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Soil moisture-based approach for estimating actual evapotranspiration

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Abstract
One of the most important words on planet Earth is stated as water. Concerning its availability, requirement, generation, transportation, and losses, the study of water is important. This water can be in various forms as well as losses. The present study concentrates on calculating the actual evapotranspiration from a small piece of land using various basic details like temperature, field capacity, wilting point, and instantaneous soil moisture. The study aimed to understand the dependence of actual evapotranspiration losses on soil moisture. It was found that the AET calculated using the Bergstrom method gives satisfactory results. In support, actual evapotranspiration calculated from soil moisture of hydra probe (ground data) and satellite data both justifies the values to true environmental condition. With lots of future scope for research, the experiment done was found enough satisfactory. This research may help get an idea about actual evapotranspiration from a limited land area with less meteorological data available daily, weekly, monthly, or yearly.

Keywords: Evapotranspiration, actual evapotranspiration, potential evapotranspiration, losses, soil moisture

1. Introduction
Evapotranspiration (ET) reflects the flow of water from the Earth's surface to the atmosphere through soil evaporation and plant transpiration. It is an essential part of the hydrological cycle to understand climate dynamics, agricultural productivity, and water balance [1]. Potential Evapotranspiration (PET) is the highest rate of evapotranspiration that may occur if water were always available, whereas Actual Evapotranspiration (AET) is the actual rate of evapotranspiration that occurs under environmental conditions [2]. Since PET does not identify which land surface it relates to, some ecologists and hydrologists believe that PET can occasionally be a hazy concept [3]. In the past, ETo was estimated indirectly, but despite several efforts by different organizations, consistent and accurate data sets are still difficult to find because of the limited number of meteorological stations [4].

The availability of soil moisture, which has a major influence on water vapour transfer to the atmosphere, is the main factor separating PET from AET [5]. AET is more representative of actual conditions, where evapotranspiration rates are constrained by water availability, whereas PET gives an upper bound on evapotranspiration. Therefore, it is essential to accurately estimate AET in order to comprehend actual water usage, particularly in areas that are susceptible to water stress. Particularly in areas where water scarcity is common, soil moisture is a crucial limiting factor in determining AET [6]. Higher evapotranspiration rates are generally supported by higher soil moisture content, while reduced soil moisture lowers AET even when PET is still high [7]. Therefore, the connection between soil moisture, PET, and AET is essential at understanding and predicting drought conditions, agricultural productivity, and water availability. An upper limit for evapotranspiration is provided by PET assuming unlimited water availability, hence becomes energy-limited and is primarily influenced by meteorological variables like temperature, solar radiation, and wind speed [8, 9]. The availability of moisture in the soil, however, limits the real amount of water lost from the land surface. Hence it is necessary to precisely calculate AET for hydrological and agricultural purposes.

AET has traditionally been estimated using ground-based data, which is usually infrequent and restricted in range. To get beyond these restrictions, satellite-based remote sensing has become a useful technique in recent years. Global coverage and high temporal resolution data on soil moisture content are provided by satellite-derived soil moisture products, including data from the Soil Moisture Active Passive (SMAP) mission and the Soil Moisture and Ocean Salinity (SMOS) project [10]. By integrating soil moisture data into evapotranspiration models, these solutions allow for the global estimation of AET and provide a more thorough and user-friendly approach to tracking actual water usage.

Numerous applications, such as crop yield prediction, drought monitoring, and water resource management, depend on the precise computation of AET. Knowing the actual evapotranspiration is essential for improving irrigation techniques and water management in areas with restricted water supplies. In contrast to conventional ground-based observations, the use of satellite-derived soil moisture for AET estimation raises concerns regarding the accuracy and reliability of satellite-based estimations. Although satellite products offer wide coverage, the intricacy of soil moisture dynamics, sensor constraints, and data processing methods can all lead to discrepancies. In contrast, although ground-based measures of soil moisture are precise, they are spatially constrained and might not adequately account for regional differences in soil moisture [11]. Thus, it is essential to compare AET derived using satellite and ground-based soil moisture data to evaluate the advantages and disadvantages of these two methods in water-scarce contexts.

Accurate AET calculations are especially important in locations with limited water resources and undergoing climate change. Better techniques for calculating AET are necessary for managing water supplies, maximizing irrigation, and evaluating the effects of droughts and climate change. The purpose of this study is to compute AET using both satellite and ground-based soil moisture data, compare the outcomes, and assess the precision and dependability of satellite-based AET predictions. The suggested approach may improve the accuracy of AET estimation and offer more reliable information for drought monitoring, hydrological modeling, and agricultural decision-making.

