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Estimation and Evaluation of Water-Balance Parameters with different Evapotranspiration Methods using Remote Sensing & GIS based ArcSWAT Model

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Abstract: The Soil and Water Assessment Tool (SWAT), a widely used watershed hydrology and water quality model using physically based spatial and non-spatial data. Potential Evapotranspiration (PET) is an important factor used in hydrological models as well as in management of irrigation projects and water-balance estimation. At the catchment level, hydrological models first calculate PET and then AET by considering soil moisture and landuse. In this study, we used the ArcSWAT model to estimate PET, ET and Runoff. The SWAT model provides three different methods for estimating potential evapotranspiration (PET) and the corresponding Actual Evapotranspiration (ET). These methods are (i) Hargreaves (HarG), (ii) Penman-Monteith (PenM) (iii) Priestley-Tylor (PreT). Due to missing weather parameters for the PenM method, a statistical weather generator embedded in SWAT, WXGEN was used in several studies to generate missing weather data and to fill in gaps in measured records. The principle aim of this study is to compute water balance parameters of PET, ET using generated and measured meteorological data and further compare surface Runoff using three embedded methods of PET in ArcSWAT Model. The model was applied to the 'Bhama' river watershed, covering an area of 398 km^2 located in Pune district of Maharashtra. The integrated methods of evapotranspiration in SWAT model was applied to predict PET, ET and surface Runoff. The average annual PET obtained from 'Bhama' watershed is 131 mm using PenM methods, which is highest value than other 2 methods. In case of ET computation HarG gives a little higher value of 57 mm and PreT method shows higher value of 20 mm Runoff than other 2 methods used in this study. This study reveals that, Priestley-Tylor method predicts higher surface Runoff, Hargreaves method predominates in prediction of Evapotranspiration and Penman-Monteith method superior to predicts Potential Evapotranspiration.

Keywords: Evapotranspiration, Hargreaves, Runoff, SWAT, Watershed.

I. INTRODUCTION

Water resource management requires knowledge of the processes influencing the water budget at the catchment scale. Evapotranspiration (ET) processes, in both climatological and hydrological studies, are among the most important in arid regions, where annual precipitation is not sufficient to provide crop water requirements [1]. ET, a collective term that includes evaporation from the plant canopy, transpiration, sublimation, and evaporation from the soil, is the primary mechanism by which water is removed from a watershed [2]. Minimum Evapotranspiration rates generally occur during the coldest months of the year and maximum rates generally coincide with the summer season. However, since evapotranspiration depends on both solar energy and the availability of soil moisture and plant maturity the seasonal maximum evapotranspiration actually may precede or follow the seasonal maximum solar radiation and air temperature by several weeks. It is thus an important component of the hydrologic cycle in the watershed, so accurate quantification of actual evapotranspiration (AET) is crucial to evaluating the effects of changing land use on water yield, environmental assessment, and development of best management practices to the quality of both surface and ground water [3]. Unfortunately, direct measurement of AET is difficult, time consuming, and costly because AET is related to a number of factors that may vary both spatially and/or temporally, including changes in leaf area, plant height, crop characteristics, rate of crop development, degree of canopy cover, canopy resistance, soil and climate conditions and management practices [4].

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A practical approach to this problem is to compute AET based on the Potential EvapoTranspiration (PET), which can be estimated using an appropriate method with available climate data as inputs. PET is generally defined as the amount of water that could evaporate and transpire from a vegetated landscape with no restrictions other than the atmospheric demand ([5], [6], [7]). In other words PET also defined as, the amount of water that could be evaporated and transpired if there was sufficient water available. PET is a representation of the environmental demand for evapotranspiration and represents the evapotranspiration rate of as short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile. It is a reflection of the energy available to evaporate water, and of the wind available to transport the water vapour from the ground up into the lower atmosphere. Evapotranspiration is said to be equal to Potential Evapotranspiration when there is ample water. PET is higher in the summer, on less cloudy days, and closer to the equator, because of the higher levels of solar radiation that provides the energy for evaporation. PET is also higher on windy days because the evaporated moisture can be quickly moved from the ground of plants, allowing more evaporation to fill its place. PET is usually measured indirectly, from other climatic factors, but also depends on the surface type, such free water (for lakes and oceans), the soil type for bare soil, and the vegetation.

