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RESEARCH ARTICLE

Time-series analysis of evapotranspiration using normalized difference vegetation index over north-eastern and north-western agro-climatic zones of Tamil Nadu

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Abstract

Estimation of evapotranspiration spatially is mandatory for water budgeting and water resource monitoring based on crop water demand. The amount of evapotranspiration can be estimated spatially from reference evapotranspiration and fractional vegetation cover over the region. The incorporation of specific characteristics like spatial variability over the land cover produced highly reliable results. The AquaCrop model gives reference evapotranspiration based on climatic parameters like temperature, rainfall, solar radiation, relative humidity and elevation. Normalized Difference Vegetation Index (NDVI) depicts the health of vegetation spatially ranging from -1 to +1. The dimidiate pixel model converts NDVI to Fractional Vegetation Cover (FVC) which was then used as a substitute for crop coefficient value. The products of these two parameters produce actual evapotranspiration spatially over the region with high spatial resolution. The average amount of actual evapotranspiration varies for each Land Use Land Cover (LULC) type over different agroclimatic zones as the climatic parameters and water usage patterns vary for each land cover type.

Keywords

actual evapotranspiration; agroclimatic zones; fractional vegetation cover; normalized difference vegetation index; reference evapotranspiration; spline

Introduction

Evapotranspiration is the consumptive water use over any land cover type. This evapotranspiration can be estimated spatially using reference evapotranspiration (ET_o) from meteorological parameters and crop coefficient value. The need for estimation of evapotranspiration in today's scenario is unavoidable for water budgeting and to meet crop water demand (1, 2). The process combines evaporation and transpiration as a single hydrological process irrespective of land cover (3). The process links soil-water relationship along with energy balance studies (4). Various methods have been used all over the world for evapotranspiration estimation *viz*., field-based instruments like Lysimeter, Bown-Ratio Energy Balance System, Scintillometer and Eddy Flux Covariance, which provide location-based evapotranspiration but lack the advantage of spatial estimation. The spatio-temporal variation of evapotranspiration can be mapped only with aid of remote sensing technologies like Surface Energy Balance Algorithm for Land (SEBAL) model, Mapping Evapotranspiration at high Resolution with Internalized Calibration (METRIC) model, Disaggregated Atmosphere Land Exchange Inverse and vegetative index based estimation (5). Quantification of such evapotranspiration is inevitable for water resource management at field and regional scales (6). This present study estimates the amount of actual evapotranspiration across two different agroclimatic zones in Tamil Nadu and its spatial variability over various LULC.

Study area

Tamil Nadu is the southernmost state in Indian Peninsula covering an area of 50000 sq. miles. The region is periodically equipped with dynamic climatic conditions with three major cropping seasons: kharif, rabi and summer. The Eastern coastal region of Tamil Nadu is characterized by Bay of Bengal, while the Kerala state lies in the West. The elevation ranges from 13 m (near Eastern Coastal region) to 914 m above sea level (near Hilly zone of Western Ghats).

Agro-climatic zones

Tamil Nadu has seven agroclimatic zones, namely North-eastern Zone, North-western Zone, Western Zone, High-altitude and Hilly Zone, High Rainfall Zone, Southern Zone and Cauvery Delta Zone. The spatially and temporally varying climatic conditions favors agriculture in specific zones due to its agro-climatic features (7). Northeastern zone covers Kancheepuram, Chengalpet, Tiruvallur, Cuddalore, Villupuram, Kallakurichi, Vellore, Tirupathur, Ranipet and Tiruvannamalai districts of Tamil Nadu. The northeastern zone is characterized by the second highest rainfall zone in low altitude regions ranging from 10-200 m above mean sea level owing to frequent cyclone damage. The majorly grown crops are rice, pearl millet, sorghum, cashew, jackfruit and sugarcane. Ground nut is the most widely cultivated rainfed crop in this region.

North-western zone is characterized by increased poultry farming and cattle breeds all over the region combined with rainfed cultivation. Major crops cultivated are sorghum, rice and millet. On average, this zone receives 400 mm of rain during the southwest monsoon. The zone includes districts of Salem, Dharmapuri and Namakkal in Tamil Nadu with an altitude ranging from 200 m to 600 m above mean sea level (8, 9). The location of study area, agroclimatic zones of Tamil Nadu and districts within each agro-climatic zone are depicted in Fig. 1. The overall methodology followed from agro-climatic zone delineation, estimation of reference evapotranspiration and actual evapotranspiration is shown in Fig. 2.

Water resources

The agro-climatic zone receives more rainfall during the Northeast monsoon than southwest monsoon. Western Ghats block the Southwest monsoon preventing it from entering the state (10). The state lies in the shade region of Western Ghats Mountain range covered with extreme vegetation and extreme aridity. The region experiences two rainfall periods: southwest monsoon in the months of June–September and northeast monsoon in the months of October–December. Stanley reservoir in North-western agro-climatic zone acts as major water source for surrounding districts including Salem, Dharmapuri, Krishnagiri and northern part of Erode districts. Thirumukkudal, a confluence of three rivers, namely Palar, Cheyyar and Vegavathi river, flows across the region as a major source for irrigation and other domestic activities. Similarly, Thenpennai river, the second longest river in the state originating from Karnataka state, flows across the region directly into Bay of Bengal.

