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Comparative assessment of evapotranspiration in Bhima sub-basin using spatial analysis for normal and ENSO years

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ABSTRACT

Evapotranspiration (ET) estimation is important for hydrological modelling and water management for irrigation. The present study estimates the reference evapotranspiration using FAO Penman-Monteith (FAO P-M) method and SWAT hydrological model, and its spatial variation during ENSO events during 1996 to 2013. The spatial variation of crop coefficient and actual evapotranspiration (ET_a) is also analyzed. The results from these methods are compared for various El Niño-Southern Oscillation (ENSO) events and normal years. MODIS NDVI data was used to generate crop coefficients which were further used for generation of ET_a.The results show that the ET_0 estimated using FAO P-M is less during the pre-monsoon period than ET_0 estimated using SWAT model. ET_0values from FAO P-M show decreasing trends while those by SWAT show increasing trends. Also, ET_0 shows higher values during post monsoon period of El Niño years as compared to La Niña and normal years.

Keywords: Evapotranspiration, SWAT, ENSO, NDVI

The available ground water and surface water resources are overexploited and reaching the limit of ecologic sustainability. Evapotranspiration is combination of two different processes; evaporation on the ground surface and transpiration in the plants and vegetation, leads to considerable loss of water resources (Thornthwaite and Mather, 1957). Accurate ET estimates are essential to improve the distribution of water resources, to categorize the time variations on irrigation needs, and to evaluate the influence of the use of the land and changes in the water balance (Shrestha and Shrestha, 2017).

Rainfall is the major source of water in India for agriculture (CWC and NRSC, 2014). Hence, reliable and consistent estimate of ET is necessary not only for environmental sustainability and biodiversity, but also in the context of agriculture. Estimation of ET is difficult particularly over complex terrains not easily approachable for measurements (Abiodun *et al.,* 2018). To overcome this problem, various methods are adopted for the calculation of the reference evapotranspiration (ET_0) by using climatological data, such as maximum and minimum temperature, solar radiations, wind speed and relative humidity.

There are various methods and equations used to calculate the reference ET_0 depending upon the availability of climatological data, such as Food and Agricultural Organization (FAO) Penman-Monteith equation (Penman, 1948; Monteith, 1965), Thornthwaite equation (Thornthwaite and Mather, 1957), Hargreaves equation (Hargreaves and Allen, 2003), Hamon equation (Hamon, 1961). FAO Penman-Monteith method is preferred as the standard and accurate method for daily ET_0 estimation however, this method has stringent requirement of collecting correct quality climatological data from field. To overcome this limitation, in recent studies, remote sensing and GIS techniques are used for quantification of ET in more accurate and easy way. Crop coefficient (K_C) is the factor which is used to calculate ET_a with the help of ET_0. Increase in K_C caused by higher temperature results in decrease in soil water and decline in NDVI, while dense vegetation induces more ET and lowers the land surface temperature (Kumar *et al*., 2013).

In this study, FAO Penman-Monteith method and SWAT model (Arnold *et al*., 1994) were used for the ET_0 estimation. Penman-Monteith method utilizes only meteorological parameters such as temperature, wind speed, solar radiation and humidity (Zotarelli *et al*.,2015) while SWAT utilizes weather parameters along with the soil data, land use land cover data and slope information. But, FAO P-M method generates results for observation points where the meteorological data is collected while the SWAT method generates only one value of ET_0 for whole watershed. K_C values are generated throughout the watershed using the NDVI. Then K_C values have been used for generation of ET_a.

The major objectives of the study hence are to estimate the ET_0 for Bhima sub-basin using Penman-Monteith method and SWAT hydrologic model; record spatial variation of ET_0 for different phases of ENSO events; estimate spatial variation of K_C and ET_a.

