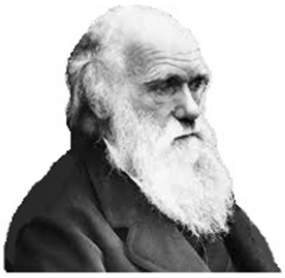
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Integrated Assessment of Evapotranspiration, Soil Moisture, Climate Variability and LULC Dynamics in the Ramganga River Basin, North India

Akash Nag[1] and **Josna Murmu**[2]

[1] G B Pant National Institute of Himalayan Environment (NIHE), Kosi-Katarmal, Almora, Uttarakhand, India

E-mail address: akashnag070@gmail.com

ORCID ID: 0000-0002-3209-8570

[2] Mission Mausam, Indian Institute of Tropical Meteorology (IITM), Ministry of Earth Sciences, Pune, India

E-mail address: josna.murmu@tropmet.res.in

ORCID ID: 0000-0003-3509-9031

ABSTARCT

Evapotranspiration (ET) is a key part of the terrestrial water cycle, especially in river basins reliant on agriculture, where climate change and land use impact water resources. This study examines long-term ET trends in the Ramganga River Basin of the sub-Himalayas for 1995 to 2024, linking them to land use changes and land cover-related meteorological factors. The average ET during this period was 766.74 ± 38.95 mm/year (CV = 5.08), with a low of 692.08 mm/year in 1998 and a high of 888.84 mm/year in 2024. The Mann–Kendall test indicates a significant upward trend ($\tau = 0.430$; $Z = 3.31$; $p = 0.000905$), and the Pettitt test identifies 2005 as an abrupt change point ($p = 0.0148$), dividing the period into ET-anomaly years (1995–2004) and later years (2006–2024). Land use change analysis from 2017 to 2024 revealed notable shifts in agricultural and urban areas, leading to declines in natural vegetation. The area of cultivated land increased by 11.17%, that of grassland expanded by 21.85%, that of forestland decreased by 29.12%, and that of urban areas increased by 14.49%. Correlation studies of ET drivers revealed that tree ET depends primarily on temperature, whereas the temperature dependence of crop ET became more pronounced from 2017 to 2024, which is consistent with increased cropland. These findings suggest that hydroclimatic regime shifts in the Ramganga watershed after the mid-2000s were driven mainly by agricultural intensification and irrigation practices rather than climate change

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alone. The results highlight the importance of accounting for land use impacts in water resource planning.

Keywords: Evapotranspiration, Mann–Kendall test, Land use/land cover change, Agricultural intensification, Irrigation, Soil moisture, Ramganga River Basin, North India

1. INTRODUCTION

Hydrology is the study of how water occurs, moves, and is distributed. Mountains cover approximately 24% of the Earth's surface and hold approximately 12% of the global population (Viviroli et al., 2007). Additionally, approximately 10% of people in the world use mountain resources for their livelihood, and 40% depend on mountain ecosystems because of their indirect needs for wood, forestry, fresh water, and rivers, which can be useful for industrial, agricultural, and domestic purposes (Schild, 2008; Viviroli et al., 2007). In addition, mountains regulate river flow and provide winter precipitation, which makes rivers perennial, especially during late spring and summer (Viviroli et al., 2003; Viviroli et al., 2011).

In the current climate scenario, the atmospheric evaporative demand is anticipated to increase because of rising temperatures (Sheffield et al., 2012), and the global hydrological cycle is expected to become more intense and accelerated (Huntington, 2006), leading to increased ET and precipitation at similar times (Douville et al., 2013). Global studies have reported that annual land ET has increased over the last two decades of the last century (Zhang et al., 2012). ET is important because it acts as both a hydrological process of the water cycle and as a flux of the surface energy balance (Xu et al., 2018). The water balance of an area over a given period can be expressed as follows:

$$P = ET + \Delta S + Q + D + F$$

where: P is precipitation, ET is evapotranspiration, ΔS is the change in soil water storage, Q is runoff discharge, D is the leakage of water below the root zone (potentially reaching the groundwater table), and F is subsurface flow out of the defined area.