Materials and Methods

Reference evapotranspiration

Reference evapotranspiration (ET_o) is the rate at which the water content is vaporized through evaporation and transpiration from the vegetation surface. Amount of ET_o is based on the crop biophysical characteristics like the structure

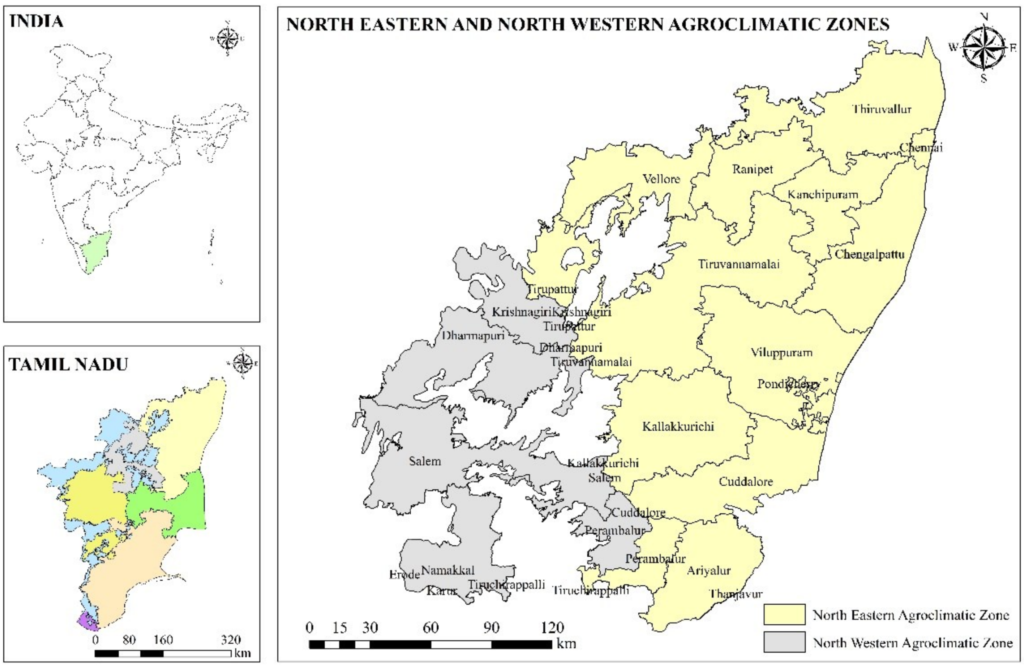

Fig. 1. Location of study area depicting North-eastern and North-western agro-climatic zones of Tamil Nadu

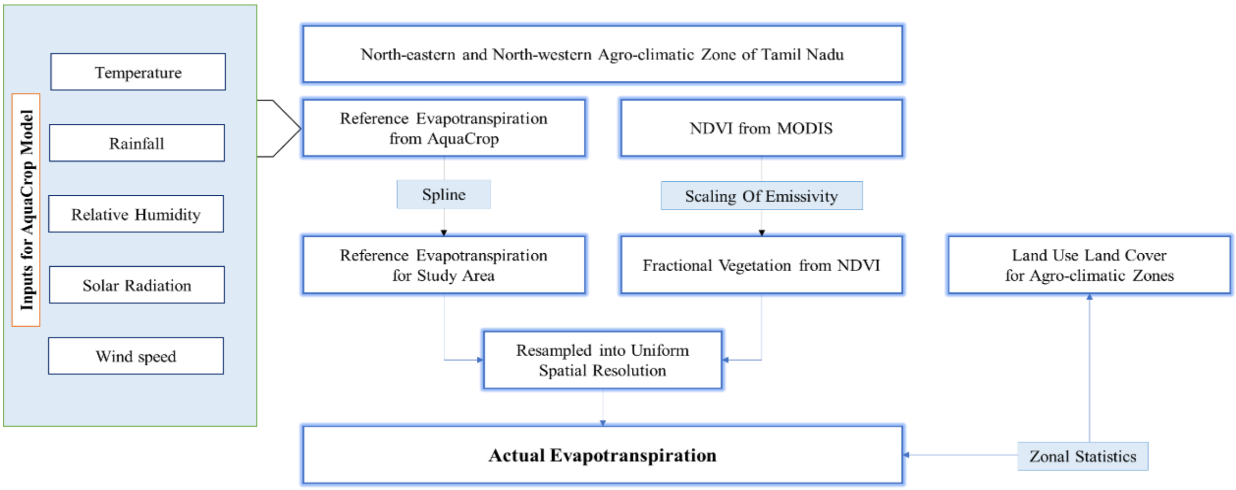

Fig. 2. Methodology to estimate ET_a from weather data and NDVI

of vegetation, density spread, growth stage, stomatal characteristics and climatic conditions (11). The standard condition where the grass completely covers the soil is assumed as optimal agronomic conditions. The evaporative demand of the atmosphere without referring to crop type and its management practices based on climatic conditions of the environment is referred to as ET_o (12, 13).

ET_o for North-eastern and North-western agro-climatic zones were calculated from AquaCrop Model (14). The control points for estimating ET_o for the entire zone are fixed based on the availability of weather parameters from NASA's Prediction of Worldwide Energy Resources (NASA POWER). Nine control points were chosen for ET_o estimation in (North-East) NE zone and 3 control points for (North-West) NW agro-climatic zone of Tamil Nadu based on NASA POWER data collection sources. For interpolation of ET_o from nearby agro-climatic zones, 31 points were chosen. ET_o was calculated for the entire study period for all 43 control points. The ground control points selected for estimation of reference evapotranspiration are shown in Fig. 3.