MATERIALS AND METHODS

Study area

The Bhima River is one of the major tributaries of the Krishna River.The study area lies between latitude 17.18 N to 19.24 N and longitude 73.20 E to 76.15 E (DRAFT report, Upper Bhima sub-basin). Location map of the study area is as shown in Fig.1.The major meteorological parameters used in the study are temperature, humidity, wind speed, and sunshine hours and solar radiations. It was observed that the minimum temperature observed was 5°C and maximum temperature was 46°C during 2002 to 2013.

Data description

The map of the study area (Fig.1) has been generated from the Water Resources Information System (WRIS) of India. The Digital Elevation Model (DEM) of the study area is used for the watershed delineation in the ArcSWAT software. The Shuttle Radar Topography Mission (SRTM) DEM with 30 m spatial resolution is used for the analysis (Fig.1) with highest elevation of 1472 m and lowest elevation of 160 m in the Eastern part of the basin.

The soil data with 10 km spatial resolution from SWAT database along with soil properties *viz.* particle size distribution, bulk density, organic carbon content and available water capacity were obtained using Reynolds *et al.* (1999) by Schuol and Abbaspour (2007). Land use map is an important input for SWAT Model. It affects the generation of run-off, soil water storage, water demand for irrigation, etc. Land use map is available on the SWAT dataset of India. The Western Ghat zone the west part of study area covered with thick forest, receives heavy rainfall (maximum of 4500 $mmyear^{-1}$), while the central part of the Upper Bhima receives the lowest rainfall less than 500 $mmyear^{-1}$(Garg *et al.*, 2012). SWAT requires daily data of precipitation, maximum and minimum temperature, solar radiation, wind speed and relative humidity. In this analysis, weather data from year 2000 to 2013 for 38 weather stations were used for the calculation of ET_0.

This study includes analysis and comparison of ET losses in the atmosphere with the help of Penman-Monteith method and SWAT Hydrological model. There are many methods adopted for the estimation of ET_0. In the SWAT Hydrological model, various datasets such as DEM, soil data, land use land cover data, weather data, etc. are required as input of the model. SWAT is the model interface with the ArcGIS software. The flow chart of the overall methodology has been shown in Fig.2.

FAO Penman-Monteith method

The FAO Penman-Monteith equation which is used in the present study is one of the standard methods of estimation of ET_0. It is a close, simple representation of the physical and physiological factors governing the evapotranspiration process. In Penman-Monteith method, there are 19 different sub-steps included in the calculation of different parameters in the Penman-Monteith equation (Zotarelli*et al.*,2015). The equation is;

$$ET_0 = \frac{0.408\Delta(R_N - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1+0.34u_2)} \quad (1)$$

Where, ET_0 is reference evapotranspiration [$mmday^{-1}$]; R_N is net radiation at the crop surface [$MJ/m^2/day$]; G is soil heat flux density [$MJm^{-2}day^{-1}$]; T is mean daily air temperature at 2 m height [°C]; u_2 is wind speed at 2 m height [ms^{-1}]; e_s is saturation vapour pressure [kPa]; e_a is actual vapour pressure [kPa]; e_s-e_a is saturation vapour pressure deficit [kPa]; Δ is slope vapour pressure curve [kPa/°C] and γ is psychrometric constant [kPa/°C].

Spatial distribution maps of ET_0 calculated using the FAO Penman-Monteith equation is used for generating spatial distribution maps of the ET_a based on the relationship between K_C and ET_0, i.e. $K_C = ET_a / ET_0$.

SWAT Hydrological model

SWAT is a basin-scale, continuous time, hydrologic distributed model that uses spatially distributed data on soil, land use, DEM, and weather data for hydrologic modeling and operates on a daily time step (Narasimhan and Srinivasan, 2001). SWAT is able to predict the impact of land management practices on soil, waterand crop growth. The main output components of the SWAT model consist of weather, hydrology, plant growth, nutrient, pesticide, bacteria and land management (Arnold *et al.*, 1994).