2. Study Area

The present study includes 3 fields where soil moisture monitoring is done. The selected fields are in different districts: Anand, Hoshangabad, and Varanasi. Anand district is in the southern part of Gujarat, covering about 2951 km^2. About 70% of the area is cultivable. The soil types are clay loam and sandy loam. At the Regional Research Station (a farm on a university campus), Anand Agricultural University hydra probe station is installed. In loam soil, 26% clay and 36% sand were found.

Hoshangabad a district of Madhya Pradesh is located on the northern fringe of Satpura plateau which lies in the central part of Narmada Valley. Except for the southwest monsoon, the region has dry climatic conditions. It is well known for its fertile black alluvial soil, which is known as “black cotton” soil. The soil is highly porous and has a fine clayey texture. The land is mostly covered with forest and agricultural land. The hydra probe station is installed at ZARS (Zonal Agriculture Research Station) in Pawarkheda. It has 76% of sand 14.1% of clay and 9.9% silt in sandy loam soil.

District Varanasi is situated in the Eastern part of UP**.** The Hydra probe stations were set up at Agricultural Research Farm, IAS, BHU with latitude 25° 18'N, longitude 83° 03' E, and altitude of 128.98 meters above the mean sea level. (Srivastava *et al*., 2020) The textural class of soil is found to be Sandy Clay loam with coarse sand at 7.4%, fine sand at 52.23%, Silt at 19.85%, and clay at 20.52%. The bulk density of soil was found to be 1.34 and the field capacity to be 19.56 [12].

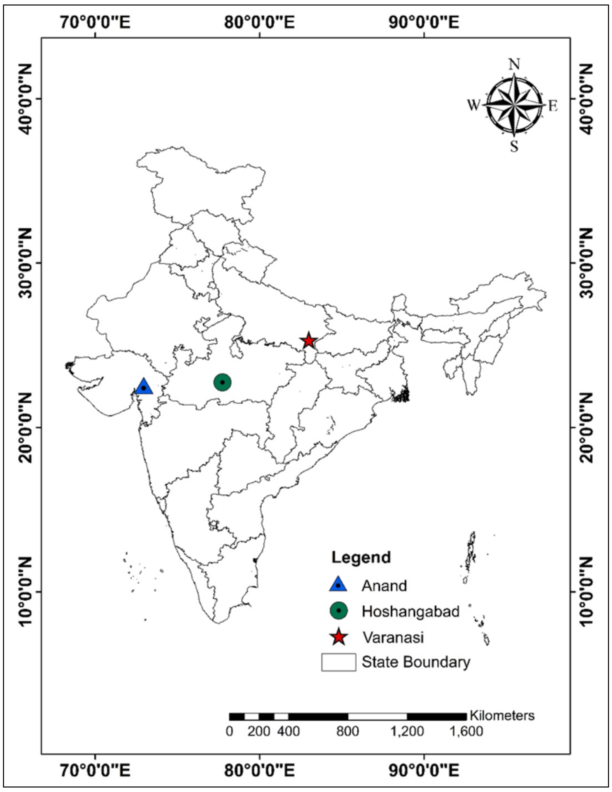

Fig 1: Location map of experimental sites

3. Datasets

3.1 In-situ data

The soil moisture data of the 3 stations (Anand, Hoshangabad, and Varanasi) were observed with a hydra probe. Hydra probe is a rugged type of soil sensor that Dielectric Reflectometry method for soil measurement which makes sensors with this method at high measurement accuracy. Its detailed signal and mathematical characterization of the dielectric spectrum help to figure out the factors causing errors in the soil moisture measurement like the effect of temperature, salinity, and soil type. Electromagnetic signals generated by the oscillator propagate in the unit and soil. The part of the signal that is reflected by the soil gives amplitude to the sensor. It works under temperatures of -10 °C to 55 °C where it can sense soil moisture from fully dry to fully saturated soil with an accuracy of ±0.03 [13, 14]. The proportion of sand, silt, and clay helps to determine the soil type, ultimately leading to field capacity and wilting point information.