Three methods were incorporated in the SWAT model to estimate PET: Penman-Monteith (PenM), Hargreaves (HarG) and Priestly-Taylor (PreT). The PenM method has been considered as a universal standard to estimate PET [8]. However, it requires five daily weather parameters that influence evaporation, solar radiation, minimum and maximum air temperature, relative humidity and wind speed. The other methods (HarG and PreT) can also provide acceptable results [9]. In numerous Mediterranean river basins, continuous data rae available for stream flow, but no for all climatic data [10]. However, daily weather data are not always available. In such cases, SWAT estimates missing data with a weather generator, WXGEN[11], which uses monthly statistics to fill the missing data in measured records. WXGEN first independently generates daily precipitation. maximum and minimum temperature, solar radiation and relative humidity are then generated based on presence or absence of rainy days. Wind speed is generated independently. Further, it was sometimes claimed that PenM is the most adequate in estimating daily PET [12]. Thus, it is important to assess the accuracy of these methods for estimating PET using weather parameters generated by WXGEN. The objective of this study is to estimate and evaluate 3 water-balance parameters (Fig.1) of ET, PET and Runoff using 3 evaporation methods embedded in ArcSWAT model of version SWAT2012 was used.

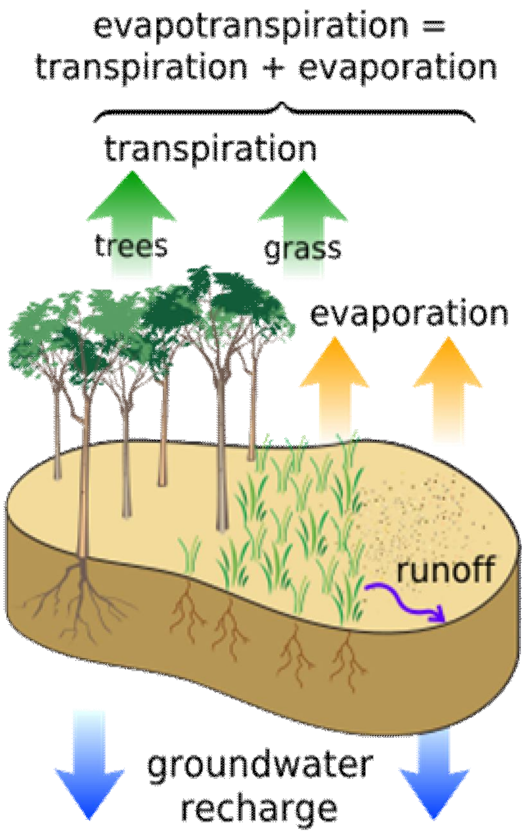

Fig.1 Schematic representation of water balance parameters

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II. MATERIALS USED & METHODOLOGY APPLIED

A. Study Area

A small watershed named as 'BHAMA' which is the name of river, is selected to carry out this study and it is a rural watershed draining 392 km^2, with elevation varies from 410-715 m above mean sea level. The upstream portion of the 'Bhama' catchment contains several mountains. Surface water stired in the 'Bhama Askhed Dam' is used for both drinking and irrigation. The main river is Bhama river flowing to meet Bhima river. The Bhama river flowing a length of 70 km from its originate point to the outlet point of watershed. Bhama river flows in between Andhra river on its right and its left Indrayani river flowing to meet 'Bhima river', which is a confluence point of these three rivers. The mean annual precipitation of 12m mm and Mean monthly temperature ranged from 25^{o}c in August to 8^{o}C in January. Upstream of the 'Bhama Askhed Dam' the hydrological regime of the main channel has continuous stream flow in wet periods and low flow in dry periods.