For understanding and spatially explicit parameterization, watershed was delineated into 37 sub-basins based on topography using an SRTM DEM. The DEM based stream definition is carried out in the watershed delineation. The area of the watershed is approximately

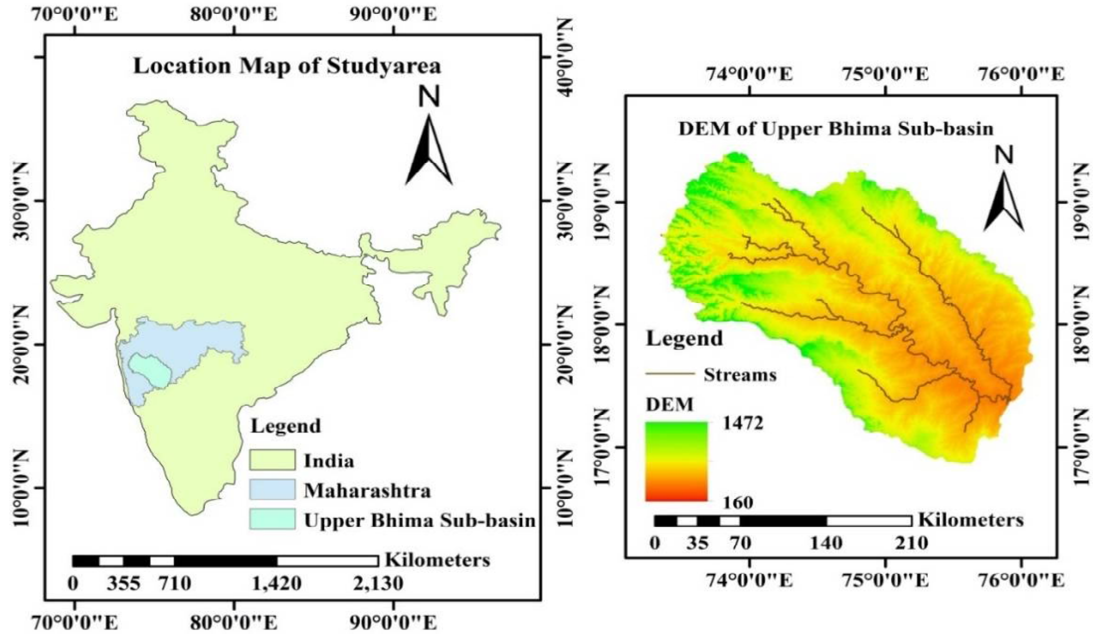

Fig.1: Location map and DEM of the Upper Bhima sub-basin

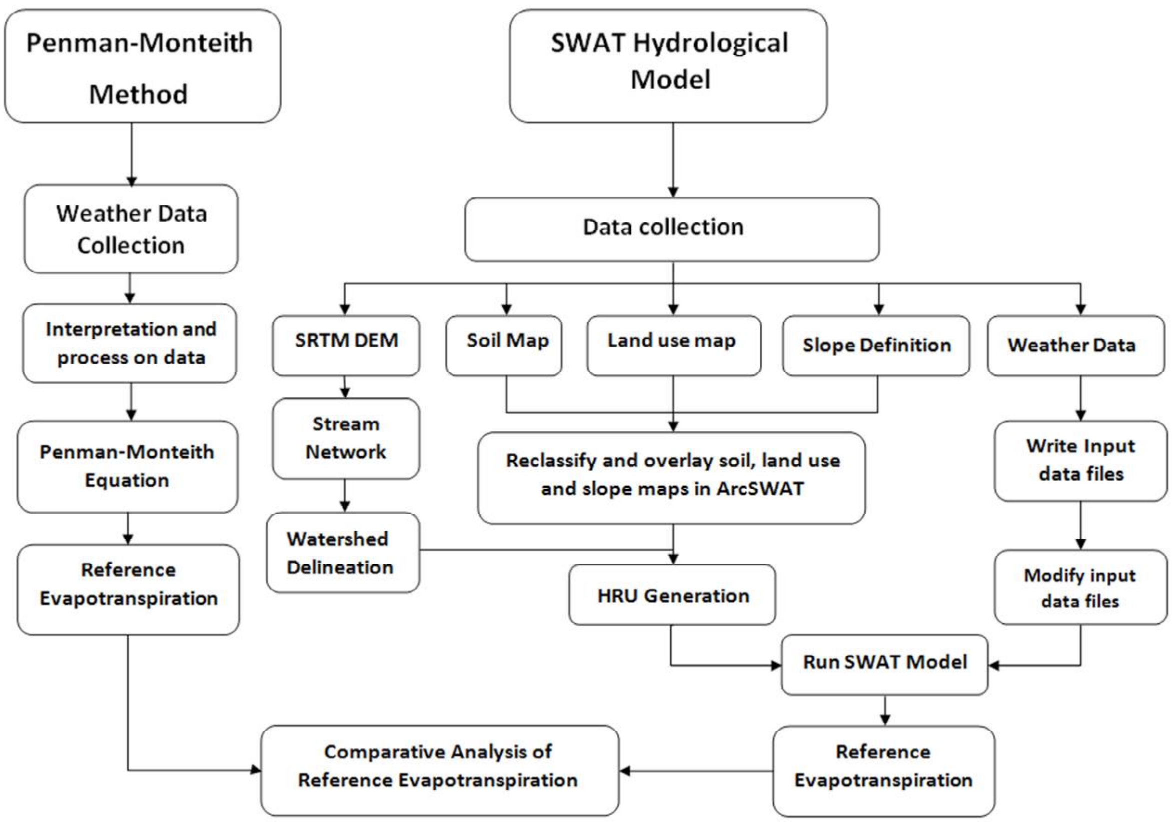

Fig.2: Overall methodology adopted for the analysis

46,066 km^2. The delineated watershed is further subdivided into Hydrological Response Units (HRUs) based on unique soil, land use and slope characteristics combinations. SWAT computes evaporation from soils and plants separately.

The water balance is calculated using the following Eq.

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - ET_a - W_{seep} - Q_{gw}) \quad (2)$$

Where, SW_t is the soil water content; SW_0 is the initial soil water content; R_{day} is the amount of precipitation; Q_{surf} is the surface runoff; ET_a is the evapotranspiration; W_{seep} is the soil infiltration and Q_{gw} is the return flow.

Spatial interpolation and map algebra