The Global Land Evaporation Amsterdam Model (GLEAM) fills this gap by estimating all major processes separately, such as transpiration, bare soil evaporation, interception loss, evaporation from open water bodies, and snow sublimation, via a framework based on the Priestley-Taylor method supported by satellite data on radiation, temperature, vegetation optical depth, and soil moisture. The validity of the GLEAM system was demonstrated by its good correlation with eddy covariance networks, with R^2 values ranging from approximately 0.83–0.78. The latest version of GLEAM4 expands the time frame of research until 2023 and has a resolution of 0.1°. In conjunction with the climate dataset, the application of zonal statistics, which involves the summarisation of a raster variable by region, such as land use and land cover (LULC) class or subcatchment (GIS Geography, 2025), requires reliable data on LULC.

The Himalayan range, which is the oldest and oldest in the world, has enormous amounts of water in the form of glaciers, snow, lakes, and springs, earning the title "Asia's water tower". Some rivers from the Himalayas provide freshwater to 1.4 billion people who live downstream (Immerzeel et al., 2010; Kumar et al., 2023).

Given the vulnerability of high mountain ecosystems to anthropogenic impacts and climate change, the ecosystem of the Indian Himalayan region (IHR) should be studied more thoroughly. The traditional methods of resource management in the Indian Himalayas have changed significantly in the past few decades because of increasing population and demand for food, fodder, grazing land, and other resources, along with market forces and social, political, and economic marginalisation (Sharma et al., 2007; Tiwari, 2010). These pressures have led to ecological limits being exceeded in the use of key resources such as land, water, and forests. Extensive deforestation, mining, quarrying, agricultural expansion, overgrazing, urbanisation, and tourism development have resulted in the depletion of resources (Tiwari, 2010; Tiwari & Joshi, 2009) and have led to severe shortages in water resources as a result of land use changes and a lack of groundwater recharge (Tiwari, 2000; Wasson et al., 2008; Jianchu et al., 2008). The region of the Himalayas is experiencing an increase in evaporative demand combined with rapid land changes and increasing pressure on scarce water resources.

The state's river basins, including the Ramganga River Basin (RGRB), are among the most affected by LULC changes because of high biotic pressure. Other regional case studies that explain LULC changes have shown that precipitation patterns and anthropogenic pressure drive these changes (Sati, 2006). Specifically, Baigaliyeva, et al. (2024) reported that the long-lasting influence of human activity led to changes in the LULC of the RGRB from 1970 to 2013/14 and its flow regime; however, they reported that the understanding of the effect of LULC on the larger hydrological regime of the studied area is still insufficient and becomes the motivation for the analysis of changes.

The Ramganga, an important tributary of the Ganges River, originates from the Doodhatoli ranges and ultimately empties into the Ramganga Dam located in Kalagarh (*c.* 33,040 km^2) of Pauri Garhwal, Uttarakhand. The basin is experiencing increasing pressure from agricultural, industrial, and urban use of water resources and is projected to increase temperatures by 1.6 to 1.9 °C by 2050, subsequently increasing mean water loss through ET (Gurjar et al., 2022). While proven tools such as GLEAM and ERA5 are being used, LULC change is shown in the RGRB. ET drivers have also been developed in similar basins, and the three aspects have not been combined to create a basin-scale understanding of the Ramganga Basin. To date, studies on the RGRB have investigated LULC as well as streamflow-related aspects (Gurjar et al., 2022). Water demand from agriculture is a growing concern basin-wide, with the river supporting extensive irrigated cropland, hydropower, domestic use (especially via groundwater), and industry, and major infrastructure such as the Kalagarh Dam, along with various barrages and weirs, has significantly altered natural flow patterns and fragmented the river system. At the wider Ganga Basin scale, more than two-thirds of the cropped area depends on groundwater irrigation, and up to 90% of the rural population relies solely on groundwater for drinking and household needs, driving overexploitation in parts of the region.

The objective of this study is to approximate the geographical and temporal distributions of ET and SM within the RGRB while also determining the alterations in LULC within the basin and what effects those changes have on hydrological operations. The data related to ET, SM, and climate will also be combined using zonal statistics to set standards that can be followed throughout the comparison process between different land use units and subcatchment areas to establish a suitable comparison standard. The final phase of the research involves determining the relationships between ET and SM, together with precipitation, temperature, and relative humidity, through correlations to determine the intensity of the influence of climate on ET.

