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ASSESSMENT OF WATER BALANCE OF THE SEMI-ARID REGION IN SOUTHERN SAN JOAQUIN VALLEY CALIFORNIA USING THORNTHWAITE AND MATHER'S MODEL

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Growing population and irrigation needs increase the demand for water requiring judicious use of limited fresh water resources. The Paramount farm in Southern San Joaquin valley, California, the world's largest supplier of almonds, is facing a problem of water storage. The resource is estimated by a water balance assessment approach using the Thornthwaite and Mather (TM) models. The result shows that high soil moisture storage occurs from November to February in the range of 25 to 36 mm, but least in May to August as evapotranspiration is a maximum in May-July. This study also illustrates that there is highest recharge of soil moisture in November to January. To avoid crop water stress, irrigation should occur when the absolute value of accumulated potential water loss is maximum in the months of May to July. The water balance calculation shows that the maximum annual runoff is from January to March and October to December. There is an annual water deficit of 135 mm and an annual surplus of about 2 mm at the farm. This area has a period of moisture surplus from November to February and the remaining months are the period of deficit.

INTRODUCTION

In semi-arid regions, water resources are limited and thereby the available groundwater for irrigation and other water uses are severely constrained. Water demand for agriculture is visible from arid to humid landscape. However, there is always the need for optimum use and planning of water resources. Southern San Joaquin Valley belongs to semi-arid climatic regions, characterized by limited water resources due to expanding urban, industrial and agricultural water demands. In semi-arid regions, the actual evapotranspiration (AET) represents a key role of the hydrological cycle. AET may account for more than 90 % of the precipitation (P) (Pilgrim et al., 1988; Huxman et al., 2005). Drought in California is a matter of serious concern particularly when there are extensive agricultural productions in Central Valley. The state experienced massive agricultural loss of $ 308 million in 2008 due to water scarcity (California Dept. of Food and Agriculture, 2009). The Central Valley Project (CVP) allowed only 10% of water allowance to farmers in 2009 compared to 40% in 2008 and 50% in 2007. Farmers relied on the groundwater to accommodate the water shortage provided by CVP. The water system especially in agricultural areas requires an understanding through the water balance method. Water balance refers to the balance between incoming water (precipitation) and outgoing water (evapotranspiration, groundwater discharge and stream flow). Therefore, such budgeting exercise is used to evaluate the amount of precipitation that becomes stream flow (or runoff), evapotranspiration, and drainage (or groundwater discharge). Among the several methods for calculating water balance, Thornthwaite and Mather (1955, 1957) introduced one of the most prominent method that is used widely. The water balance approach is very helpful in finding out the annual periods of moisture deficit and moisture surplus for an entire area. The long-term average monthly rainfall, long-term average PET, and soil-vegetation characteristics are required to compute the water balance. LaBaugh et al. (1997) used isotopes and hydrochemical tracers to study the water balance of a lake in North America. Mandal et al. (1999) attempted Thronthwaite and Mather (TM) model for estimating soil-climatic water balance throughout India for analyzing climatic indices, length of growing period of crops, and their applications in agricultural research. Boulet et al. (2000) estimated simple water and energy balance with a bulk mixed vegetation and bare soil using soil “bucket” and Soil-Vegetaion Atmosphere Transfer (SVAT) model. However, the depth of the “bucket” or hydrologically active depth were established to be critical when the water balance was translated to soil moisture (Boulet et al. 2000). The objective of this study is to investigate the water balance of a region using the TM model and to record the periods of moisture deficit and moisture surplus in the study area.

STUDY AREA AND DATA

The 402 km^2 Paramount Farm located at the Lost Hill of Kern County in southern San Joaquin valley of Central Valley, California (35°30’N, 119°39’W) (Figure 1). The valley occupies two-thirds of the southern Central Valley in California. San Joaquin River flows in the northern part of the San Joaquin Valley and drains to the San Francisco Bay. About 4 percent of the basin area is urban. Although most of the basin’s populations focus on agricultural activities, Bakersfield is well known for its oil fields. Southern San Joaquin is the world’s largest supplier of almonds with more the 4,000 acres of almond orchards which is over 4 billion dollar industries. Geographically, the southern part of the San Joaquin Valley is the Tulare Basin, bordered by the Sierra Nevada on the east, the Tehachapi Mountains on the south, and Coast Ranges on the west. The northern extent corresponds to the Kings River. Significant geographic features include the Tulare Lake Basin and the Kettleman Hills. The main land use is agriculture, Bakersfield located south of study area was known for oil fields.