Inverse Distance Weighted (IDW) method which works best for dense, evenly-spaced sample points is used for spatial interpolation of ET_0 using data at 38 weather stations in the study area. K_C maps were generated by using the NDVI maps. NDVI based K_C is one of the best suitable method since there is a linear relation between NDVI and K_C (Kamble *et al.*, 2013; Chengote and Katpatal, 2016). The difficulty of collecting K_C data from the field is overcome by using this method. The K_C varies in space and time, land use pattern, type and stages of crops, precipitation variation, emissivity, vegetation amount and atmospheric boundary conditions, such as air temperature, wind speed and vapour pressure deficit. The linear relation between NDVI and K_C was given by Kamble *et al.* (2013) as equation

$$K_{CNDVI} = 1.457NDVI - 0.1725 \quad (3)$$

Where, K_{CNDVI} is the NDVI based K_C; NDVI is Normalized Difference Vegetation Index (-1 to +1). This equation is carried out by the tool Map Algebra in ArcGIS for the generation of K_C.

RESULTS AND DISCUSSION

The study is carried for the period from 2000 to 2013. The results discussed in this section are for the representative months and years only. The results obtained from two different methods i.e. the Penman-Monteith method and simulation of the SWAT hydrological model are compared for various ENSO events, i.e. El Niño, La Niña and Normal years.