2. METHODOLOGY

2. 1. Study area (Ramganga River Basin)

The Ramganga River is a Himalayan River originating from the Dudhatoli range in Pauri district, Uttarakhand, at an elevation of 3100 meters (**Figure 1**). It stretches 596 km and flows through the West Himalaya region and the Upper Gangetic Plains. The river is fed by tributaries such as Khoh, Gagan, Aril, Kosi, and Deoha (Garra), which eventually merge into the Ganges Basin. Its catchment covers approximately 3.77% of the Ganga Basin. Ramganga flows through districts in Uttarakhand (Pauri Garhwal, Chamoli, Almora, and Nainital) and districts in Uttar Pradesh (including Bijnor, Moradabad, Rampur, Bareilly, Budaun, Shahjahanpur, Hardoi, and Farrukhabad). A dam near Kalagarh with a capacity of 198 MW supplies hydroelectric power and irrigation. The climate varies: winters (October–February) are dry and cool; summers (March–June) are hot and dry; and the monsoon (mid-June to September) causes heavy rainfall, with annual precipitation ranging from approximately 2,200 mm in the north to 800 mm in Hardoi. In the plains, winter temperatures range from 5 to 25 °C, whereas summer temperatures can exceed 40 °C. The upper basin falls under the Himalayan Moist Temperate Forest (*Quercus incana, Q. dilatata*), Western mixed coniferous forest (*Picea, Cedrus, Abies pindrow*), Moist temperate deciduous forest (*Aesculus indica, Acer* spp.), and Subtropical Pine Forest (*Chir pine – Pinus roxburghii*), following the Champion and Seth Forest classification. It provides refuge to the Vulnerable smooth-coated otter, Critically Endangered gharial, and Endangered golden mahseer (Roy, R., & Mishra, V. (2026).

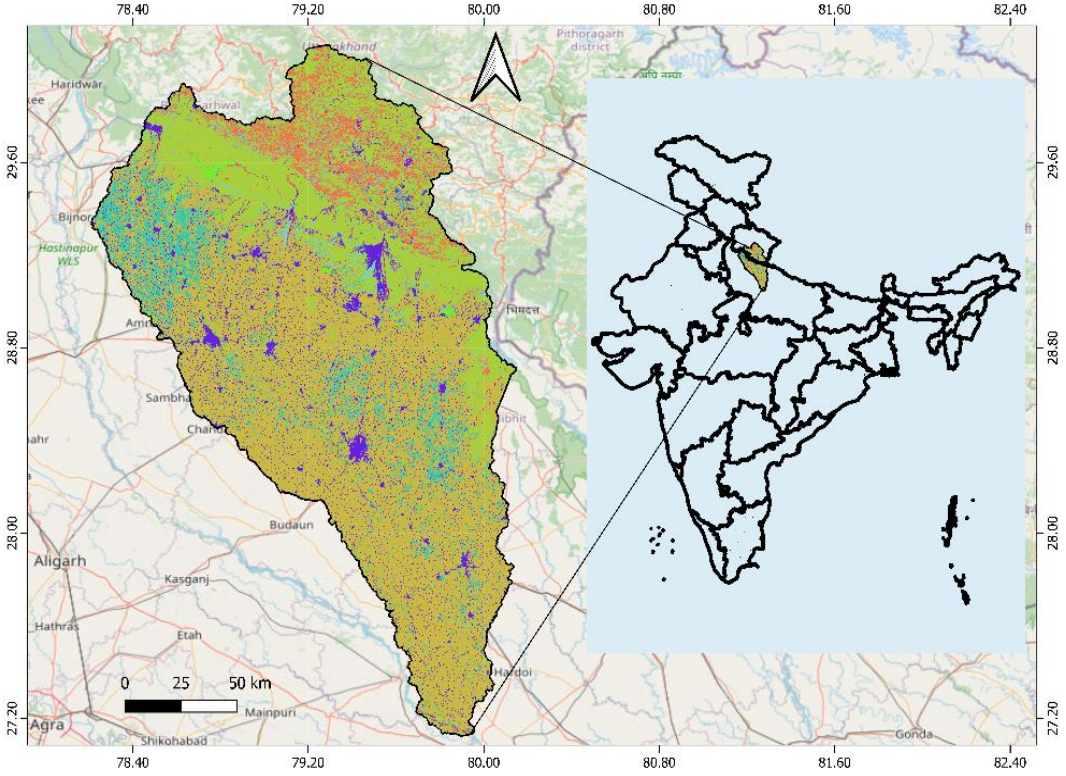


Figure 1. Study area map of the Ramganga River Basin.