Weather data

The AquaCrop model calculates ET_o based on Penman-Monteith equation using several weather parameters like maximum temperature (°C), minimum temperature (°C), mean temperature (°C), solar radiation (MJ/sq. m), relative humidity (%), rainfall (mm) and wind speed (m/s) (15). The model requires all input parameters precisely defined from the starting date to the end date for the simulation, the elevation of the input sites and the latitude of a particular location. The model incorporates all weather parameters to calculate ET_o for a defined period (16).

The month of November received very high rainfall from 2021 to 2023 for entire NW and NE agro-climatic zones other than Cuddalore block. Solar radiation was minimal during November of 2021. In 2022 and 2023, the month of January received minimal or no rainfall. The temperature curve over the region shows a wavy format, especially increasing pitch in March and April months during the study period, indicating a high air temperature. The relative humidity is at peak during high rainfall conditions. Despite minimal rainfall, the Relative Humidity (RH) is high in Cuddalore block. On average, the wind speed ranged from 2 m/s to 4 m/s.

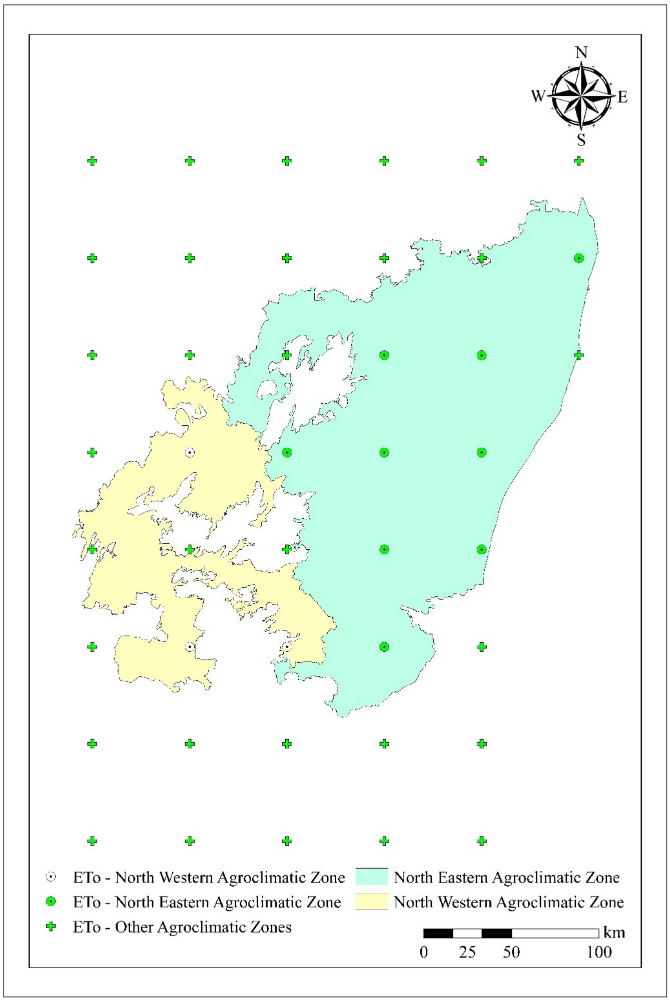

Fig. 3. Ground control points for estimating ET_o using AquaCrop model for North-eastern and North-western agro-climatic zones of Tamil Nadu

Normalized difference vegetation index (NDVI)

NDVI represents the health of vegetation spatially, based on the spectral reflectance of canopy. The health dynamic status is independent of seasons and climatic conditions (17). The spatial distribution of plants over the region is influenced by climatic conditions and other high-impacting factors like elevation and soil parameters. NDVI is the normalized ratio between the surface reflectance of Red (R) and Near Infra-red (NIR) bands. In other words, NDVI typically represents the chlorophyll content of the plant (18). NDVI measures the greenness and density of vegetation from spatial data (19). NDVI can be calculated from the bands using the formula:

NDVI = (NIR-R)/(NIR+R) (Eqn. 1)

NDVI value ranges from -1 to +1. Values near -1 suggest barren areas, rock and snow. Values between 0.2 and 0.3 correspond to shrubs and grasslands. Higher values near 0.6 to 0.8 correspond to temperate and tropical rainforests. Actual Total Evapotranspiration (ET_a) can be predicted from NDVI by leveraging the Surface Energy Balance Algorithm for Land (SEBAL) model (20). Water balance methods utilize remotely sensed vegetation indices to quantify the more temporally stable biomass amount that would be transpiring in well-watered conditions. The amount of Total Evapotranspiration in the grape field can be estimated using the Crop-coefficient (k_c) value and NDVI value of the field (21).

Fractional vegetation cover

FVC for a ground is the ratio of vegetation covered area to the total area. FVC depicts the distribution of vegetation over the earth's surface and the interaction between land surface, atmosphere and hydrological processes (22–24). Various models in the vicinity use estimation of FVC from spatial vegetation indices are statistical model and dimidiate pixel model.

i. *Statistical model* considers the correlation and sensitivity indices to vegetation information and reflects its ability to estimate FVC. Based on correlation analysis, primary linear models, quadratic, cubic and exponential statistical models can be developed.

ii. *Dimidiate pixel model* assumes that any image is composed of two components *viz*., vegetation and non-vegetation. This model considers the biophysical parameter relating morphological structure and physiological characteristics of the crop, which can be derived spatially from NDVI (18, 25). The FVC value of each pixel can be calculated from NDVI using the formula:

$$FVC = [(NDVI - NDVI_0) / (NDVI_{max} - NDVI_0)]^2 \quad \text{(Eqn. 2)}$$

Here, $NDVI_0$ denotes NDVI value of barren soil and $NDVI_{max}$ denotes maximum NDVI of the region under study (26).