Monthly variation of actual evapotranspiration for El Niño, La Niña and normal years

The SWAT model was simulated from 1996 to 2013 including first 3 years as warming up period for the model. As ET_a is the parameter which strongly depends on the weather parameters, it is important to discuss variation of ET_a. This variation gives information about the rate of ET_a during the El Niño, La Niña and normal years. Since El Niño is a warm phase of the ENSO event, the values of ET_a in June 2003 and June 2009 is59.473 mm and 41.7989 mm, respectively which is much more than the La Niña years; 22.127 mm inJune 2007 and 30.753 mm in June 2011. Fornormal years (June 2005 and 2012), ET_a values are32.95 mm and22.930 mm,respectively (Fig.4). In general, from the results of the estimated monthly ET_a shown in Fig.4, it is observed that the monthly ET_a increases from relatively low values (June to September) to high values (February to May).

Comparing ET_0 and ET_a in the El Niño, La Niña and Normal years, it is observed that the annual average values of ET_0 and ET_a during El Niño years is maximum, moderate in normal year and minimum in La Niña year as shown in Fig.3. Statistical analysis of ET_a calculated by Penman-Monteith method and SWAT model is carried out to compare the results from both the methods. SWAT model also utilizes PM method but generates only one value of result for whole area under consideration while FAO PM Equation has been used to generate result for each weather station in the study area which highlights the spatial variation. Spearman's rho and Kendall's Tau_b methods have been used for correlation. The correlation coefficients are shown in Table 1. It may be observed that correlation is maximum for normal years and minimum for La Niña years whereas it is moderate for El Niño years. Spearman's rho coefficientfor El Niño years is 0.825, is 0.663 for La Niña years and is 0.867for normal years. Whereas,Kendall's Tau_b coefficient is same for El Niño and Normal years (0.667); and is 0.560 for La Niña years.In the month of June and July, the rate of ET_a variation depends on the starting of the monsoon rainfall. Generally, the monsoon period starts in the month of June, but because of climate change events such as ENSO, it alters the starting date of the rainfall and its intensity during monsoon. As the ENSO affects the temperature and rainfall, it also affects the rate of ET_a.

Spatial distribution of ET_0

ET_0 values calculated for 38 weather stations in the study area by using the Penman-Monteith equationwere interpolatedusing the IDW method. Spatial distribution of ET_0 indicates its variation throughout the sub-basin. As ET_a maps are generated by using ET_0 maps, it is important to generate the spatial distribution of ET_0 maps (Fig.5).

Spatial distribution of NDVI based crop coefficient (K_C)

MODIS NDVI data are collected for the period from year 2000 to 2013. The impact of warm and cold phases of ENSO (El Niño and La Niña) can be distinguished from the vegetation patterns over India if the consequent years of warm and cold phases are considered (Kumar *et al.*, 2013).Variation in the NDVI values hence is based on temperature, precipitation, available moisture, type of the crop or vegetation and growing stage of the vegetation (Rishma and Katpatal, 2016). The change in NDVI would certainly affect the ET_a which is estimated using K_C.It can be easily observed that the K_C is higher in September and