Agriculture dominates land use in the middle and lower basins. The major crops are rice, wheat, and sugarcane, with rice grown in the kharif (monsoon) season, wheat in rabi (winter), and sugarcane as a perennial crop. In the hilly upper reaches of Uttarakhand, irrigation relies mainly on surface water, whereas in the plains, groundwater and canal systems are more prominent.

This mirrors the broader Ganga Basin pattern, where the crop profile includes subsistence cereals as well as cash crops such as sugarcane, oilseeds, pulses, tobacco, and cotton, and farmers practice multiple cropping across large parts of the basin, resulting in a gross irrigated area of approximately 484,240 km.

2. 2. Data retrieval and analysis

This methodology involved obtaining data, processing the information, and conducting spatial analysis, leading to correlation analysis of the study area RGRB in Uttarakhand. The process also uses the GLEAM data to assess ET and SM. In addition, the ERA5 reanalysis data were analysed to obtain T, RH, and R data for the years 2017–2024. We also integrated LULC data into the river basin hydrology analysis to document LULC changes (**Table 1**). GLEAM and ERA5 data were analysed and combined with the LULC data to determine the spatial and temporal variability in hydroclimatic parameters using zonal statistics across various land use types and subcatchment zones. Moreover, LULC changes were assessed independently to determine the major changes in land cover. Finally, correlation analysis was used to study the relationships between ET or SM and R, T, and RH (**Figure 2**) (GIS Geography, 2025).

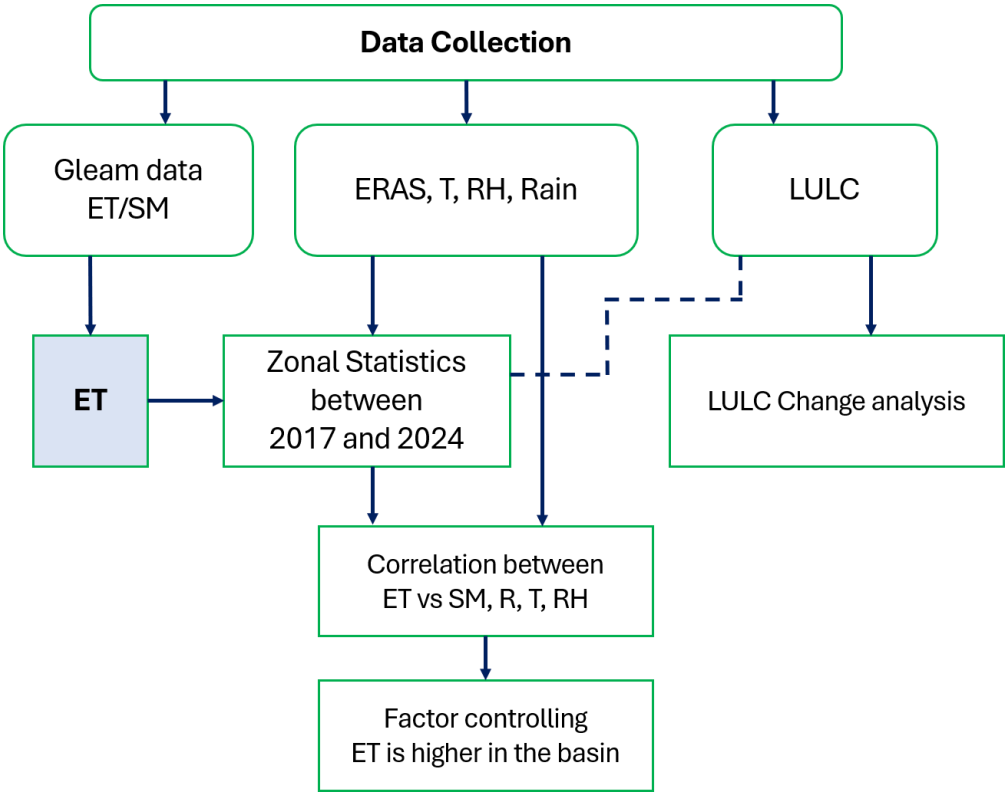


Figure 2. Flow diagram showing the methodology followed for this study**.**

Table 1. List of data used in the study.