Hydrogeology

The hydrogeology of the study area is derived from the large, northwest trending; asymmetric structural trough which comprises marine and continental sediments up to 10 km thick (Gronberg and others, 1998). These sediments are significantly deposited largely by streams draining from the mountains from time to time. The sediments in southern San Joaquin Valley are dominated by coarse grains. The alluvial fans in this area are derived from the glaciated portion of the Sierra Navada (Faunt, Hanson, and Belitz, 2009). Although, fine-grained sediments (clay, sandy clay, sandy silt, and silt) are distributed throughout the San Joaquin Valley, stream (fluvial) and lake (lacustrine) deposited sediments are susceptible to compaction. The Corcoran Clay forms a separation in the basin-fill deposits into an upper unconfined to semi-confined zone and a lower confined zone in southern San Joaquin Valley (Williamson and others, 1989, Burow et al., 2004). Sierra Nevada raises to an elevation of more than 4,200 m (14,000 ft) in the east of the valley; whereas, west of the valley area is bounded by the Coast Ranges, which are a series of parallel ridges with moderate elevations (Mendenhall et al., 1916). During predevelopment, ground water generally moved toward the center of the valley and northward to the San Francisco Bay; over the prolong period of time, surface waters diversions from streams and ground-water fluctuations have altered the natural flow. Development of the groundwater basin initiated the irrigation water to percolate, which became the primary form of groundwater recharge and irrigation drawdown

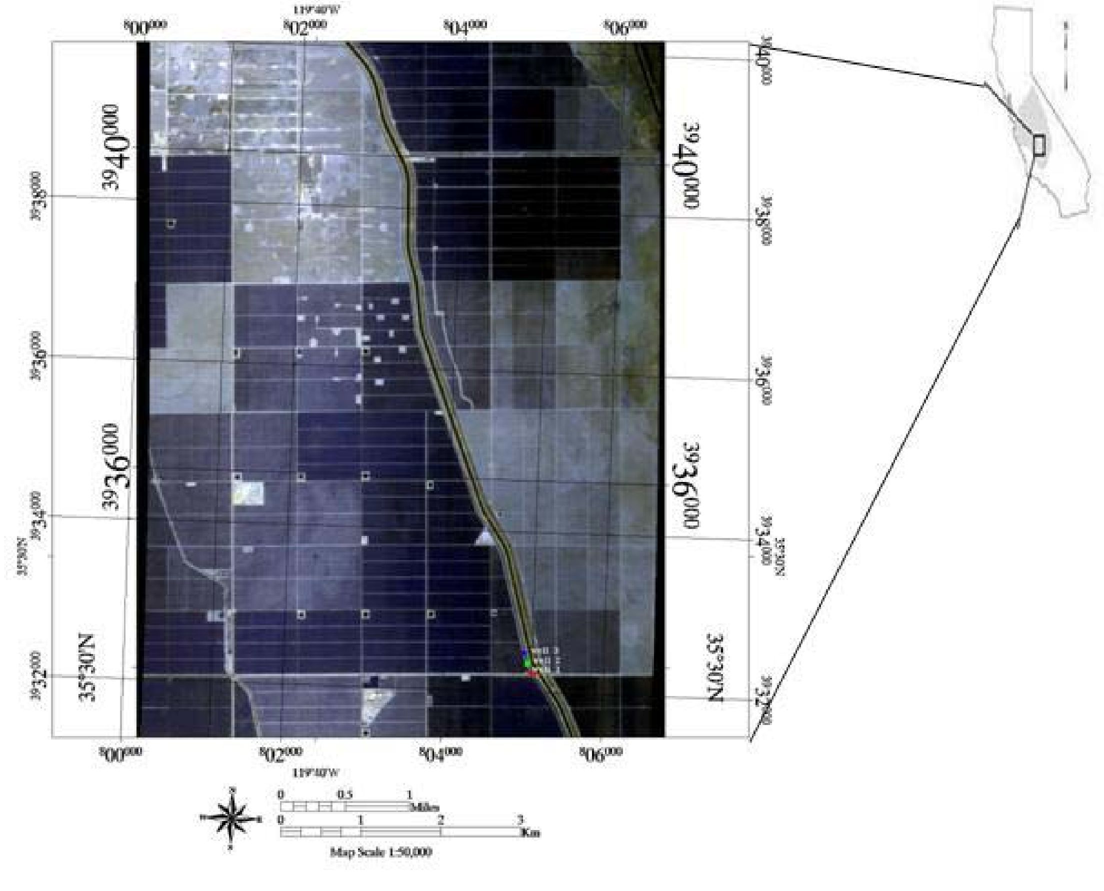

Figure 1. Location of the study area in Southern San Joaquin Valley, California.