3.2 Satellite Data

The NASA (National Aeronautics and Space Administration) launched the Soil Moisture Active Passive (SMAP) satellite mission on 31 Jan, 2015. The observatory aimed for global mapping of high-resolution soil moisture and freeze-thaw states. Soil moisture data was collected every 2 to 3 days using L-band radar (active) and L-band radiometer (passive). However, soil moisture products from the radiometer have been available only since July 7, 2015, due to a failure in the radar hardware. Since March 31, 2015, the mission has provided observations of L-

band (1.4 GHz) passive microwave brightness temperature from an altitude of 685 km, at a resolution of 40 km, in a near-polar sun-synchronous orbit.
These observations affect the land surface water balance and are highly sensitive to temperature and surface soil moisture. Soil moisture is the most critical parameter from which SMAP brightness temperature data is derived. Soil retrieval from SMAP data is carried out using various developed algorithms. The data is distributed globally by the National Snow and Ice Data Centre (NSIDC). The SMAP soil moisture results are measured on a volume basis in cm^3/cm^3. The L band radiometer is utilized due to its low frequency of 1.4 GHz and a longer wavelength of 21 cm, compared to the X and C band radiometers, which exhibit low sensitivity to soil moisture in the presence of even small amounts of vegetation, leading to significant retrieval errors in soil moisture.
The dataset of the satellite was downloaded freely from https://earthdata.nasa.gov/Which has been made available by the NSIDC.

4. Methodology

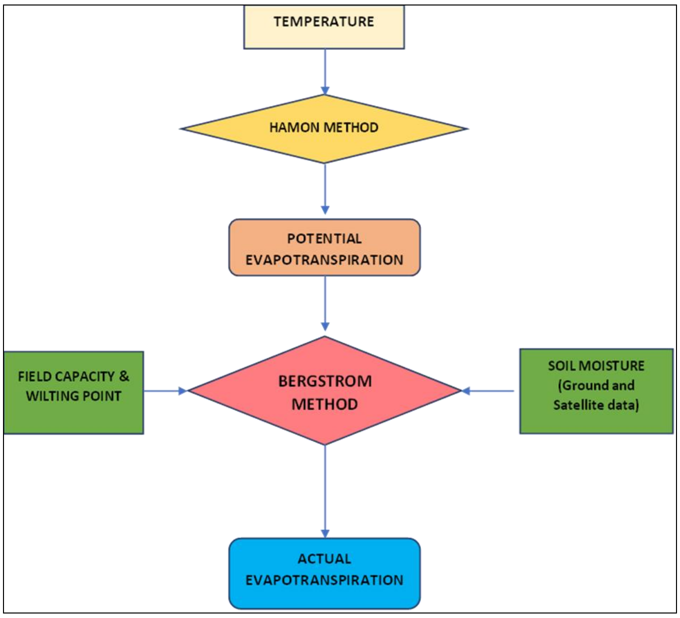

Fig 2: Flow chart of the methodology

4.1 Hamon Method

The Hamon method [15] is a temperature-based method for evapotranspiration calculation. The method uses an empirical relationship between net radiation and temperature. In the Hamon method at mean daily temperature, the potential evapotranspiration is directly proportional to saturated water vapor. Daytime hour adjustments are done according to net radiation, plant response, and duration of turbulence [16,17]. The Hamon equation is given as

$$PET = 0.165 * 216.7 * k * N * \frac{e_s}{T + 273.3}$$

Where,
PET = potential evapotranspiration [mm/day]
k = proportionality coefficient = 1 [unitless]
N = daytime length [x/12 hours]
e_s = saturation vapor pressure [mb]
T = average monthly temperature [°C]

4.2 Bergstrom Method

Bergstrom gave a relation of AET and PET considering their relation with soil moisture. It is easy to calculate PET from available meteorological data rather than calculating AET from a vegetated surface. Moreover, the water loss is not always the same (does not follow potential rates) and depends on the factor of continuous water supply. Also, actual rates are less than potential rates when the vegetation is unable to abstract moisture. Hence, it is stated that the relationship between AET and PET exists with soil moisture [18].
It is supposed that when soil moisture is at field capacity the AET is equal to PET and when soil moisture is lesser than soil moisture at the wilting point AET becomes zero.