Category	Dataset Name	Source	Spatial Resolution	Temporal Scale	Availability
Rainfall	ERA5-Land	ECMWF	~9 km	Daily	1940-till date
Temperature	ERA5-Land	ECMWF	~9 km	Daily	1940-till date
Relative Humidity	ERA5-Land	ECMWF	~9 km	Daily	1940-till date
Evapotranspiration	GLEAM	ESA	0.1°	Daily	1980-2025
Soil Moisture	GLEAM	ESA	0.1°	Daily	1980-2025
LULC	ESRI LULC	ESA	10 m	Annual	2017-2025

3. RESULTS

3. 1. ET trend over the years

Long-term ET was analysed for the Ramganga Basin for the years 1995–2024 to examine the interannual variability and long-term trend in annual total ET. Annual trends revealed that ET was low in 1998, 2003, 2010, 2013, and 2022 but increased in 2009, 2012, and 2024 (**Figure 3)**. The ET range is approximately 692–889 mm/yr. The mean annual ET was 766.74 ± 38.95 mm/year, and the median annual ET was 766.98 mm/year, with a coefficient of variation of 5.08%. The minimum annual ET was 692.08 mm/year in 1998, and the maximum annual ET was 888.84 mm/year in 2024.

The 5-year moving average decreases short-term year-to-year fluctuations and tends to increase throughout the study period. During the mid-2000s, the annual ET increased until 2009–2014, followed by a renewed increase in later years. The linear regression indicated an increase of approximately 2.69 mm/year^2 ($R^2 = 0.372$, $p = 0.0003$), corresponding to an increase of approximately 3.52% per decade. This increasing trend was supported by the results of the Mann–Kendall test, which indicated a positive trend, with a Kendall's tau = 0.430, Z = 3.31, and p value = 0.000905.

The Pettitt test results indicate an abrupt change in the central value. Pettitt K 151, and the Pettitt p-value is 0.014842. The mean annual ET increased from 738.63 mm before the change point to 783 mm after 2005, an increase of 44.36 mm. The change occurred in 2005, and the ET values shifted after 2005 (**Figure 4**).

The Pettitt test results reveal negative ET anomalies and below-average ET conditions. After 2005, positive anomalies became more frequent and shifted toward higher ET values. However, some years also show negative anomalies that continue to occur, indicating persistent interannual variability.

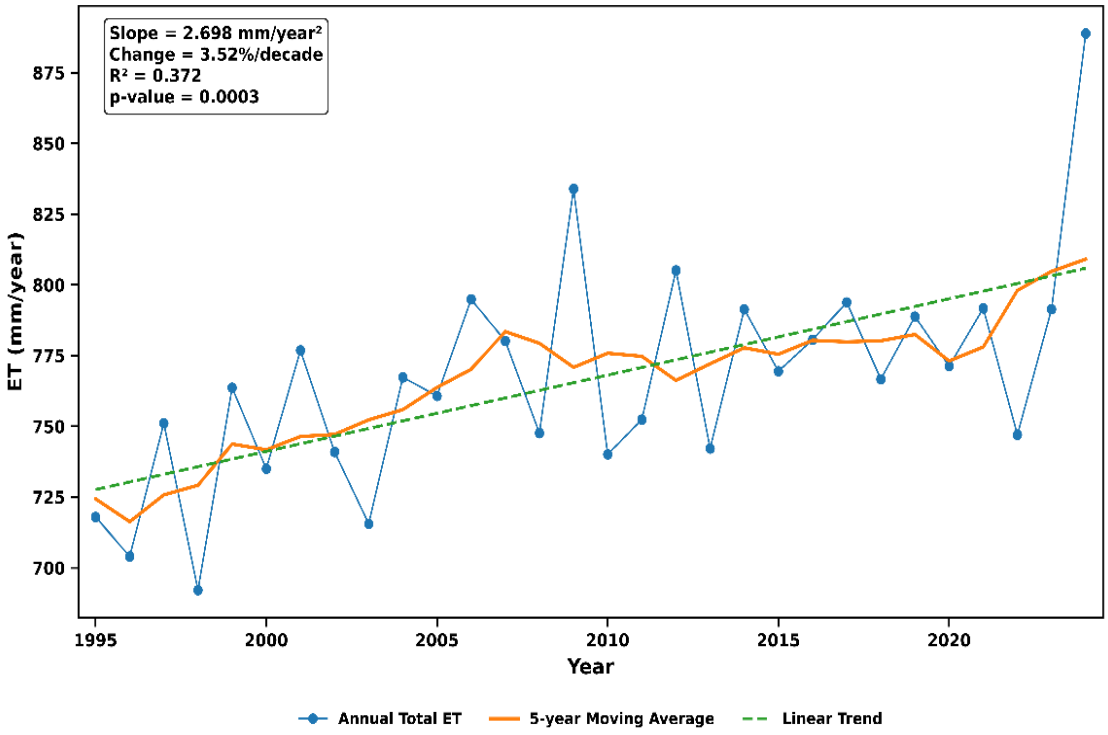


Figure 3. Annual trend of ET from 1995 to 2024 across the Ramganga Basin, annual total ET, 5-year moving average, and linear trend.