The main use of FVC is that crop coefficient value will be similar despite the spatial variability over a large scale. FVC was calculated using the Enhanced Vegetation Index from Moderate Resolution Imaging Spectroradiometer (MODIS) data over non-forest regions in Republic of Korea to estimate soil moisture (27).

Computation of actual evapotranspiration (ET_a)

ET_a can be calculated from FVC and ET_o assuming that ET_o increases proportionally as the fractional vegetation cover increases (28, 29). It is obvious that the surface area for evapotranspiration to occur increases as the area of vegetation increases (30). Accounting these parameters into the calculation of ET_a, FVC approximately denotes the crop coefficient value of the crop, then ET_a is given by:

$$ET_a = FVC * ET_o \quad \text{(Eqn. 3)}$$

Results and Discussion

This study describes the methodology for estimating ET_a from NDVI and ET_o with higher accuracy. The use of NDVI from MODIS data and ET_o from AquaCrop Model favors evapotranspiration estimation over various LULC in North-eastern and North-western agroclimatic zones of Tamil Nadu.

Land Use Land Cover (LULC)

LULC depicts the socio-economic parameters like population density, transportation, agricultural activities, water resources and other factors relating to human habitat (31, 32). LULC of the North-eastern agro-climatic zone was characterized by five different classes *viz*., agricultural land, barren land, settlement region, forest and waterbodies (including wetlands), whereas the North-western agro-climatic zone varied with one additional positive zone namely grass/grazing land. Agricultural land in the North-eastern zone occupied an area of 2.26 million ha and North-western zone occupied 1.15 million ha. The forest region in the North-eastern zone occupied an area of 0.35 million ha and North-western zone occupied 0.38 million ha. Barren land in the North-eastern zone occupied an area of 0.09 million ha and the North-western zone occupied 0.05 million ha. Settlements and buildings in the North-eastern zone occupied an area of 0.24 million ha and the northeastern zone occupied 0.05 million ha. Waterbodies and wetlands in the North-eastern zone occupied an area of 0.32 million ha and the North-western zone occupied 0.09 million ha. Grazing land in the North-western zone accounted for a very less area of 300 ha. Various LULCs over North-eastern and North-western agro-climatic zones of Tamil Nadu are shown in Fig. 4.

Clearly, the water use over the settlement region cannot be mapped and visualized. NDVI and ET_o for the specific land use has been masked out for both agroclimatic zones of Tamil Nadu. Rainfall was simulated from 1982 to 2006 using the RegCM model. The rainfall conditions increased over decades due to land-mass under forced conditions of Era-Interim (33).

Reference evapotranspiration

ET_o over North-eastern and North-western agro-climatic zones of Tamil Nadu were calculated from daily weather parameters including maximum temperature (°C), minimum temperature (°C) and mean temperature (°C), rainfall (mm), relative humidity (%), solar radiation (MJ/sq. m) and wind speed (m/s). The AquaCrop model incorporates the weather parameters for the defined time. Forty-three ground control points were selected for ET_o estimation covering the entire study area. The model describes daily weather parameters for each location from Jan 2021 to Dec 2023. The daily ET_o was averaged to scale into monthly mean ET_o. Scaling from daily ET_o to monthly mean ET_o increased accuracy.

The monthly mean evapotranspiration for 43 control points was interpolated for entire agro-climatic zone. Spline was considered as the best interpolation technique for evapotranspiration as the spatial variability over a large scale is smooth for such parameter. The spline fits a curve throughout the sample data so that values are assigned to the entire study area. Spline creates a smooth surface that passes through all points with the least possible change in slope of all points in the study area with minimal curvature surface. The ET_o for two different agro-climatic zones was interpolated from AquaCrop model and Spline technique and the same is shown in Fig. 5.

The amount of evapotranspiration and rainfall was studied over Pollachi watershed in the Coimbatore district of