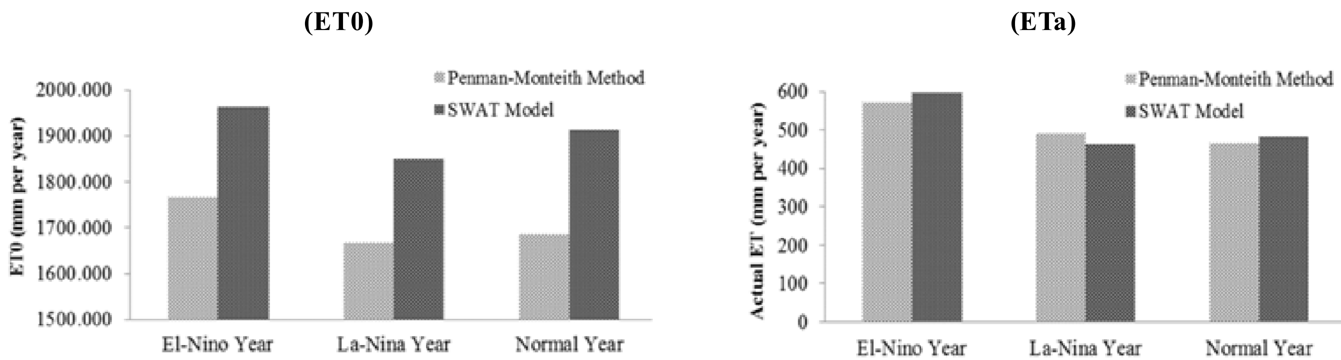

Fig.3: Annual average ET_0 and ET_a variation during the El Niño, La Niña and Normal years