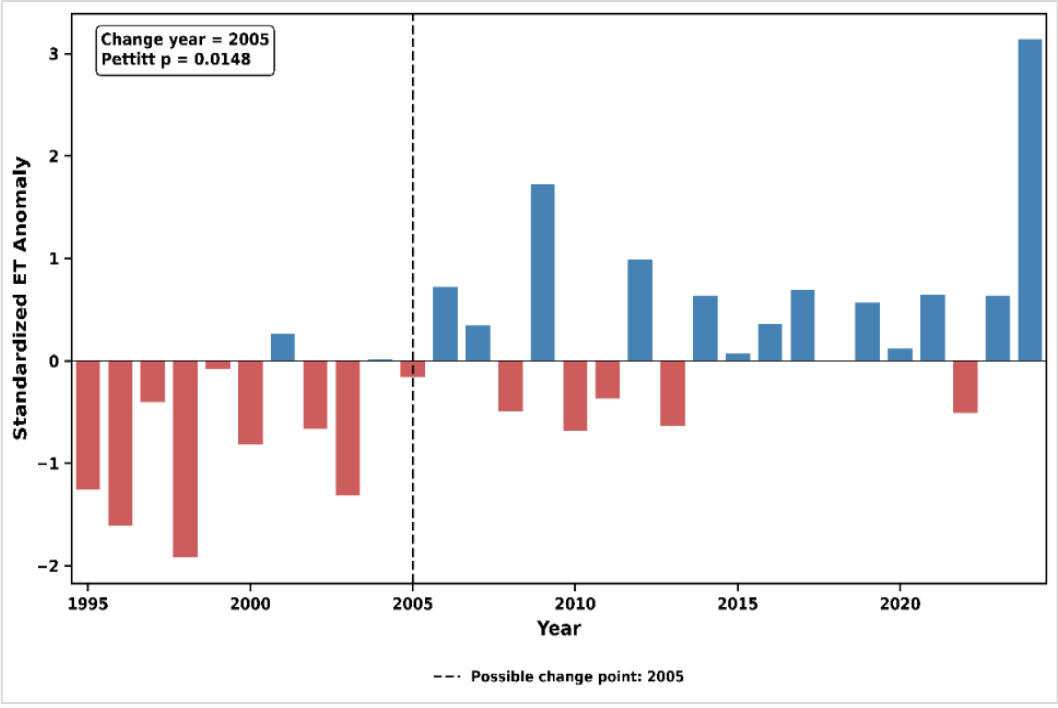


Figure 4. Pettitt test and annual ET anomalies over the Ramganga Basin.

3. 2. LULC change analysis for 2017 and 2024

Table 2. LULC change class comparison between 2017 and 2024.

LULC class	Area 2017 (km^2)	Area 2024 (km^2)	Change (km^2)	Change (%)
Water	358.708	351.936	-6.772	-1.89
Trees	9433.079	6686.449	-2746.63	-29.12
Flooded vegetation	18.642	18.196	-0.447	-2.4
Crops	17210.211	19132.571	1922.36	11.17
Built area	2379.194	2723.939	344.745	14.49
Bare ground	115.143	94.072	-21.07	-18.3
Rangeland	2324.583	2832.397	507.815	21.85