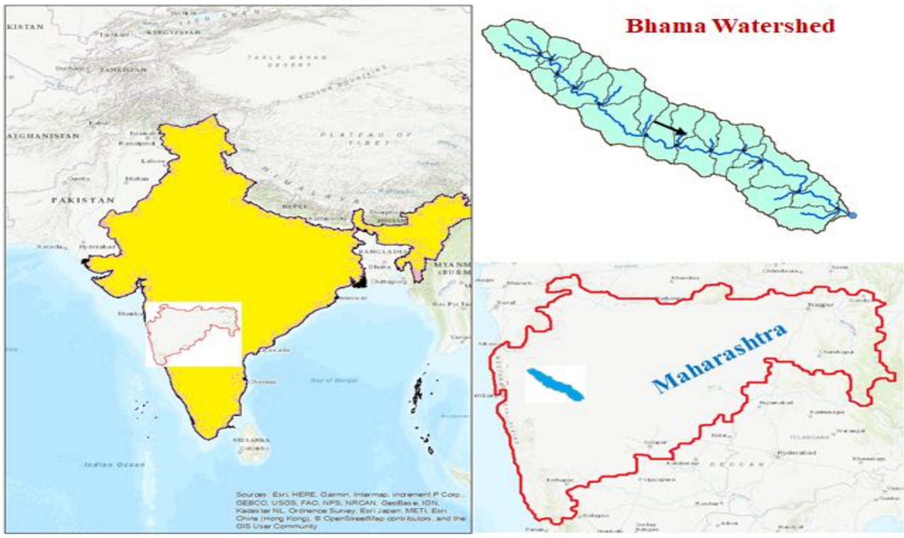

Fig 2 Location Map of 'Bhama' Watershed

B. Input Data

The input data used for simulation of ArcSWAT model divided into two basic categories of (i) Spatial Data and (ii) Non-spatial data. In spatial data category, the basic input data of Digital Elevation Model (DEM), which was downloaded from SRTM web portal of 90 m spatial resolution. The land use land cover (Lu/Lc) map of 2016 was downloaded from Bhuvan web site of NRSC-ISRO. The other important spatial data of soil map downloaded from FAO-USGS web portal. Non-spatial data of weather data could be obtained from NASA-POWER web portal. This weather data includes daily precipitation, Minimum-Maximum air temperature, Net Solar Radiation, Relative humidity and Wind speed. The spatial data and the derived catchment are shown in Fig.3

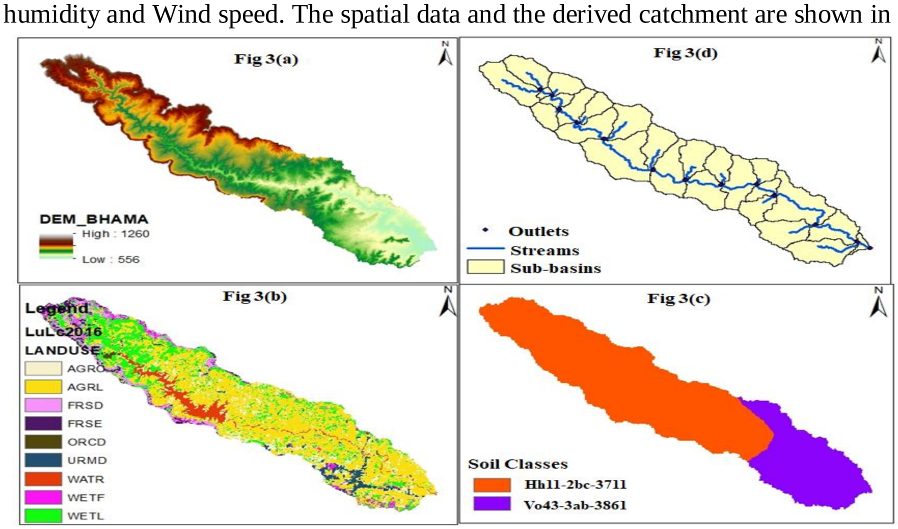

Fig 3 Input layers of SWAT model (3a) DEM (3b) LuLc (3c) Soil Map (3d) Sub-basin delineation

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C. Soil And Water Assessment Tool (SWAT)

ArcSWAT model is a plug-in software to ArcGIS which is designed as a physically based hydrological model available free of cost and widely used across the world. It was developed to evaluate the impact of land management practices on water, sediment and agricultural chemical yields in large complex catchments [13].