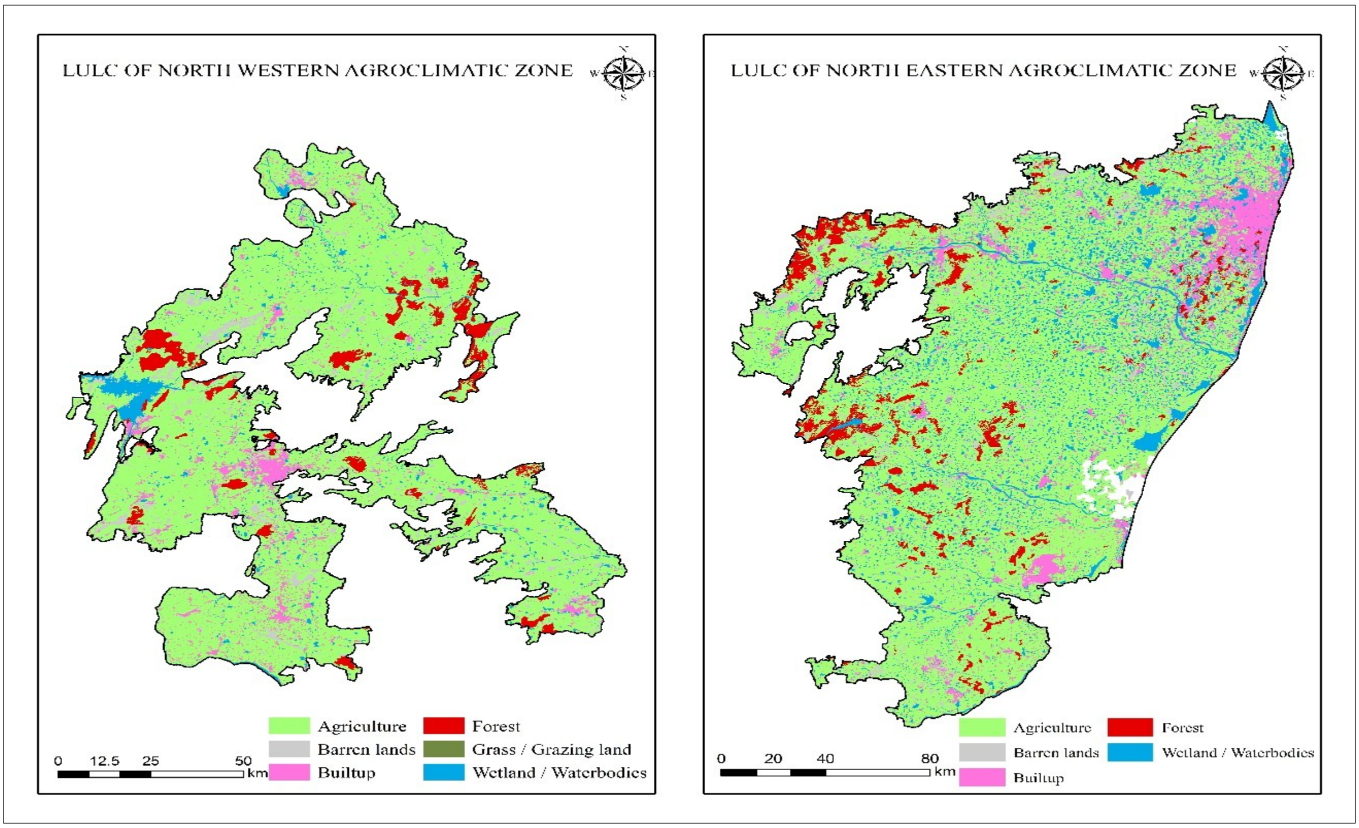

Fig. 4. LULC of North-eastern and North-western agro-climatic zones of Tamil Nadu

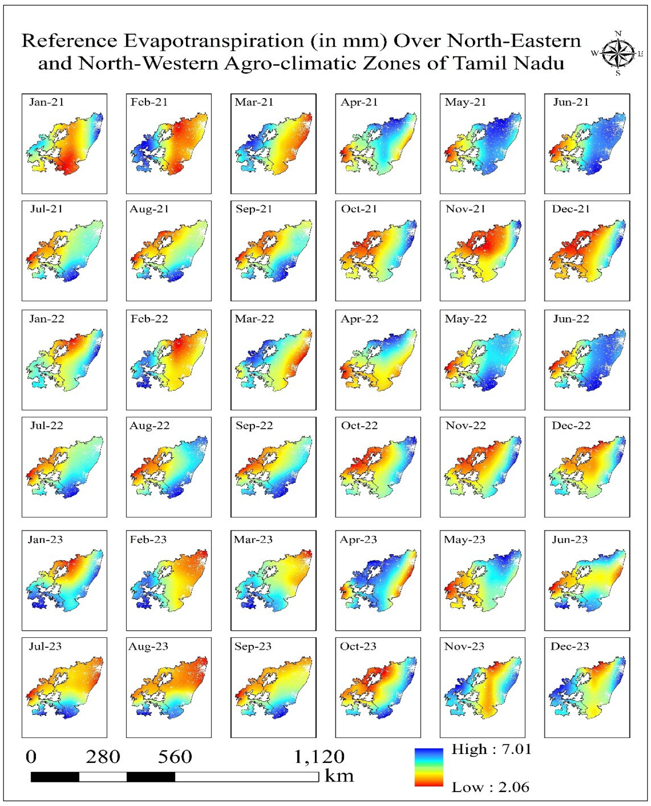

Fig. 5. ET_o (in mm) interpolated over North-eastern and North-western agro-climatic zones of Tamil Nadu

Tamil Nadu using CropWat software from the Food and Agricultural Organization (FAO). The variation in rainfall and evapotranspiration over the region was seen during the months of October and November (34).

Normalized difference vegetation index (NDVI)

NDVI depicts the health of vegetation based on chlorophyll content. The reflectance pattern of chlorophyll in the visible electromagnetic spectrum, specifically in 0.45 µm and 0.67 µm, known as chlorophyll absorption bands, clearly indicates the health condition of vegetation. Ghorbanian *et al.* (35) assessed the potential of Sentinel-2 optical satellite data in developing crop phenology from parameters like NDVI in Sahiwal district of Pakistan. Healthy vegetation causes a moderate amount of total transpiration from the canopy, whereas barren land and rock show a lower amount of total evapotranspiration.