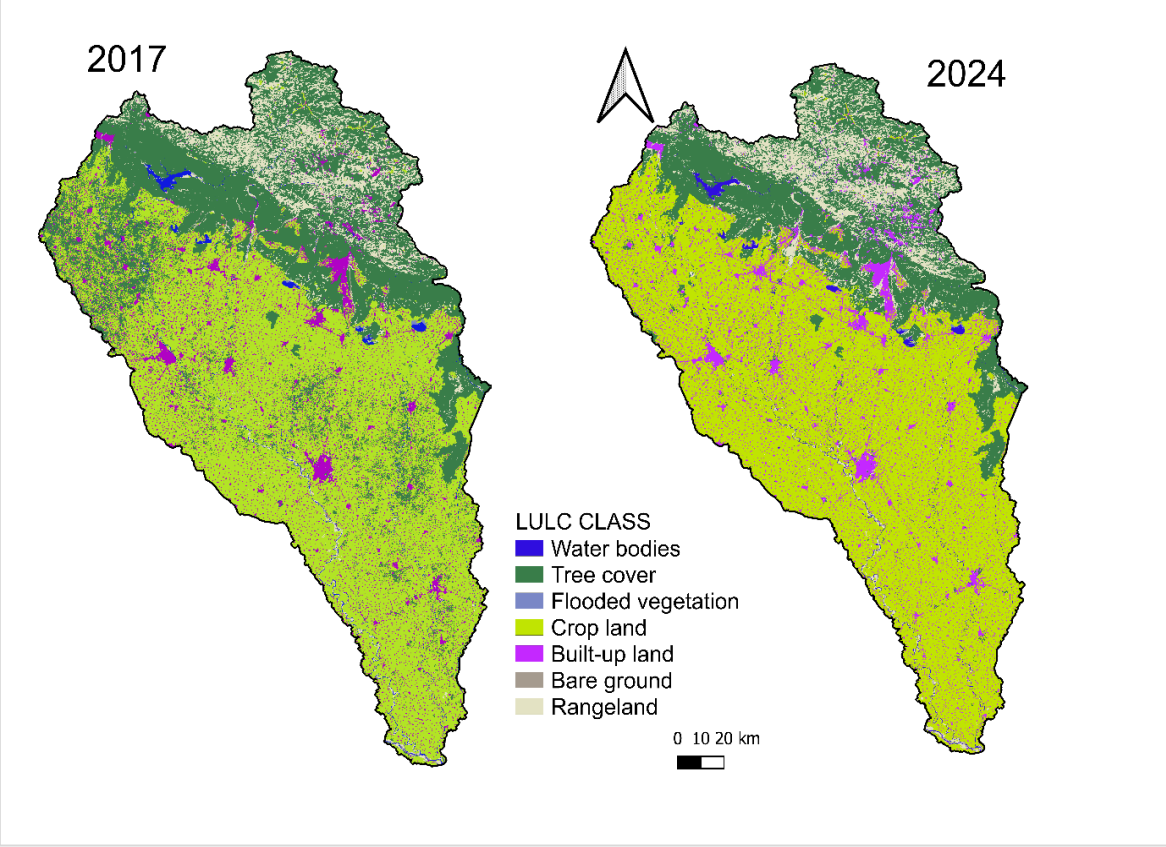


Figure 5. LULC map for the years 2017 and 2024.

The LULC analysis revealed considerable changes in the spatial extent of different land cover classes in the basin from 2017 to 2024 (**Table 2**). The total area of the individual LULC classes showed both increasing and decreasing trends during the study period. The cover experienced the greatest reduction, decreasing from 9433.079 km^2 in 2017 to 6686.449 km^2 in 2024, which is a 29.12% decrease. This is the greatest absolute increase among the expanding LULC classes. The area under the crop increased from 1922.36 km^2 in 2017 to 19132.57 km^2 in 2024, representing an 11.17% increase. The rangeland area increased from 2324.58 km^2 in 2017 to 2832.39 km^2 in 2024, representing a 21.85% increase. The built-up area increased from 2379.19 km^2 in 2017 to 2723.93 km^2 in 2024, a 14.49% increase. This finding highlights the notable changes in the developed area and urbanisation in the basin. Water bodies decreased from 358.70 km^2 in 2017 to 351.93 km^2 in 2024, a reduction of 1.89%. The area of flooded vegetation decreased only slightly, from 18.64 km^2 to 18.19 km^2, representing a 2.20% decrease. Bare ground areas decreased from 115.14 km^2 in 2017 to 94.07 km^2 in 2024, resulting in a reduction of 18.30% (**Figure 5**).