became the primary form of ground-water discharge in the southern San Joaquin Valley (Davis et al., 1959). The soil texture in southern San Joaquin valley comprises alluvial fans that are derived from the glaciated parts of the Sierra Nevada. They are coarser grained than the alluvial fans to the north (Faunt, Hanson, and Belitz, 2009, p. 2). Generally, thin, discontinuous lenses of fine-grained sediments (clay, sandy clay, sandy silt, and silt) are distributed throughout the San Joaquin Valley and demonstrate field capacity and soil moisture for various soil texture (Table 1).

The available water capacity of a soil is typically given as inches of water holding capacity per foot of soil thickness. Ratliff et al., (1983) computed the field measurement of soil water availability for each soil type shown in the Table 1. The rooting depth of the orchards is 6 feet. The maximum soil water capacity is calculated as available water capacity times the rooting depth. If the infiltrated water exceeds the maximum soil water capacity then the water contributes as recharge to groundwater.

Available data

Within the study area, California Irrigation Management System (CIMIS) station is located at Belridge in Kern County. The climatic stations contain daily measurements of wind speed, global radiation, and daily minimum and maximum values of both air temperature and relative humidity. These data are used to calculate the daily PET by the Penman-Monteith method. A soil map of the southern San Joaquin Valley is obtained from United States Department of Agriculture, Natural Resources Conservation Service (2007). There are 70 different types of topsoil identified in the catchment. However many of the soil types are similar in description, therefore the 70 soils types were reclassified into eleven major soil types (Table 1). A land use map is shown in Figure 2. The vegetation is reclassified into almond orchards, pistachio crops, and other photosynthesis vegetation. The classification also includes urban land, non-photosynthesis vegetation, soil, and water.

Table 1. Estimated available water capacities for various soil-texture group.

Soil texture	Available water capacity (inches per foot of thickness)	Maximum soil water capacity (inches)
Sand	1.2	7.2
Loamy sand	1.9	11.4
Sandy loam	2.5	15
Loam	3.2	19.2
Silt loam	3.6	21.6
Sandy clay loam	3.5	21
Sandy clay	3.4	20.4
Clay loam	3.8	22.8
Silty clay loam	4.3	25.8
Silty clay	4.8	28.8
Clay	4.8	28.8

METHODOLOGY

The Thornthwaite and Mather's (TM) Model

The TM model is one of the simplest models to determine water balance of the region from individual fields to small watershed. Such model is use to determine a general estimate of water balance regime for individual fields to small watersheds. The monthly potential evapotranspiration computed using the following equation (Singh et al., 2004) :

$$PET = 1.6 \times C \times \left(10 \times \frac{T}{I}\right)^{a} \tag{1}$$

where PET is the potential evapotranspiration (mm month^{-1}); T is the mean monthly temperature (°C); I is the annual heat index for the 12 months in a year ($I = \Sigma i$); i is the monthly heat index ($i = [T/5]^{1.514}$); $a = 6.75 \times 10^{-7} \times I^3 - 7.71 \times 10^{-5} \times I^2 + 1.792 \times 10^{-2} \times I + 0.49239$; and C is a correction factor for each month ($C = [m/30] \times [d/12]$), where m is the number of days in the month and d is the monthly mean daily duration (number of hours between sunrise and sunset, expressed as the average for the month).