To account for spatial heterogeneity, the 'Bhama' catchment was first divided into 25 sub-basins based on digital elevation model (DEM). Sub-basins were then divided into number of hydrologic response units (HRUs), which are unique combination of soil and landuse characteristics. Hydrological processes in SWAT are simulated in each HRU. Model components include weather, hydrology, erosion/sedimentation, plant growth, nutrients, pesticides, agricultural management, channel routing, and pond/reservoir routing **[11].**

SWAT model predicts evaporation from soil and plants separately and uses PET to estimate actual ET. PET represents the amount of water that can be evaporated and transpired if soil water is unlimited. Potential soil water evaporation is estimated as a function of PET and leaf area index.

Actual soil evaporation is estimated using exponential functions of soil depth and water content. Plant transpiration is estimated as linear function of PET, leaf area index and root depth and can be limited by soil water content **[9]**.

Basic spatial data required to SWAT model are a Digital Elevation Model (DEM), a Land-use/Land Cover (Lu/Lc) map, a soil map including soil profile properties and agricultural practices. It also requires daily rainfall and weather information, which are not always available, have low quality or have many missing values.

In this study 35 years from 1985 to 2019, of daily rainfall, minimum-maximum temperature, net solar radiation, relative humidity and Wind speed data were collected and the SWAT model simulation used for estimation of ET, PET and Surface Runoff using 3 different evapotranspiration methods embedded in SWAT model. In case lack in observation data, SWAT includes a stochastic weather generator model WXGEN.

Three methods for estimating potential ET are integrated in SWAT model: HarG (Hargreaves and Samani, 1985 [14]), PreT (Priestley and Taylor, 1972 [15]) and PenM (Monteith, 1965 [16]). Arnold et al. showed that HarG or PreT methods provide options that give realistic results in most cases.

D. Penman-Monteith Method (PenM)

Penman-Monteith approach was recommended by the United Nation Food and Agriculture Organization (FAO) and is widely used over the globe. The penman-Monteith technique is generally considered as the best method for the estimation of reference evapotranspiration in all climatic conditions.

In view of this FAO56-PenM method often recommended as a standard procedure for accurate estimation of reference ET where there is no measured lysimeter data on reference evapotranspiration. The PenM (eqn.1) combines components that account for the energy needed to sustain evaporation, the strength of the mechanism required to remove water vapour and aerodynamic and surface resistance terms:

$$\lambda E = \frac{\Delta.(H_{net} - G)\rho_{air}.c_p.[e_z^o - e_z]/r_a}{\Delta + \gamma.(1 + r_c/r_a)}$$ ....eqn.(1)

where λ is the latent heat flux density (MJ/m2/d), E is the depth rate evaporation (mm/d), Δ is the slope of the saturation vapour pressure-temperature curve, de/dT (kpa/oC), H_{net} is the net radiation (Mj/m^2/d) G is the heat flux density to the ground (Mj/m^2/d), ρ_{air} is the air density (kg/m^3), Cp is the specific heat at constant pressure (MJ/kg/^{o}C), e_z^0 is the saturation vapour pressure of air at height z (kpa), e_z is the water vapour pressure of air at height z (kpa), γ is the psychometric constant (kpa/^{o}C), γ_c is the plant canopy resistance (s/m), and γ_a is the diffusion resistance of the air layer (aerodynamic resistance) (s/m). For well-water plants under neutral atmospheric stability and assuming logarithmic wind profiles, the PenM equation (2) may be written as **[7]:**

$$\lambda E_t = \frac{\Delta.(H_{net} - G) + \gamma.K_1.(0.662.\lambda.\rho_{air}/p).(e_z^0 - e_z)/r_a}{\Delta + \gamma.(1 + r_c/r_a)}$$ ....eqn.(2)

where λ is the latent heat of vaporization (MJ/kg), E_t is the maximum transpiration rate (mm/d), K_1 is a dimensionless coefficient needed to ensure the two terms in the numerator have the same units, and p is the atmospheric pressure (kpa).