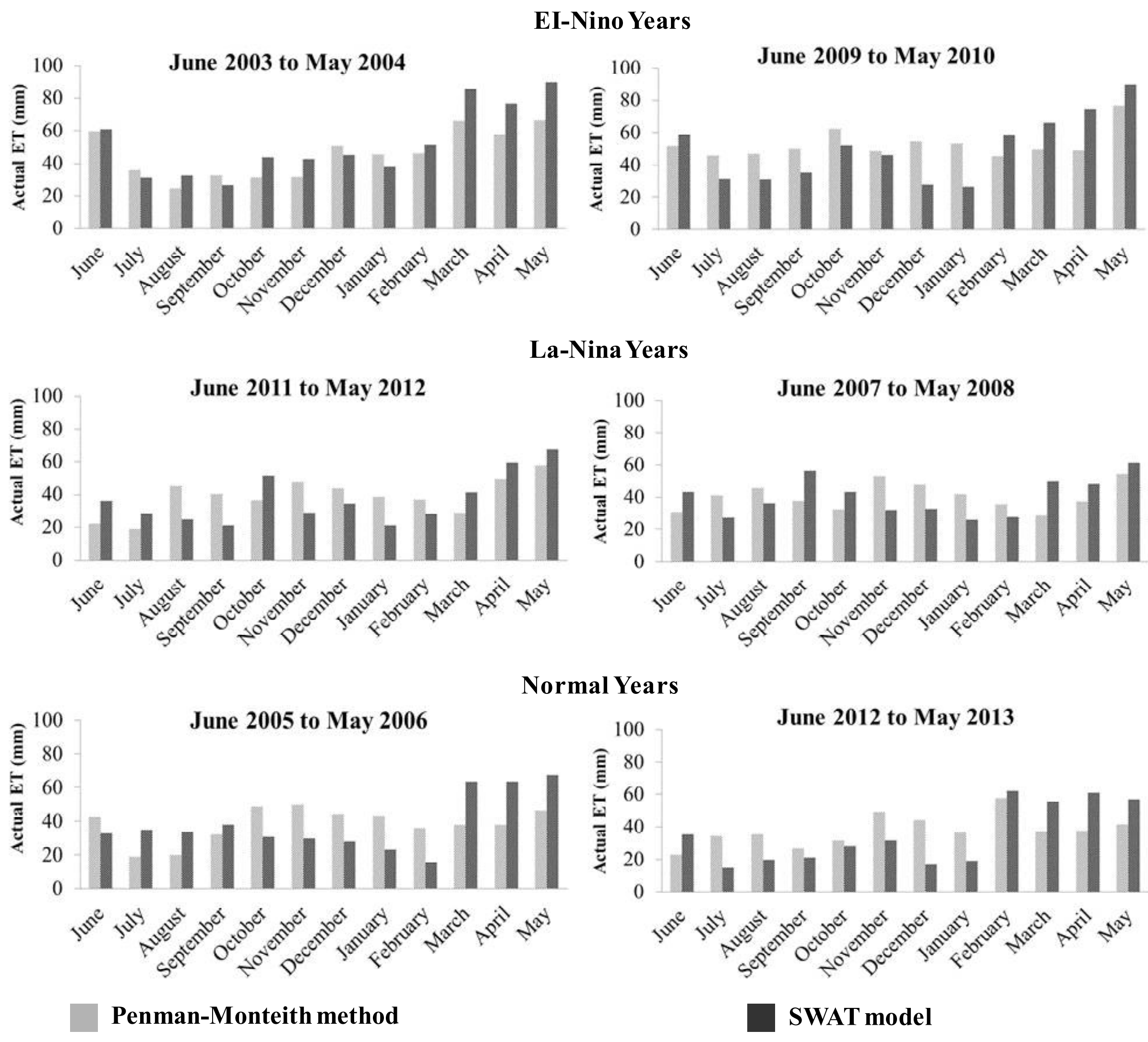

Fig.4: Monthly variation of ET_a for El Niño, La Niña and Normal years

December than in February, May and July. After the monsoon period, there is an increase in the growth of the crops which results in the more K_C values. K_C maps of pre-monsoon, monsoon and post-monsoon period for the 2001, 2002, 2007 and 2013 are shown in Fig.6.

Spatial distribution of Actual ET

The spatial distribution maps of May month show the maximum ET_a; these are nothing but the ET from the water bodies' i.e. Bhima river in the sub-basin. This value ranges from 5.20 mm/day to 8.60 mm/day. Annual average of ET_a