P - PET, is a quantitative estimation of the water excess (+) or deficit (–), P as precipitation. Accumulated potential water loss ($APWL$) is the potential deficiency of soil moisture associated with low moisture contents of a soil below water holding capacity. Accumulated potential water loss is increased 1) during dry seasons to meet the demands of PET when insufficient supply of water, 2) reduced during wet seasons from soil moisture recharge, and 3) equals zero when soil moisture equal to the available water holding capacity of the soil. The accumulated values $APWL$

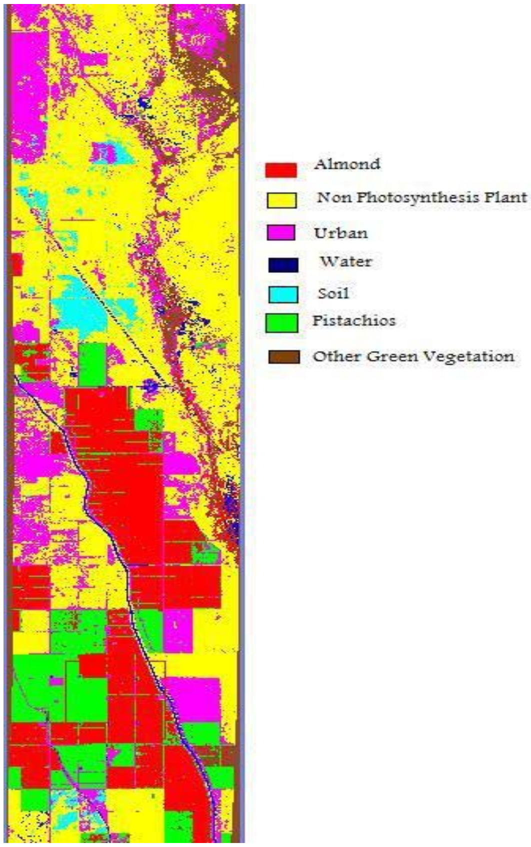

Figure 2. Land use land cover classification.

for each month, were calculated by running the sum of the daily *P-PET* values during the periods when (*P-PET*) is negative value given in Table 2. Those months having positive (*P-PET*) have*APWL* zero. The actual storage of soil moisture (*STOR*) for each month was calculated as follows:

$$STOR=AWC \text{ x } e^{AWPL/AWC} \tag{2}$$

where *AWC* is the moisture storage capacity, also known as available water capacity of the soil, which based upon the land use, soil texture and rooting depth as suggested by Thornthwaite & Mather (1955, 1957). The results were summarized in Table 2.

$$\Delta SM_{\text{month}}=STOR_{\text{month}}-STOR_{\text{previousmonth}} \tag{3}$$

A negative value ofΔSM means discharge of water from the storage because of evapotranspiration, whereas a positive value of ΔSM implies infiltration of water into the soil that contribute to the soil moisture storage.

The actual evapotranspiration (*AET*) was computed for all the months, as given in Equations (4) and (5):

$$AET = \Delta SM + \text{P} \qquad \Delta SM < 0 \tag{4}$$

$$AET = PET \qquad \Delta SM > 0 \tag{5}$$

where *PET* is the potential evapotranspiration.

The water deficit (*DEF*) was calculated for those months having negative value of *P-PET* as follows

$$DEF = PET - AET \tag{6}$$

Moisture surplus (*SUR*) is defined as the excess water that cannot be stored when soil moisture storage attains its saturation; *SUR* is calculated using Equation (7):

$$SUR = P\text{-}PET \tag{7}$$

No surplus exists if soil storage is not at its capacity. If moisture storage capacity of the soil is just satisfied, then, *SUR* is obtained using Equation (8):

$$SUR = P\text{-}(AET + \Delta SM) \tag{8}$$

where ΔSM is the change in actual soil moisture storage. Studies show that actual runoff should be equal to the available annual surplus (Singh et al., 2004). Considering the study area classified in homogeneous land-use land cover occupying only agriculture of almond orchards; therefore, the total amount of annual *ET* and runoff calculated from the monthly water balance. Thus, the monthly runoff and the monthly *AET* from the farm are area-weighted values (Table 3).

RESULTS AND DISCUSSION

Water Balance Computations

Within the study area, California Irrigation Management System (CIMIS) station is located at Belridge in Kern County. The climatic stations contain daily measurements of wind speed, global radiation, and daily minimum and maximum values of both air temperature and relative humidity. These data are used to calculate the daily PET by the Penman-Monteith method. A soil map of the southern San Joaquin Valley is obtained from United States Department of Agriculture, Natural Resources Conservation Service (2007). There are 70 different types of topsoil identified in the