AET = PET when $h \geq h_{fc}$

AET = 0 when $h \leq h_{wp}$

For soil moisture between soil moisture at field capacity and soil moisture at wilting following equation is given as

$$AET = PET * \frac{h - h_{wp}}{h_{fc} - h_{wp}}$$

Where,
AET= Actual evapotranspiration [mm/day]
PET= Potential evapotranspiration [mm/day]
h= soil moisture [m]
h_{fc}= soil moisture at field capacity [m]
h_{wp}= soil moisture at wilting point [m]

4.3 Root Mean Square Error

Root mean square error also known as root mean square deviation is frequently used to measure the error magnitude. Because of its predictive power, it is helpful to read the deviation level of the observed and obtained values. Deviation (residuals) is calculated to know the variation within the sample and error is calculated to know about the difference present between the two sets of data. It is a nonnegative value. It could be understood that the lower the value of RMSE, the better the result obtained.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(fi - oi)^2}$$

Where:
n: number of samples
f: forecasts
o: observed values

4.4 Bias

The bias or absolute bias measures the deviation of measured values from actual values. The bias can be either positive or negative. A low magnitude value indicates more accuracy with the optimal value of bias being 0. It is calculated using the following relation.

$$\text{Bias} = (\bar{y} - \bar{x}) \ldots [5]$$

Where,

$\bar{x}$ = is the mean of ground-based measurements

$\bar{y}$ = is the mean of estimated measurements.

4.5 Correlation

Correlation is a statistical parameter that measures the degree of the relation between two variables. It mentions the association, and how the values are related to each other. It is expressed numerically with the help of a coefficient. The correlation coefficient ranges from 1 to -1. 1 shows the perfect positive correlation between variables i.e., these variables move in the same direction. Whereas for -1 perfect negative correlation is seen where variables move in opposite direction. Here zero value of the correlation coefficient implies no linear relationship between variables.

$$r = \frac{\sum (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum (X_i - \bar{X})^2 \sum (Y_i - \bar{Y})^2}}$$

where,

r - correlation coefficient of linear relationship between the variable x and y

Xi - value of the x variable in a sample

$\bar{X}$ - the mean of the values of the x variables

Yi - the value of the y variable in a sample

$\bar{Y}$ - the mean of the values of the y variables

5. Results and Discussion

The six experimental sequence tenures of all three districts, Anand, Hoshangabad, and Varanasi were observed via statistical parameters results. The Gantt chart (Fig. 3) shows the time slots of stations. Experiencing the good results of these factors a common time slot was taken and checked (i.e., from 30/9/17 to 28/10/17) for all 3 experimental sites for better understanding of the results and comparison.

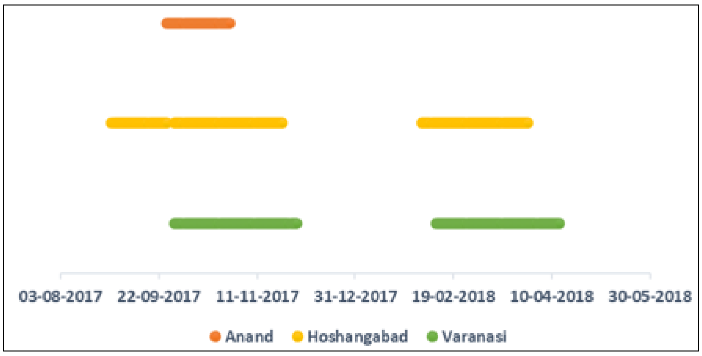

Fig 3: Time slots for experiment for Anand, Hoshangabad, and Varanasi stations.

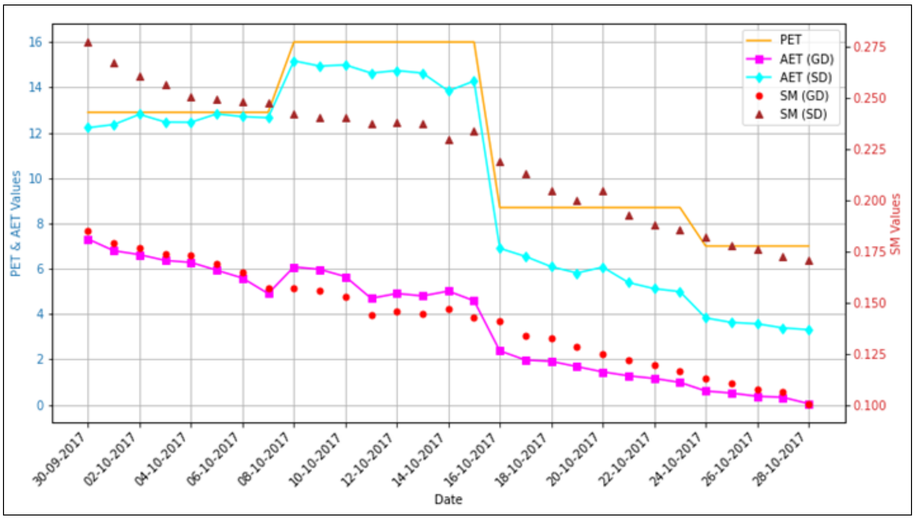

Fig 4: Details of SM (GD), SM (SD), PET, AET (GD) and AET (SD) for district Anand.