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E. Hargreaves method (HarG)

The HarG method estimates PET using only maximum and minimum temperatures. Several improvements were made to the original equation, and the form used in SWAT was published in 1985 by the eqn.(3). In this method Hargreaves analyzed eight years of grass evapotranspiration data from a lysimeter kept in Davis, California using expressions for 5-day time step and found that 94% of the variance in measured ET could be explained by average temperature and radiation. Hargreaves published this result and expressing ET as a function of the two atmospheric variables:

$$\lambda E_o = 0.0023.\ H_o.\ (T_{mx} - T_{mn})^{0.5}\ .\ (T_{av} + 17.8)\ldots\ldots\ldots\ldots\ldots\ldots\text{eqn.(3)}$$

where E_o is the PET (mm/d), Ho is the extra-terrestrial radiation ($MJ/m^2/d^1$), T_{mx} is the maximum air temperature for given day (^oC), Tmn is the maximum air temperature for given day (^oC), and T_{av} is the mean air temperature for a given day (^oC).

F. Priestly-Taylor method (PreT)

Priestley and Taylor (1972) [15] developed a simplified version of the combination Eq. (4) for use when surface area are wet. The aerodynamic component was removed and the energy component was multiplied by a coefficient, α_{pet} – 1.28, when the general surroundings are wet or under humid conditions. This method requiring only radiation and temperature for the estimation of evapotranspiration. The idea for this simple equation is based on the fact that the radiation is the major source of energy and hence a potential factor compared with other factors (wind speed, relative humidity etc.) for the estimation of ET. Priestley found that about two-third radiation component contributes to the evolution of ET. Hence, it was proposed that estimation of ET can be done using radiation component as defined below:

$$\lambda E_0 = \alpha_{pet}\ .\ \frac{\Delta}{\Delta+\gamma}\ .\ (H_{net} - G)\ldots\ldots\ldots\ldots\ldots\text{eqn. (4)}$$

where E_0 is PET (mm/d).

III. SWAT MODEL APPLICATION - RESULTS AND DISCUSSIONS

The SWAT model used spatial data of DEM, Lu/Lc, and soil map along with non-spatial data of rainfall, temperature, relative humidity, wind speed. ArcSWAT model was applied to predict on a monthly time step runoff, PET and ET using the three ET methods integrated in SWAT model (PenM, HarG, and PreT) for estimating and evaluation of water-balance parameters.

1) PET Evaluation: The SWAT model applied using 3 methods of PenM, HarG, and PreT. The results of PET were in the form of graph and shown in Fig.4. The 3 methods of PenM, HarG, and PreT are followed the same trend for the first two months of Jan and Feb. The PenM method shows higher values from mid March to mid of October than other two methods of HarG and PreT. HarG method of potential Evapotranspiration shows higher values from beginning of the month Jan, Feb, mid-March and at the end of the year of Oct, Nov, and December months. The PreT method of PET estimation indicates lower values throughout the year when compare to other two methods of PenM & HarG. The results indicate that PET was higher during cold season from HarG method and PenM method depicts higher values during wet season and PreT method predicts lower value of PET during entire season of the year than other two methods of HarG and PenM methods.

