ur river basin

Station	Livestock population	Water demand (MCM day^{-1})	During monsoon season (MCM)	During non-monsoon season (MCM)
Jatara	121602	0.005	0.739	1.036
Palera	12590	0.001	0.077	0.107
Tikamgarh	103775	0.004	0.631	0.884
Baldevgarh	113262	0.005	0.689	0.965
Total	351229	0.015	2.135	2.992

Table: 8
Groundwater outflows and inflows in Ur river basin

Outflows/Inflows	During monsoon season (MCM)	During non-monsoon season (MCM)
Groundwater outflow	0.034	0.045
Groundwater inflow	0.068	0.081

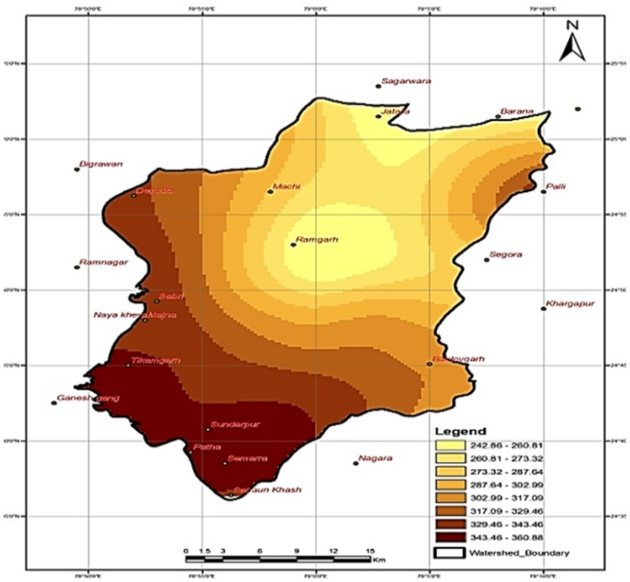

Fig. 10a. Groundwater table contour map during pre-monsoon

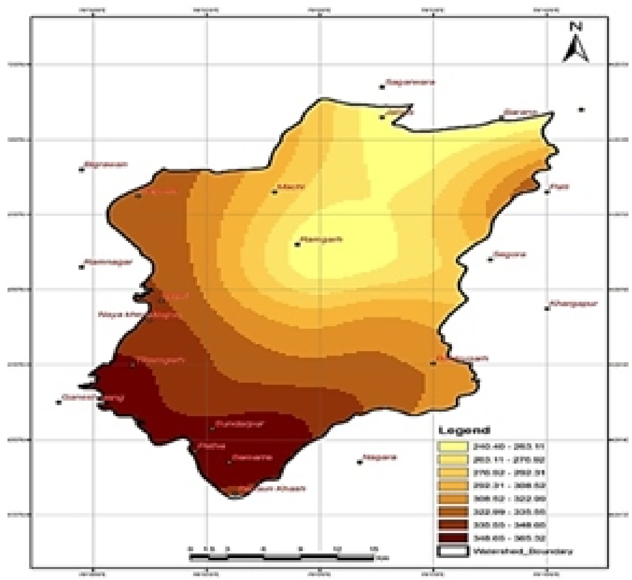

Fig. 10b. Groundwater table contour map during post-monsoon

season (November-May). The water budget during the monsoon season yields an estimate of the major components, and also helps to identify those components which can be utilized more effectively to conserve the precious water resources within the watershed. By conserving these resources, efficient and effective planning can be done for agricultural production as well as the livelihood in the basin. The water budget computations for Ur river basin is presented in Table 9.

Table: 9
Water budget of Ur river basin

Components		Values in MCM	
		Monsoon season	Non-monsoon season
Inflow	Rainfall	517.55	35.97
	Groundwater inflow	0.068	0.081
Outflow	Surface runoff	69.85	0.52
	Domestic demand	7.51	10.524
	Livestock demand	2.135	2.992
	Evapotranspiration (crops)	52.615	80.65
	Evapotranspiration (forested areas)	103.139	60.967
	Groundwater outflow	0.034	0.045
Change in storage (SW)		-	-
Change in storage (GW)		318.25	-150.839
Un-accounted water		-35.915	31.192

4. CONCLUSIONS

The un-accounted water varies between 35.915 MCM in monsoon season to 31.192 MCM in the non-monsoon season. The quantity of unaccounted water includes the errors in estimation of individual components and some of the components of lesser significance which have not been estimated. The unaccounted water indicates the accuracy in estimation of the water budget components, and seems to be satisfactory as it is limited to 6.94% of the seasonal rainfall, considering the complexities in the estimation of all the major water balance components. The water budgeting study indicates that about 69.85 MCM of water flows down the stream (storage in tanks included in this value) in monsoon season. Surface water potential is immense and the available surface water can be tapped at various places in the basin for bringing additional agricultural areas under irrigation. Few sites for creating additional water storage structures can be identified in the watershed depending on topography, catchment area and possible command area. Efforts can also be made to use the surface water for creating grazing lands for the livestock population of the villages, which is otherwise creating pressure on the forest resources in the watershed. Artificial recharge of groundwater can be given more thrust for recharging the depleted aquifers, which can be used as an alternative source of water supply during droughts.