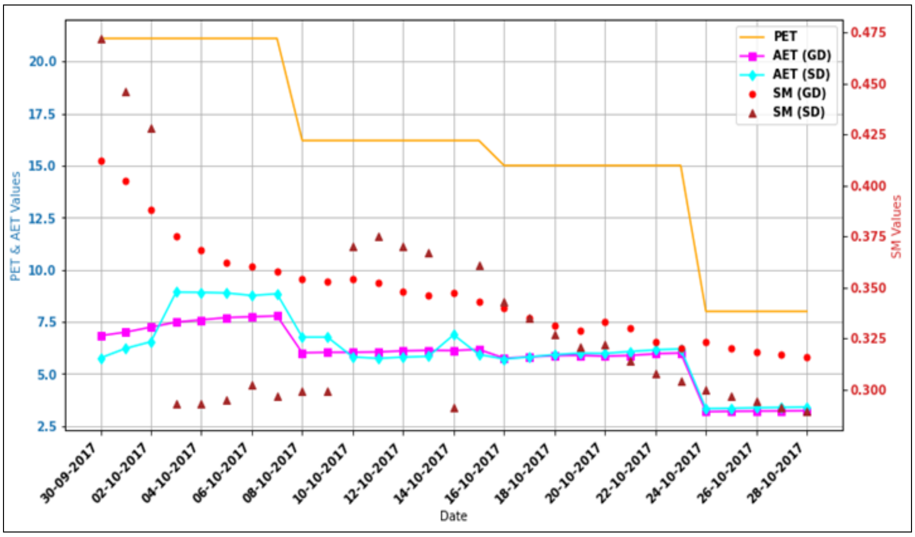

Fig 5: Details of SM (GD), SM (SD), PET, AET (GD) and AET (SD) for district Hoshangabad.

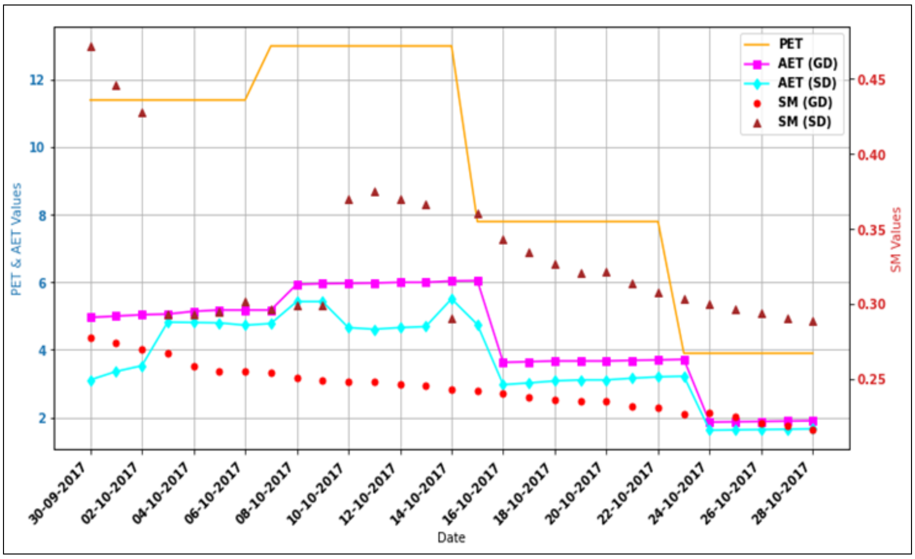

Fig 6: Details of SM (GD), SM (SD), PET, AET (GD) and AET (SD) for district Varanasi.

Figures 4, 5, and 6 show the trends of soil moisture (m), PET (mm/day), and AET (mm/day) for Anand, Hoshangabad, and Varanasi. As the experimental sites are different agroclimatic zones, the variation in results can be observed. Even after such variating data PET values the AET calculated from hydra probe data and satellite data shows the same trends for all three sites. The maximum AET value is on 30/9/17 (first day) & lowest is on 28/10/17 (last day). As the time slot is of autumn season the decreasing AET values stand true for the season span. For these continuous data days, the heatmaps (Figures 7,8 and 9) were generated between the datasets and the following results were found.