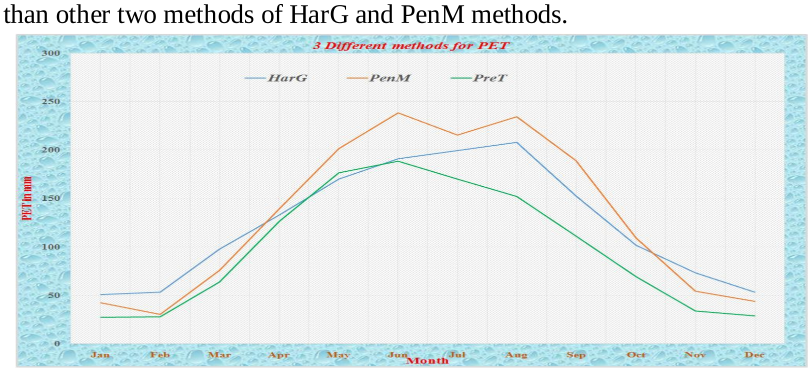

Fig. 4 PET estimation from 3 different methods of PenM, HarG & PreT

From Jan. to May there is a little variation of PET between these 3 methods. The variation of PET is higher from the month of June to September and variation shows decreasing trend from Sept. to December. The main variation of PET takes place between HarG and PenM methods throughout the year. PreT method predicts lowest values throughout year than other two methods of HarG & PenM.

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2) *ET Evaluation:* The figure reveals that the HarG method obtained higher ET during cold weather from Jan to mid-March and from Sept. to Dec. The ET during summer periods from April to mid-June PenM method shows higher ET and remaining months shows lower than HarG method. PreT method shows lower ET for 8 months of non-monsoon months of Jan-April and post monsoon months of Aug, Sept. also winter months of Oct. Nov. and Dec. The results of all these three methods of ET estimation as shown in Fig.3. PreT method predicts lowest value of ET throughout the year than other 2 methods of HarG and PenM. HarG method predominates in the first 3 months of cold season and in the last 3 months of same weather. PenM method dominates in hot atmosphere and diminish during rainy season. The rise and fall of ET values in all the 3 methods follows the similar trend lines from Jan to Dec.

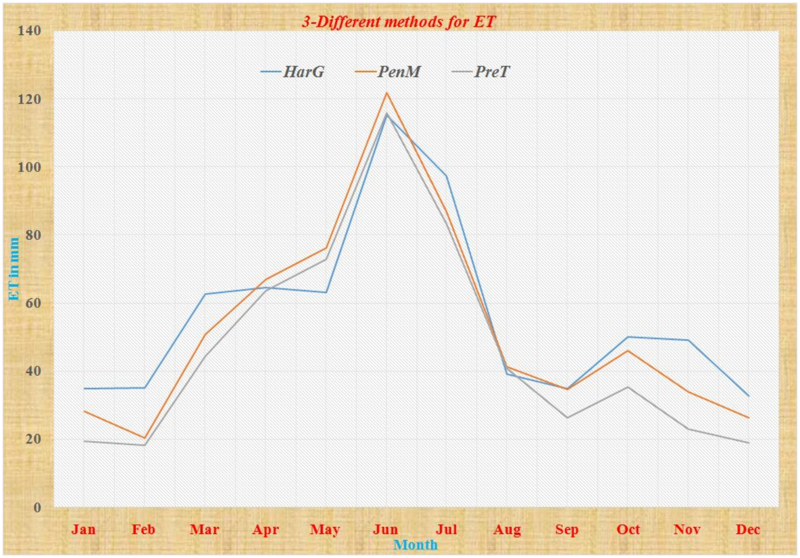

Fig. 5 ET estimation from 3 different methods of PenM, HarG & PreT

3) *Runoff Evaluation:* PreT method predicts higher Runoff than other two methods throughout the year. The trend shows that, in the first 3 months of dry period depicts higher Runoff and in winter season of last two months of Nov and Dec. depicts higher Runoff. The Runoff values shows sudden fallen trend from March to April and maintain lower runoff from April to September. The runoff prediction shows a rising trend from the month of Sept. to Nov. The Fig. 4 shows that HarG method predicts least runoff than other 2 methods from Jan to April and from mid Oct. to Dec. HarG method shows runoff prediction very close to PenM method.