NDVI value ranges from -1 to +1. In general, -1 indicates very poor condition of vegetation, probably barren land or rock. +1 indicates a dense forest region (36). The standard increase in NDVI values from -1 to +1 was seen in both the North -western and North-eastern agro-climatic zones of Tamil Nadu from January 2021 to December 2023. The NDVI over North-eastern and North-western agro-climatic zones is shown in Fig. 6. NDVI value in both agro-climatic zones ranged between 0.92 to -0.75, indicating a wide range of vegetation conditions and health status of plants.

Fractional vegetation cover – dimidiate pixel model

The method assumes that there is a fixed or a minimal predictable relationship between ET_o and transpiration from canopy. Water stress of a crop is a resultant character from soil and atmospheric parameters along with crop water requirements (37). An increased plant surface area indicates more stomatal count and more conductance for water vapor from leaves as transpiration (18). Though the spatial application of crop coefficients to wide ecosystem provides biased estimation of consumptive water use by more than 50%, optimization theory states that the predicted crop coefficient value from vegetative indices or any other sources like leaf area index or NDVI will be more like the actual crop coefficient values. Mapping spatial variability using NDVI achieves highly varying FVC over the region (38).

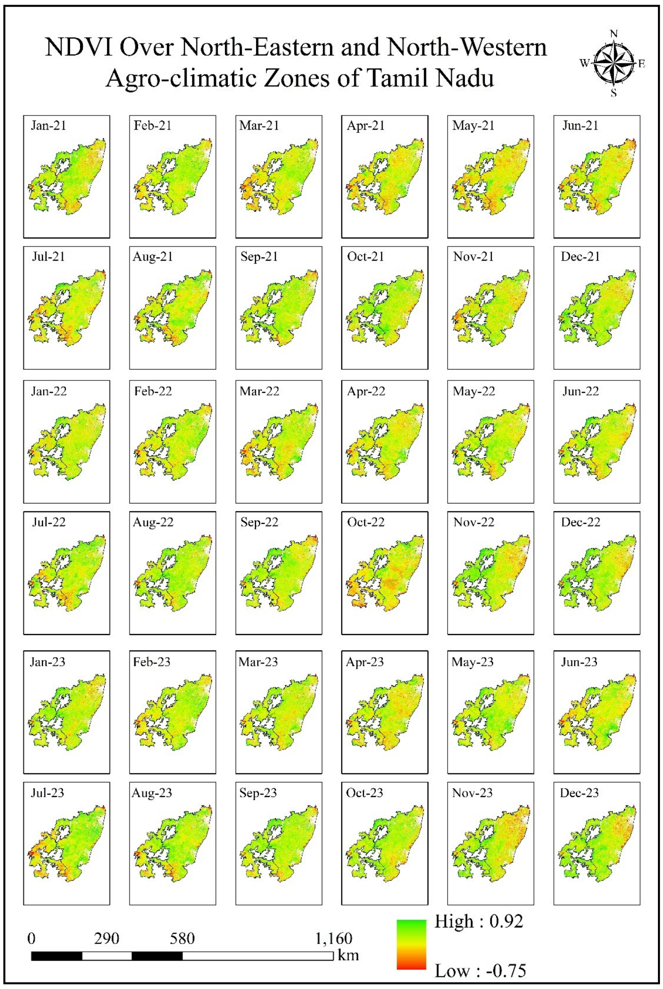

Fig. 6. Monthly average NDVI over North-eastern and North-western agro-climatic zones of Tamil Nadu from MODIS

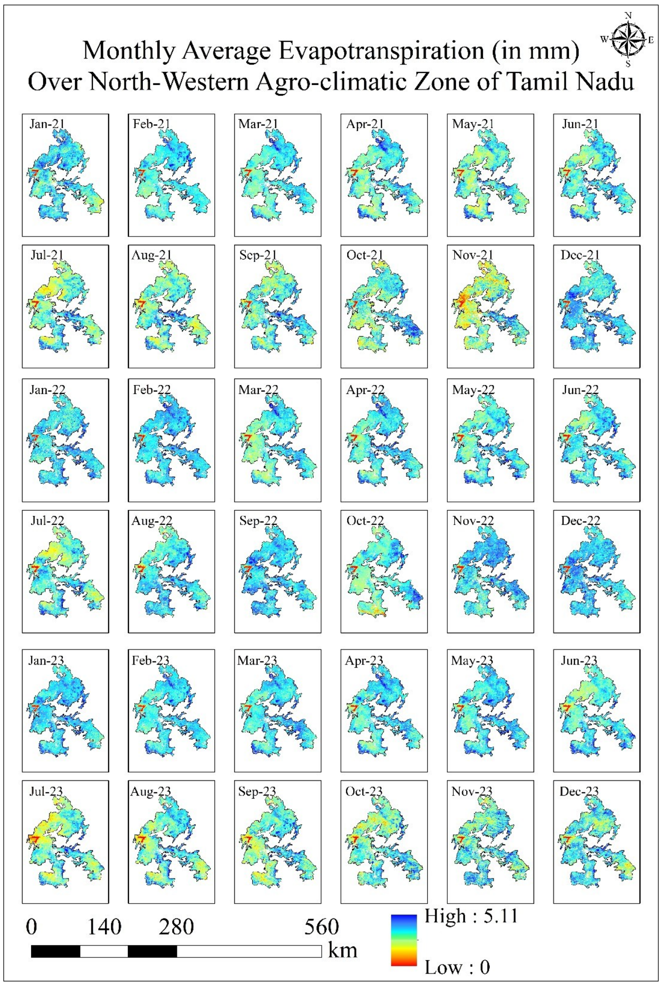

Fig. 7. Monthly average ET (in mm) over North-western agro-climatic zone of Tamil Nadu

Actual evapotranspiration

ET_a was estimated from ET_o and FVC from MODIS-NDVI with a very good spatial resolution of 500 m. Considering the vast area of the agroclimatic zones, spatial variability over the region can be clearly seen within 500 m spatial resolution (39). The product of FVC and ET_o is regarded as spatial ET_a because FVC represents crop coefficient (kc) value.