Anand

The soil moisture gradually decreases from 0.19 to 0.10 for ground data and from 0.28 to 0.17 for satellite data. PET values vary from 7 to 16 while AET (GD) and AET (SD) vary from 7.31 to 0.05 and 15.22 to 3.31 respectively. SM (GD) has a great correlation (0.98) with SM (SD). The PET has a better relation with satellite soil moisture data with a 0.80 correlation coefficient. AET calculated using SM (GD) has a 0.96 correlation coefficient with SM (GD) whereas AET (SD) has a 0.93 correlation coefficient with SM (SD). Though while calculating AET, PET is common for both situations the soil moisture differs still because of the great correlation between SM (SD) and SM (GD) the AET (GD) and AET (SD) too show great correlation with a 0.96 correlation coefficient.

Hoshangabad

The SM (GD) values show decrement from 0.41 to 0.32 whereas SM (SD) shows decrement from 0.47 to 0.29. The PET values range from 21.1 to 8. The AET (SD) ranges from 7.78 to 3.18 whereas the AET (GD) ranges from 8.92 to 3.33. For the station, the SM (SD) & SM (GD) show an optimum correlation coefficient of 0.68. On one side where PET shows a good correlation with SM (GD) with a 0.84 correlation coefficient whereas on the other side SM (SD) shows less than average correlation with PET with a correlation coefficient of 0.45. Even after a moderate correlation between SM (GD) & SM (SD), the SM (GD) has the same correlation with AET ((SD) and AET (GD) with a coefficient of 0.92. But for SM (SD) its correlation with AET (GD) is observed to be very less with a correlation coefficient of 0.51. It has a 0.84 correlation coefficient with AET (SD).

Varanasi

At Varanasi station, the SM (GD) varies a little from 0.28 to 0.22 whereas the Satellite soil moisture varies from 0.47 to 0.29. The minimum PET value calculated was 3.90 and the maximum was 13. Influenced by soil moisture the AET (GD) varies from 6.05 to 1.86 whereas the AET (SD) varies from 5.51 to 1.62. At this site, the soil from the satellite and ground shows the least relation among all sites with a correlation coefficient of 0.61. Ground soil moisture has a good relation with PET whereas SM (SD) has negligible relation with PET with values of correlation coefficient of 0.75 & 0.37 respectively. It has been observed that SM (GD) has a good correlation with AET (GD) & AET (SD) (0.86 & 0.81 correlation coefficient respectively). Considering the relation of satellite soil moisture data with SM (GD) & PET its relation with AET (GD) is very low with a correlation coefficient of 0.47 but it gets better with AET (SD) with a 0.78 correlation coefficient.

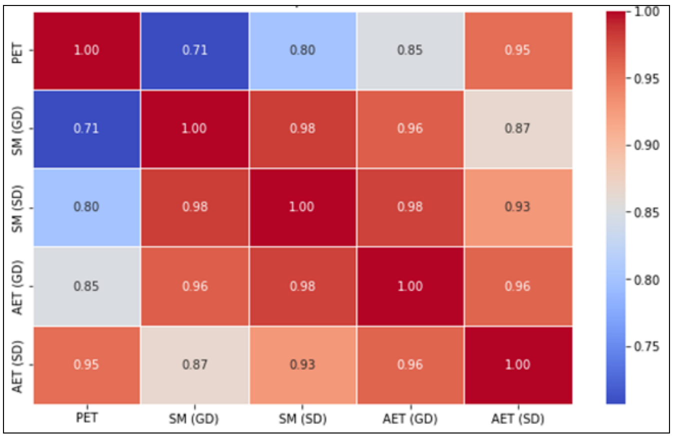

Fig 7: Correlation between SM (GD), SM (SD), PET, AET (GD) and AET (SD) for district Anand.

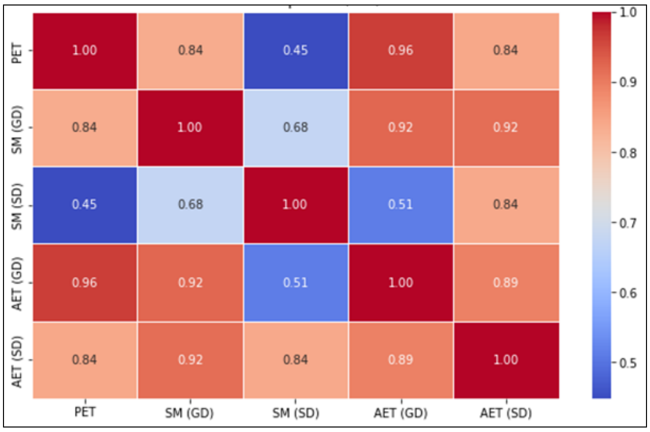

Fig 8: Correlation between of SM (GD), SM (SD), PET, AET (GD) and AET (SD) for district Hoshangabad.