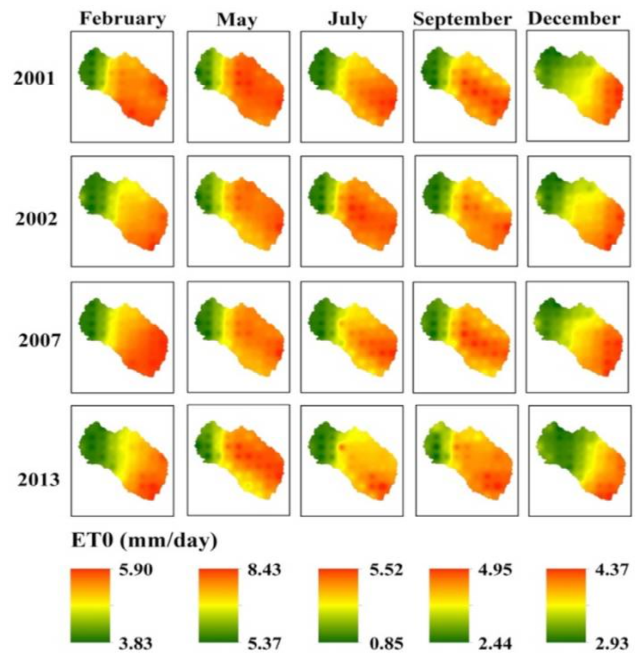

Fig.5: Spatial distribution of ET_0

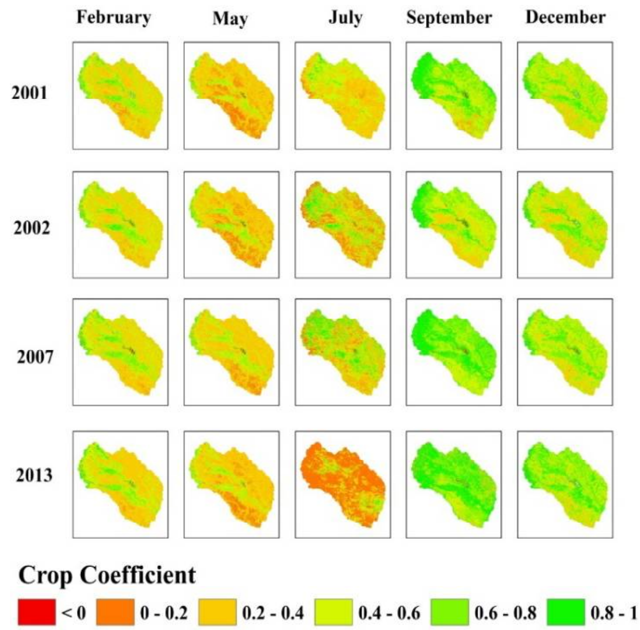

Fig.6: Spatial distribution of crop coefficient

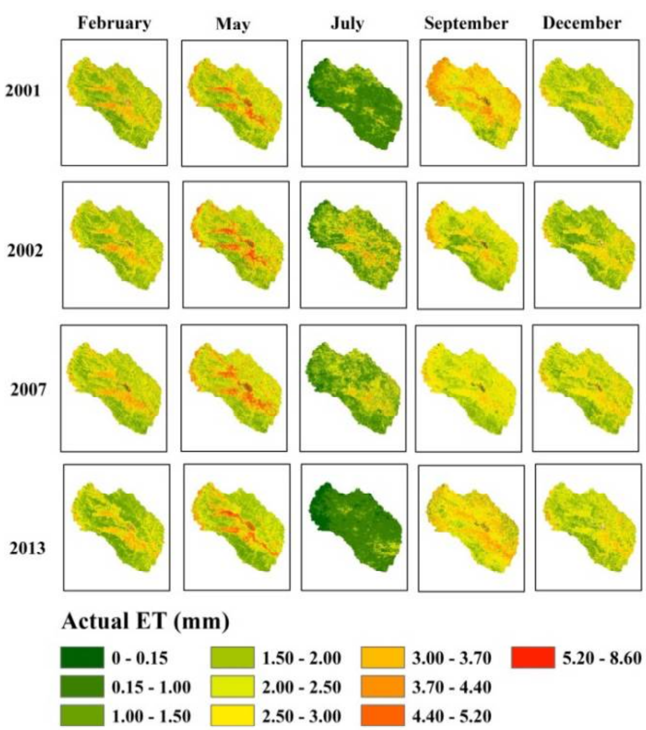

Fig.7: Spatial distribution of actual ET

during Julyis minimum. Almost the whole study area shows minimum value ranging from 0 to 1 mm/day of ET_a (Fig.7). The maximum and minimum ET_a is seen in the month May and July respectively which can be validated in Fig.7. Comparing the ET_0 in the different ENSO years, normal year shows the minimum ET_a as compared to El Niño and La Niña year. In 2002, an El Niño year shows the maximum ET_a than La Niña and normal year. The year 2013 was the major drought year in Maharashtra because of the lowest rainfall in 2012. Due to this, as the available moisture was very less in 2013, the ET_a is also less as compared to other years.

Table1: Summary of statistical analysis between ET_a by Penman-Monteith Method and SWAT Model

	Spearman's rho	Kendall's Tau_b
El Niño Years	0.825	0.667
La Niña Years	0.663	0.560
Normal Years	0.867	0.667

CONCLUSION

In this study, ET_0 estimated using FAO Penman-Monteith method and SWAT model have been analyzed for the period from 2000 to 2013 to evaluate the impact of various ENSO phases on changes in ET_0 patterns across Upper Bhima Sub-Basin. Comparisons between ET_a from Penman-Monteith method and SWAT model indicate the annual magnitude and general outlines in ET_a across the study area. The temporal analysis of monthly ET_a shows that the summer period from February to May contributes up to 65% of annual ET_a, of which ET_a in May accounts for 25%. Results suggest that the El Niño yearshave a greater influence on the ET_0 and ET_a change patternsas compared to those of La Niña and normal years. The spatial distribution of ET_a, estimated from NDVI based K_C and ET_0 gives the actual status of evapotranspiration in the Upper Bhima sub-basin.

This study proposes an appropriate approach for the estimation of ET_a and assesses its spatio-temporal variations at the watershed scale with high spatio-temporal resolution. The analysis of the ET_a for ENSO events such as El Niño, La Niña and normal years provides important knowledge to study its variation at watershed scale. Future research may include the correlation of the different meteorological parameters affecting on the ET_a and its spatio-temporal variations according to the various agro-climatic zones within the study area.

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