Table 2. Calculation of accumulated potential water loss (*APWL*).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
P	13.716	39.624	3.556	5.842	0.254	0	0	0	0	3.302	5.842	26.416	98.552
PET	39.878	56.896	115.316	154.432	197.866	197.104	214.122	181.61	146.558	98.298	55.88	34.544	1492.504
P-PET	-26.16	-17.27	-111.76	-148.59	-197.61	-197.10	-214.12	-181.61	-146.55	-94.99	-50.03	-8.128	-1393.95
APWL	-36.06	-51.62	-111.5	-155.7	-197.86	-204.21	-213.1	-181.61	-151.89	-94.99	-53.08	-29.97	-1481.59

catchment. However many of the soil types are similar in description, therefore the 70 soils types were reclassified into eleven major soil types (Table 1). A land use map is shown in Figure 2. The vegetation is reclassified into almond orchards, pistachio crops, and other photosynthesis vegetation. The classification also includes urban land, non-photosynthesis vegetation, soil, and water.

The output can be compiled in a very useful manner by collating the data into long-term averages. This is useful to track soil moisture status throughout the year in order to determine periods of soil water deficit, soil water recharge, soil water utilization, and soil water surplus. Figure 6 demonstrated the different status of soil moisture throughout the year. It was observed that the area-weighted average annual deficit in the farm was 11.30 mm and the annual surplus was 0.14 mm. The area-weighted average annual deficit in the watershed is 11.30 mm and the annual surplus is 0.14 mm. These periods are shown in Figure 3.

CONCLUSION

This study uses TM water balance model to evaluate various component of water balance in Paramount farm region. Such estimation of water balance components showed that the TM model is useful in plant-soil-groundwater dynamics at a monthly scale. It is also helpful in finding out the periods of moisture deficit and moisture surplus for the region. The model computes evapotranspiration, runoff, soil moisture, and recharge separately on monthly basis. The TM model uses rainfall data, temperature data, soils, land-use and rooting depth of almond orchard vegetation for calculating the soil moisture deficit, soil moisture surplus, evapotranspiration, surface runoff

Table 3. Average monthly water balance computation for almond orchard (*AWC*= 63.5 mm).

	P	*PET*	*P-PET*	*STOR*	Δ*SM*	*AET*	Deficit	Surplus	Runoff
Jan	13.716	39.878	-26.162	35.98729	-314.013	36.25273	3.625273	291.476	53.85943
Feb	39.624	56.896	-17.272	28.16631	-7.82098	51.72364	5.172364	0	120.0773
Mar	3.556	115.316	-111.76	10.96967	-17.1966	104.8327	10.48327	0	212.7351
Apr	5.842	154.432	-148.59	5.468867	-5.50081	140.3927	14.03927	0	0
May	0.254	197.866	-197.612	2.815485	-2.65338	179.8782	17.98782	0	0
Jun	0	197.104	-197.104	2.547556	-0.26793	179.1855	17.91855	0	0
Jul	0	214.122	-214.122	2.214739	-0.33282	194.6564	19.46564	0	0
Aug	0	181.61	-181.61	3.636566	1.421828	165.1	16.51	0	0
Sep	0	146.558	-146.558	5.807042	2.170476	133.2345	13.32345	0	0
Oct	3.302	98.298	-94.996	14.2269	8.419855	89.36182	8.936182	0	176.7349
Nov	5.842	55.88	-50.038	27.52609	13.2992	50.8	5.08	0	84.99591
Dec	26.416	34.544	-8.128	39.6096	12.0835	31.40364	3.140364	0	52.75404
Total	98.552	1492.504	-1393.95	178.9761	-310.39	1356.822	135.6822	291.48	701.1567

All figures are in mm. Soil : Sandy loam

Table 4. Summary of *P*, *PET*, *AET*, and Runoff.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
P	13.72	39.62	3.56	5.84	0.25	0.00	0.00	0.00	0.00	3.30	5.84	26.42
PET	39.88	56.90	115.32	154.43	197.87	197.10	214.12	181.61	146.56	98.30	55.88	34.54
AET	36.25	51.72	104.83	140.39	179.88	179.19	194.66	165.10	133.23	89.36	50.80	31.40
Runoff	256.75	184.48	60.63	0.00	0.00	0.00	0.00	0.00	0.00	105.96	218.93	259.81