Monthly average ET_a over various LULC from January 2021 to December 2023 is shown in Fig. 7 and 8 and in Table 1. The highest ET_a was seen in August 2023, 3.44 mm per day in North-western agroclimatic zone followed by 3.40 mm per day in same month in North-eastern agro-climatic zone. In June 2021, North-western and North-eastern agro-climatic zones showed ET_a of 3.28 mm per day and 3.34 mm per day, respectively. The highest ET_a was observed in forest type of Land Cover in both, North-eastern and North-western agro-climatic zones of Tamil Nadu. In agriculture land type, August 2023 exhibited the highest ET_a of 2.98 mm per day and 2.97 mm per day in the North-eastern and North-western agro-climatic zones, respectively. Waterbodies/wetlands showed an ET_a of 2.7 mm per day in the month of July in 2023. Ironically, the North-western zone showed 2.31 mm per day of Eta as a higher amount followed by 2.03, which is much less when compared to the north-eastern agro-climatic zone.

In barren lands, North-western zone had the highest ET_a of 2.77 mm per day in the month of April 2023, while the North-eastern agro-climatic zone showed the highest ET_a of 2.76 mm per day in barren land in August 2023. Grazing land in the North

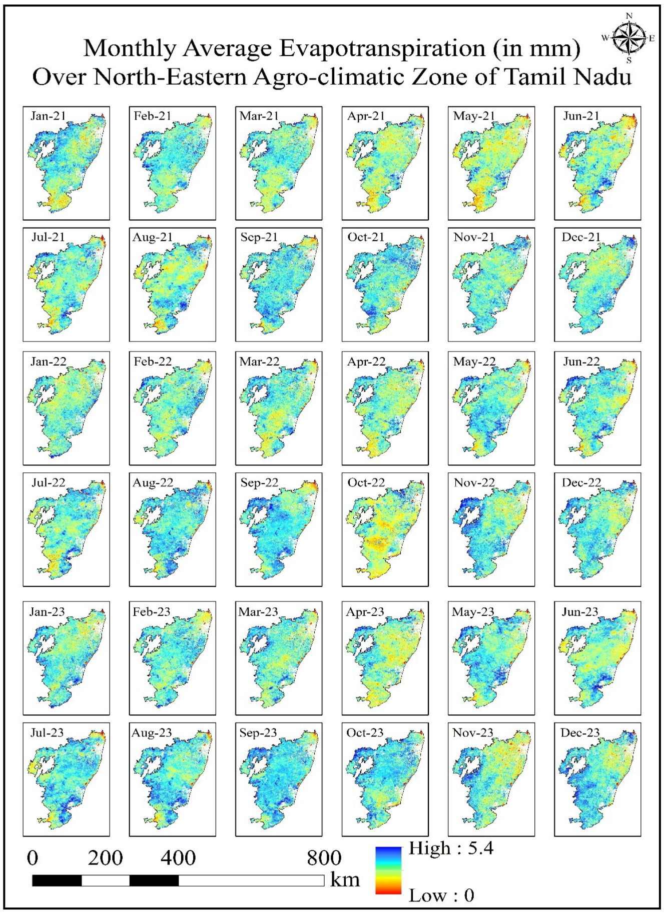

Fig. 8. Monthly average ET (in mm) over North-eastern agro-climatic zone of Tamil Nadu

Table 1. Monthly average evapotranspiration (in mm) over North-eastern and North-western agro-climatic zones of Tamil Nadu under various LULC

Year: 2021

	Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Forest	**NE**	1.63	2.86	3.07	2.8	2.76	3.31	2.64	2.66	2.71	2.27	0.84	1.83
	NW	1.74	2.94	2.9	2.57	2.44	2.95	2.42	2.67	2.85	2.16	0.7	2.04
Grazing land	**NW**	1.39	1.87	2.07	1.93	1.8	2.19	1.76	1.7	2.25	1.92	0.85	1.58
Barren land	**NE**	1.41	2.18	2.41	2.37	2.25	2.47	2.2	2.26	2.37	1.99	0.8	1.63
	NW	1.52	2.27	2.33	2.3	2.15	2.37	2.03	2.31	2.42	1.97	0.73	1.85
Waterbody	**NE**	1.27	2.1	2.47	2.48	2.35	2.59	2.22	2.25	2.25	1.88	0.64	1.43
	NW	1.22	1.79	1.92	2	1.8	1.9	1.69	1.83	2.02	1.7	0.6	1.4
Agriculture lands	**NE**	1.45	2.39	2.74	2.66	2.54	2.81	2.39	2.46	2.5	2.07	0.84	1.7
	NW	1.54	2.31	2.51	2.45	2.21	2.39	2.05	2.27	2.41	1.99	0.78	1.79