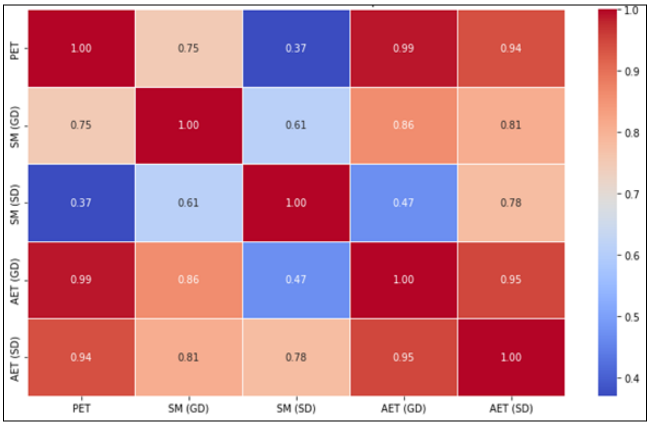

Fig 9: Correlation between SM (GD), SM (SD), PET, AET (GD) and AET (SD) for district Varanasi.

PET V/S AET

Lower values of RMSE allow us to accept the fact that AET values do not show much magnitude of error produced by PET values. The bias values tell us the less difference in data sets. Its positive values define the real state i.e. actual evapotranspiration is less than potential evapotranspiration. However, the high correlation shows a high linear relationship of data. Hence from all these parameters AET values from both hydra probe and satellite soil moisture data are justified to be relevant with PET calculated on the ground. Table 1 shows all the details.

For Anand, the AET calculated with satellite soil moisture data performs better, with less bias value of 1.58 and an error value of 2.29. The correlation of PET and AET (SD) is highest among all three stations, at 0.95. Also, it is greater than AET with ground soil moisture data, which is 0.85. For Hoshangabad the AET (SD) has less bias & error (9.70 & 10.14) but it is worth noticing that the bias & error values of AET (GD) with PET are very close to AET (SD). The correlation of AET (GD) seems to be better than that of AET (SD) with PET, which has a correlation coefficient of 0.96. For Varanasi, the bias & error values are low with AET (GD) when compared to bias and error values with AET (SD) with PET. The correlation of PET and AET (GD) is highest among all three sites with a value of 0.99.

Table 1: Statistical Analysis of PET v/s AET.

Stations	Bias		Correlation		RMSE	
	Ground SM Data	Satellite SM Data	Ground SM Data	Satellite SM Data	Ground SM Data	Satellite SM Data
Anand	7.92	1.58	0.85	0.95	8.13	2.29
Hoshangabad	9.91	9.70	0.96	0.84	10.34	10.14
Varanasi	5.16	5.87	0.99	0.94	5.47	6.25

AET (GD) V/S AET (SD)

A comparative study was done between AET values (from ground and satellite) that can be seen in Figure 10 and 11. The results obtained support the research on high grades. It depicts very high values of R^2 and low values of RMSE. Bias can be seen varying from low value to negative value. Anand has the best results of correlation between AET (SD) and AET (GD) with a correlation coefficient value of 0.96. The negative bias (-6.33) shows that AET(SD) is greater than AET (GD). With a correlation coefficient of 0.95 Varanasi shows good results. Among all sites, Hoshangabad shows the lowest error (0.64), nearly no bias (-0.21), and good correlation between AET (SD) and AET (GD) with a coefficient of 0.93