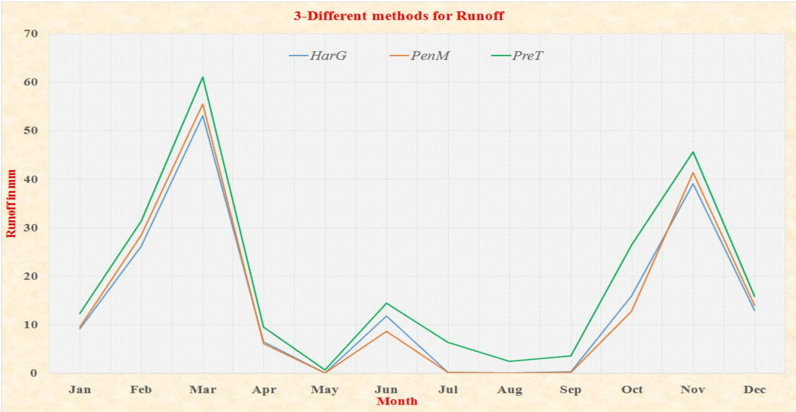

Fig. 6 Runoff estimation from 3 different methods of PenM, HarG & PreT

PreT method reveals that the surface runoff will be high during cold weather and fallen during hot weather. The similar atmospheric conditions followed by other 2 methods of PreT and HarG in prediction of runoff event. The most common observation is that, these 3 methods follows similar trend line for all the months from Jan to Dec. The other observation is that, in all seasons the 3 methods predicts the similar quantity of water balance parameters of ET, PET and Runoff.

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IV. CONCLUSIONS

This research paper intended to estimate and compare different water-balance parameters of ET, PET and Runoff using different ET methods of PenM, HarG and PreT. As a matter of fact, that 'Bhama' catchment was selected to apply these methods using Remote Sensing data and GIS based ArcSWAT model. The SWAT model simulation successful and The conclusions are listed in the following paragraphs

A. During cold periods of Jan, Feb and March, PET showing in increasing trend and it shows a decreasing trend during non-monsoon and post monsoon months from Aug. to Dec. using all the 3 methods of HarG, PenM and PreT. The peak and highest PET showing during June, July months in all method.

B. The peak ET obtained in the month of June for all the three methods. The continues increasing trend of ET exhibits from Feb to June. Interestingly, the decrease of ET starts after June and it continues to till the month of Dec. for all the 3 methods of PenM, HarG and PreT. There is a little increasing of ET starts after September month till October and later decreasing ET for next 3 months of Oct, Nov. and Dec. All the 3 methods not showing continue domination of ET throughout the year. These 3 different methods depict highest ET in different methods during entire year.

C. PreT method of estimation of ET depicts higher runoff among all other 2 methods of HarG & PenM. Prestly-Tylor method predicts higher Runoff throughout the year, even there are some variations in different methods. During Jan, Feb, and March the runoff increases and peak obtained in March. Again increased runoff from Sept. to Nov. and peak shown in the month of Nov. The decrease in runoff in dry period of March, April & May, also during Nov. to Dec. Months. In this study 3 methods used for estimation of PET, ET and RO. Different methods depicts shown variations in high and low values. The PreT method only predicts higher runoff throughout the year than other 2 methods.

It is concluded that the PET and ET rate is high in summer season for all the 3methods used for estimation, because soil water content evaporated more in the summer season. Henceforth, land should cover with crops or instead of keeping open land afforestation should be done. Crop cover or plantation cover reduce the evapotranspiration rate and maintain the water content in the soil. Reducing the ET will increase the water balance of the study area. This study reveals that PenM method predicts higher ET, due to consideration of all the Hydro-meteorological parameters of Rainfall, Temperature, solar radiation, relative humidity and wind speed. Runoff prediction from PreT method obtained higher values, and HarG & PenM methods attributed a very little difference between these two methods.