and other parameters. The average annual precipitation of the farm is 8.21 mm. February receives the highest precipitation of 39.6 mm. Average PET of this region 124.3mm and the highest was observed in July where the precipitation was zero. The range of AET is 45 to 246 mm/month. High soil moisture storage was observed from November to February in the range of 25 to 36 mm, but least in May to August as the ET process is maximum in May-July. This shows that there is highest recharge of soil moisture in November to January. To avoid crop water stress, irrigation should apply when the absolute value of APWL is maximum in the months of May to July. The water balance calculation shows that the maximum annual runoff results from January to March and October to December. The area-weighted total runoff was calculated as 1086.56 mm from the total precipitation of 98.55 mm for the study period. The annual deficit in the watershed is 135.85 mm and the annual surplus is 1.77 mm. This region undergoes a period of moisture deficit in the months of May to July. Mid September to October are months of soil water recharge; From mid-November to early February is the period of water surplus as the area is subjected to winter precipitation. Winter months are subjected to surplus, whereas deficit in the remaining time of the year shows strong exchange phenomenon among atmosphere, surface water, groundwater, energy balance and water balance in the farm. Local populations are benefitted from such water balance studies. This helps them to decide their crop calendar, irrigation requirements, and water conservation based upon the periods of deficit or surplus.

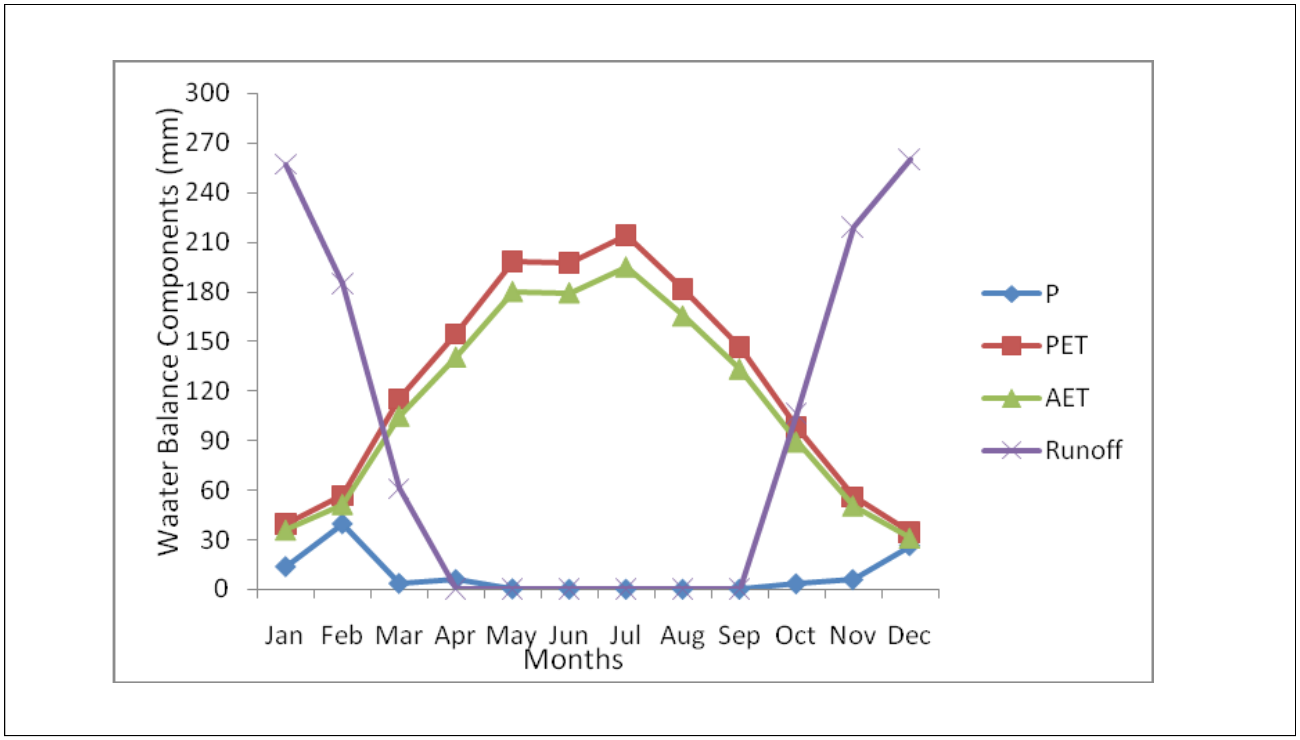

Figure 3. Water balance status of the study area.

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