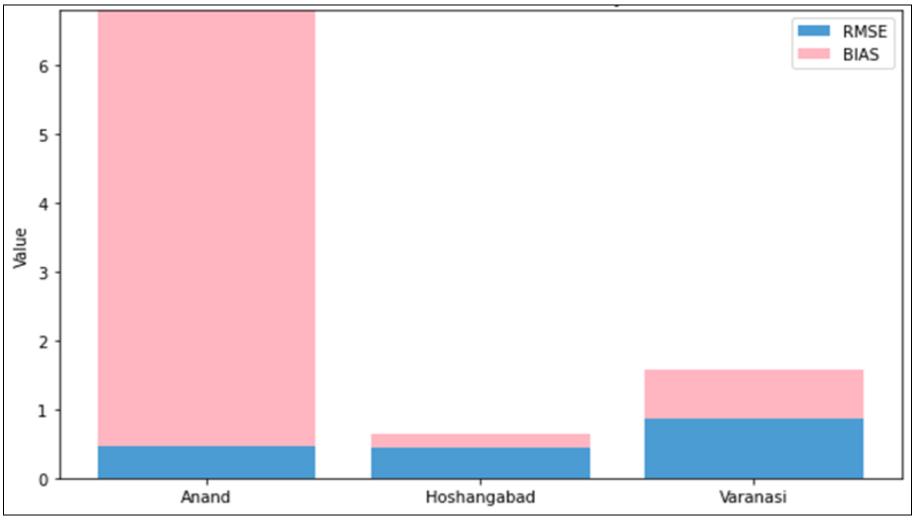

Fig 10: Statistical analysis of AET (Hydra probe) v/s AET(Satellite).

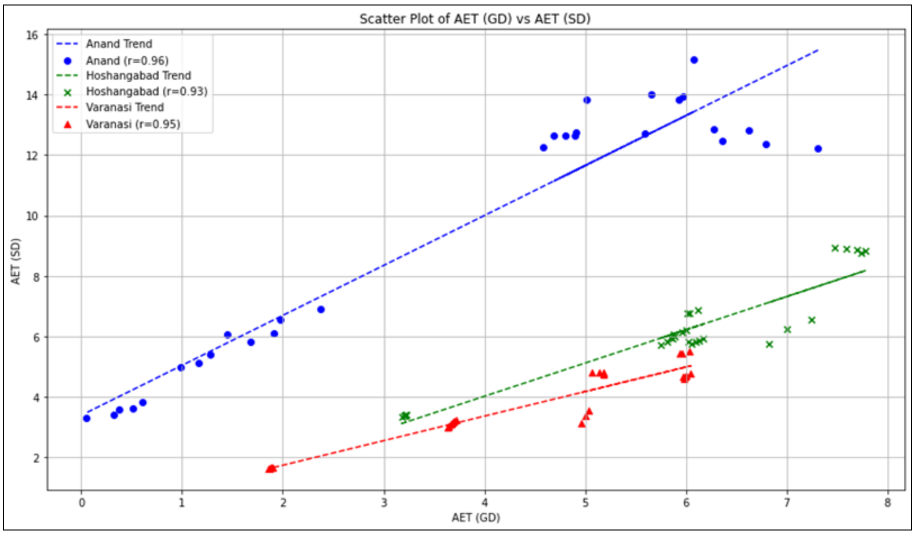

Fig 11: Correlation between AET (Hydra probe) v/s AET(Satellite).

6. Conclusion

AET is an essential entity to know and understand to have knowledge about water loss from any field. We may surely calculate the potential rates of evapotranspiration but also know the actual requirement of water in the field. The water present in the land is nothing but soil moisture that evaporates and is transferred to plants which is used in the process of transpiration. Hence, we understand that the actual evapotranspiration is a portion of potential evapotranspiration which depends on soil moisture availability. The present study uses the Bergstrom method to calculate actual evapotranspiration using potential evapotranspiration and soil moisture details (instantaneous soil moisture, field capacity & wilting point). On one side PET is calculated using the Hamon method whereas on the other side, soil moisture data is collected from the hydra probe and SMAP satellite for a specific period. The time span has been kept short and the calculation process has been kept simple. The experiment is done on three sites at Anand, Hoshangabad, and Varanasi where a hydra probe has been installed. At Anand, both AET and PET relations are good with soil moisture data sets. Also, SM(GD) & SM(SD) have very good relations. For Hoshangabad the SM(GD) gives better results than SM(SD). The SM(SD) at Varanasi has the least relation with PET because of its sudden change in value otherwise SM(GD) shows good relation with a high correlation coefficient. The study reveals the relation of AET with PET and soil moisture also it is significant to calculate AET with fewer data and details. Also remotely sensed data can be used for the calculation of AET after proper check for a particular site. However, the research has its shortcomings and limitations of short-duration experiments. The values of AET can also be validated with some other methods as well and soil moisture from different satellites can be used and checked. The research has a lot of future scope in the section of knowing AET with simple methods and fewer data.

Authorship contribution statement

Harshita Rani Ahirwar: Conceptualization, Investigation, Methodology, Visualization, Writing- original draft.
Anupam Kumar Nema: Supervision, Validation, Writing- review & editing.
Prashant Kumar Srivastava: Conceptualization, Data Curation, Supervision.
Samikshya Panda: Writing- review & editing
Rakhi Mahto: Writing- review & editing

Ethical declaration

Not applicable: This manuscript does not include human or animal research.

Declaration of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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