Penman-Monteith method predominates in estimation of PET, Hargreaves method for ET and Priestley-Tylor method for Runoff.

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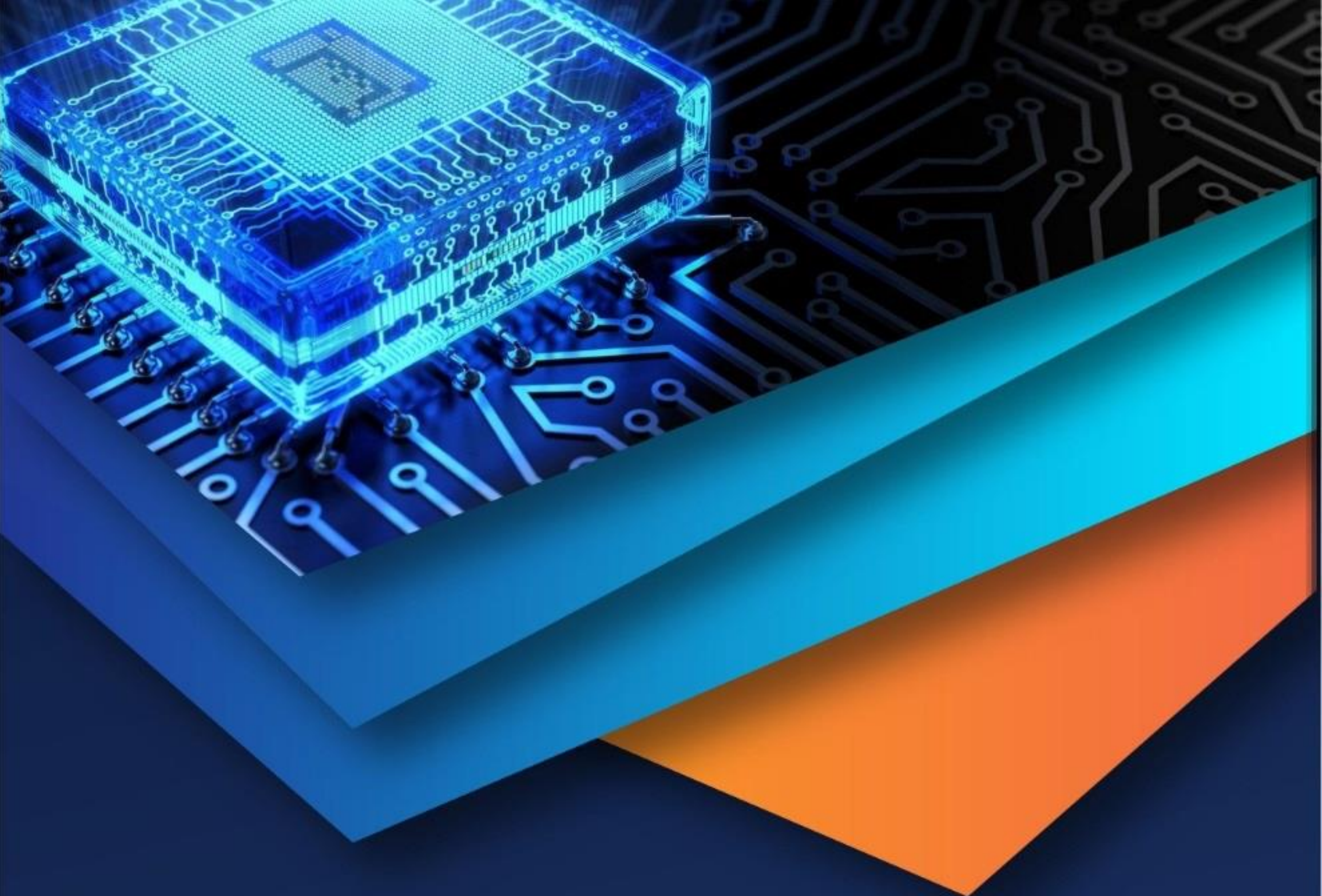

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