REFERENCES

BIS:1172. 1993. Code of basic requirements for water supply, drainage and sanitation, Bureau of Indian Standards, New Delhi.

Cai, J., Liu, Y., Lei, T. and Pereira, L.S. 2007. Estimating reference evapotranspiration with the FAO Penman–Monteith equation using daily weather forecast messages. *Agric. Forest Meteor*, 145(1-2):22-35.

CWC. 2005. Hand book of water resources statistics, New Delhi, India: Ministry of Water Resources, Government of India.

GoI. 2012. Final report of minor irrigation and watershed management for the twelfth five year plan (2012-2017). New Delhi: Planning Commission, Government of India.

Hatfield, J.L., Sauer, T.J. and Prueger, J.H. 2001. Managing soils to achieve greater water use efficiency. *Agron. J.,* 93(2): 271-280.

Jana, C., Rawat, M., Sena, D.R., Alam, N.M., Mandal, U., Kaushal, R. and Mishra, P.K. 2016. Application of SEBAL model to estimate Evapotranspiration in Doon Valley, India. *Indian J. Soil Cons*, 44(2): 191-197.

Kijne, W., Barker, R. and Molden, D. 2003. Water Productivity in Agriculture: Limits and Opportunities for Improvement. CABI Publishing, Wallingford, UK, 332 p.

Oweis, T., Zhang, H. and Pala, M. 2000. Water use efficiency of rainfed and irrigated bread wheat in a Mediterranean environment. *Agron. J.,* 92(2): 231-238.

Rockström, J., Hatibu, N., Oweis, T.Y., Wani, S.P., Barron, J., Bruggeman, A., Farahani, J., Karlberg, L. and Qiang, Z. 2007. *Managing water in rainfed agriculture.* In Molden, D. (ed.), Water for food, water for life: a comprehensive assessment of water management in agriculture, International Water Management Institute, London, UK: Earthscan; and Colombo, Sri Lanka, pp 315–348.

Rockström, J., Karlberg, L., Wani, S.P., Barron, J., Hatibu, N., Oweis, T. and Qiang, Z. 2010. Managing water in rainfed agriculture-The need for a paradigm shift. *Agric. Water Manage.*, 97(4): 543-550.

Singh, G., Singh, S., Singh, R.M., Kumar, R. and Mishra, C.D. 2017. Assessment of natural groundwater recharge in Sonar sub-basin using HELP3 model: A case study. *Indian J. Soil Cons.*, 45(2): 176-182.

Singh, G., Singh, R.M., Chandola, V.K. and Nema, A.K. 2019. Rainfall analysis for crop planning under rainfed condition at Mirzapur district in Vindhya plateau of Indo-Gangetic Plain. *Indian J. Soil Cons.*, 47(1): 30-36.

Thiessen, A.H. 1911. Precipitation averages for large areas. *Monthly Weather Rev.,* 39(7): 1082-1089.

USDA, SCS. 1972. National engineering handbook, section 4: Hydrology. Washington, DC.

Wallace, J.S. 2000. Increasing agricultural water use efficiency to meet future food production. *Agric., Ecosyst. Environ.,* 82(1-3): 105-119.

Wani, S.P., Garg, K.K., Singh, A.K. and Rockstrom, J. 2012. *Sustainable management of scarce water resource in tropical rainfed agriculture.* Lal R., Stewart B.A. (eds.), Soil Water and Agronomic Productivity. Advances in Soil Science, CRC Press, United Kingdom, pp 347–408.

Wani, S.P., Rockström, J. and Sahrawat, K.L. 2011. Integrated Watershed Management in Rainfed Agriculture, CRC Press, ISBN 9780-415882774.

Wani, S.P., Rockstrom, J., Venkateswarlu, B. and Singh, A.K. 2011. *New paradigm to unlock the potential of rainfed agriculture in the semi-arid tropics.* R. Lal and B.A. Stewart (eds.), World Soil Resources and Food Security, Advances in Soil Science, CRC Press, United Kingdom, pp 419–469.

Wani, S.P., Sreedevi, T.K., Rockström, J. and Ramakrishna. Y.S. 2009. *Rainfed agriculture – past trends and future prospects.* Wani S.P., Rockström J. and Oweis T. (eds.), Rainfed Agriculture: Unlocking the Potential. Comprehensive Assessment of Water Management in Agriculture Series, CAB International, Wallingford, UK, pp 1–35.