Year: 2022

	Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Forest	**NE**	1.9	2.72	2.91	2.98	2.97	3.34	2.39	2.73	2.54	1.71	1.86	1.67
	NW	1.97	2.73	2.69	2.72	2.98	3.28	2.29	2.67	2.51	1.43	1.92	1.92
Grazing land	**NW**	1.47	1.86	2.07	1.83	2.19	2.12	1.66	2.18	1.93	1.34	1.74	1.23
Barren land	**NE**	1.64	2.17	2.38	2.38	2.37	2.61	2.08	2.32	2.05	1.51	1.49	1.4
	NW	1.69	2.17	2.3	2.33	2.5	2.68	1.93	2.23	2.18	1.3	1.7	1.67
Waterbody	**NE**	1.53	2.1	2.42	2.46	2.41	2.6	2.06	2.23	1.88	1.38	1.29	1.23
	NW	1.26	1.66	1.99	1.99	2.01	2.12	1.5	1.59	1.54	1.01	1.32	1.24
Agriculture lands	**NE**	1.75	2.38	2.69	2.72	2.67	2.86	2.24	2.5	2.18	1.49	1.56	1.47
	NW	1.67	2.26	2.5	2.51	2.48	2.65	1.94	2.23	2.12	1.26	1.71	1.67

Year: 2023

	Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Forest	**NE**	2.25	2.93	2.79	3.34	3.2	3.22	3.13	3.4	3.2	2.91	1.68	1.63
	NW	2.61	2.93	2.87	3.35	3.04	2.98	2.82	3.44	3.22	2.9	1.88	1.93
Grazing land	**NW**	1.75	2.07	2.14	2.2	2.23	2.13	2.16	2.41	2.7	2.44	1.66	1.7
Barren land	**NE**	1.87	2.32	2.27	2.64	2.53	2.59	2.73	2.76	2.67	2.51	1.4	1.41
	NW	2.15	2.31	2.46	2.77	2.52	2.45	2.33	2.71	2.69	2.61	1.72	1.78
Waterbody	**NE**	1.72	2.31	2.3	2.64	2.53	2.52	2.7	2.64	2.51	2.35	1.24	1.23
	NW	1.66	1.81	2.1	2.31	2.03	1.95	1.93	2.26	2.31	2.27	1.47	1.49
Agriculture lands	**NE**	2	2.62	2.6	2.93	2.81	2.84	2.95	2.98	2.83	2.56	1.45	1.51
	NW	2.17	2.46	2.72	2.97	2.56	2.51	2.43	2.81	2.71	2.61	1.77	1.81

-western agro-climatic zone showed the optimal amount of ET_a (2.7 mm per day) in September 2023. The minimum amount of ET_a was seen in the month of November 2021, wherein the amount reached to as low as 0.6 mm per day in waterbodies and as high as 0.84 mm per day in forest areas in the North-eastern agro-climatic zone. The highest amount of ET_a was seen in the forest region of North-western agro-climatic zone (~2.83 mm per day), whereas in the North-eastern zone, the amount of ET_a was 2.81 mm per day. In agriculture land, the North-eastern agro-climatic zone showed ET_a of 2.51 mm per day whereas the North-western agro-climatic zone showed 2.46 mm per day. Hu *et al*., analyzed the spatial variability of the amount of ET over the Aksu River Basin for the period of 2001 to 2020. They concluded that high values of ET were seen in cropland and low amounts of ET were seen in unused and low-cover grassland (39). High rainfall and high RH act as driving forces for ET to occur.

The scope for groundwater recharge considering ET as a factor in Southern parts of Andaman was studied (40). The amount of ET was high during the peak dry season indicating no scope for groundwater recharge. Additionally, the study showed that the southern parts of Andaman experienced a minimal amount of ET during the rainy season indicating a higher scope for groundwater recharge.

Conclusion

Estimation of ET_a using ET_o and FVC from NDVI produces more reliable results over a large scale covering two different agro-climatic zones of Tamil Nadu. This model overcomes the barrier of using several parameters like radiation flux, surface energy balance, ground heat flux and so on (41, 42). Field-wise estimation of ET under standard environmental conditions is limited by practical methods. The spatial variability over the amount ofET is mainly due to the LULC parameters of the area (43). Very common LULC classes like agriculture lands, settlement regions, barren lands and waterbodies including wetland agriculture systems were seen prominently in agro-climate zones. ET_o is the amount of ET from reference surfaces like grasses or Alfalfa worldwide. This ET_o was estimated from basic meteorological parameters like temperature, RH, rainfall and solar radiation over the region during the specific period using AquaCrop model. These essential parameters were derived from the open access NASA POWER portal. Crop coefficient (k_c) values, which are specific to each crop, were like FVCs derived from vegetation index, NDVI. Unlike biased estimates using any other model, FVC from NDVI was stable as it was derived using dimidiate pixel model (38). The product of FVC and ET_o was the actual spatial evapotranspiration rate (ET_a). The spatial ET_a varied over the various LULC under different agro-climatic zones.

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Authors' contributions

SM aided in concept formulation. RKP contributed to overall methodology. PS and TS supported by providing necessary sources of data for entire period. SS, SAP and KR helped in data collection for entire period. MAJ and CK helped in writing and final drafting of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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