3. 3. Correlation between ET and the control parameters in the years 2017 and 2024

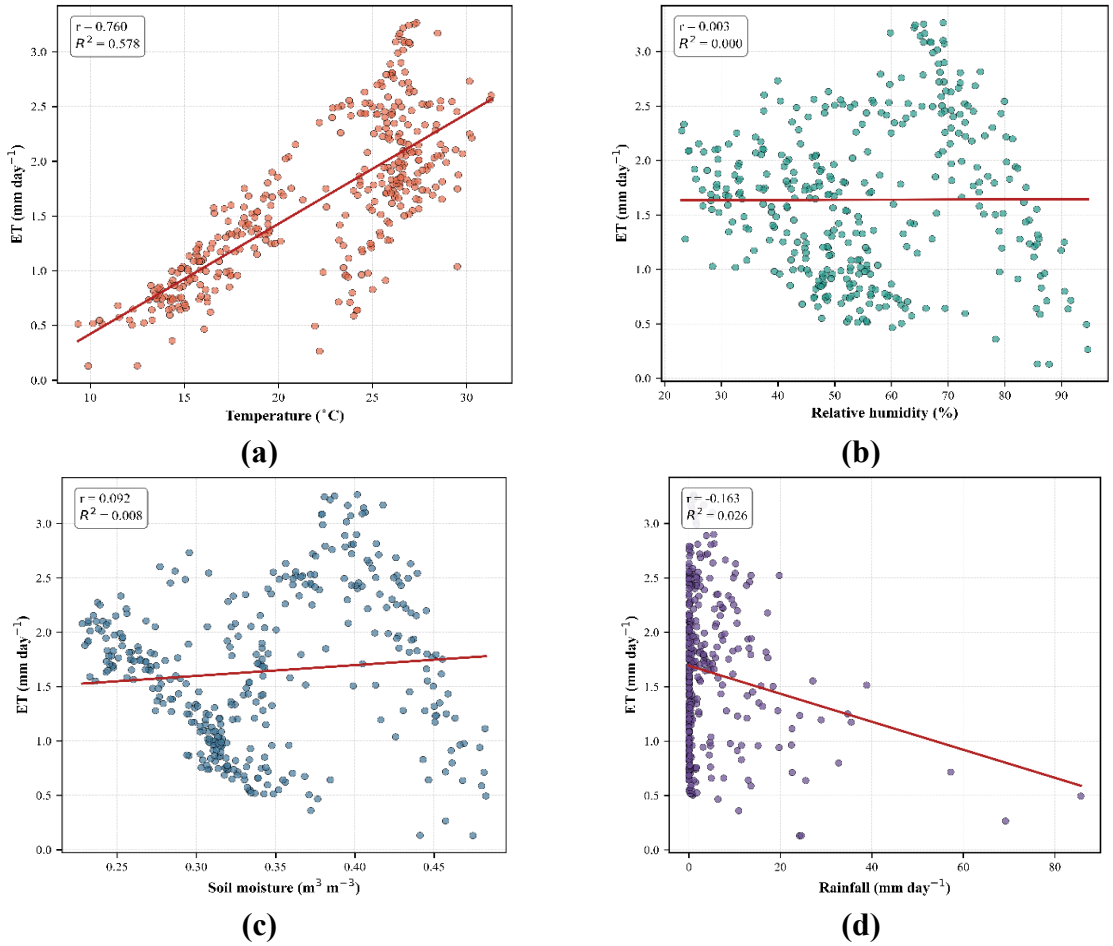


Figure 6. The daily scatter plots of ET with T, RH, R, and SM for the LULC tree class for 2017 are shown in Figure 6(a), (b), (c), and (d), respectively.

Relationships of daily ET with T, RH, R, and SM for the three classes in 2017 (**Figure 6**). The red line denotes the least-squares linear regression; Pearson's correlation coefficient (r) and coefficient of determination (R^2) are calculated for each plot. T had the strongest positive relationship with ET (R^2: 0.57). The positive slope indicates that the daily ET increased with increasing air temperature. More than 50% of the daily observations of ET are associated with T through a simple linear relation.

The other parameters are very weakly related to RH, SM, and R, with very low R^2 values, which may be because RH interacts with parameters such as T and the vapour pressure deficit and cannot serve as an independent controlling factor. Rain has a weak negative relationship and acts as a factor that increases water availability in the soil, which depends on many other parameters. SM is weakly positively related; if SM is high, it indicates high vegetation transpiration. Weak relationships indicate that ET was not strongly water-limited during the year 2017 or that SM is surface moisture and does not represent the deeper root zone water to trees. SM does not show high variability, which could explain the weak relationships.

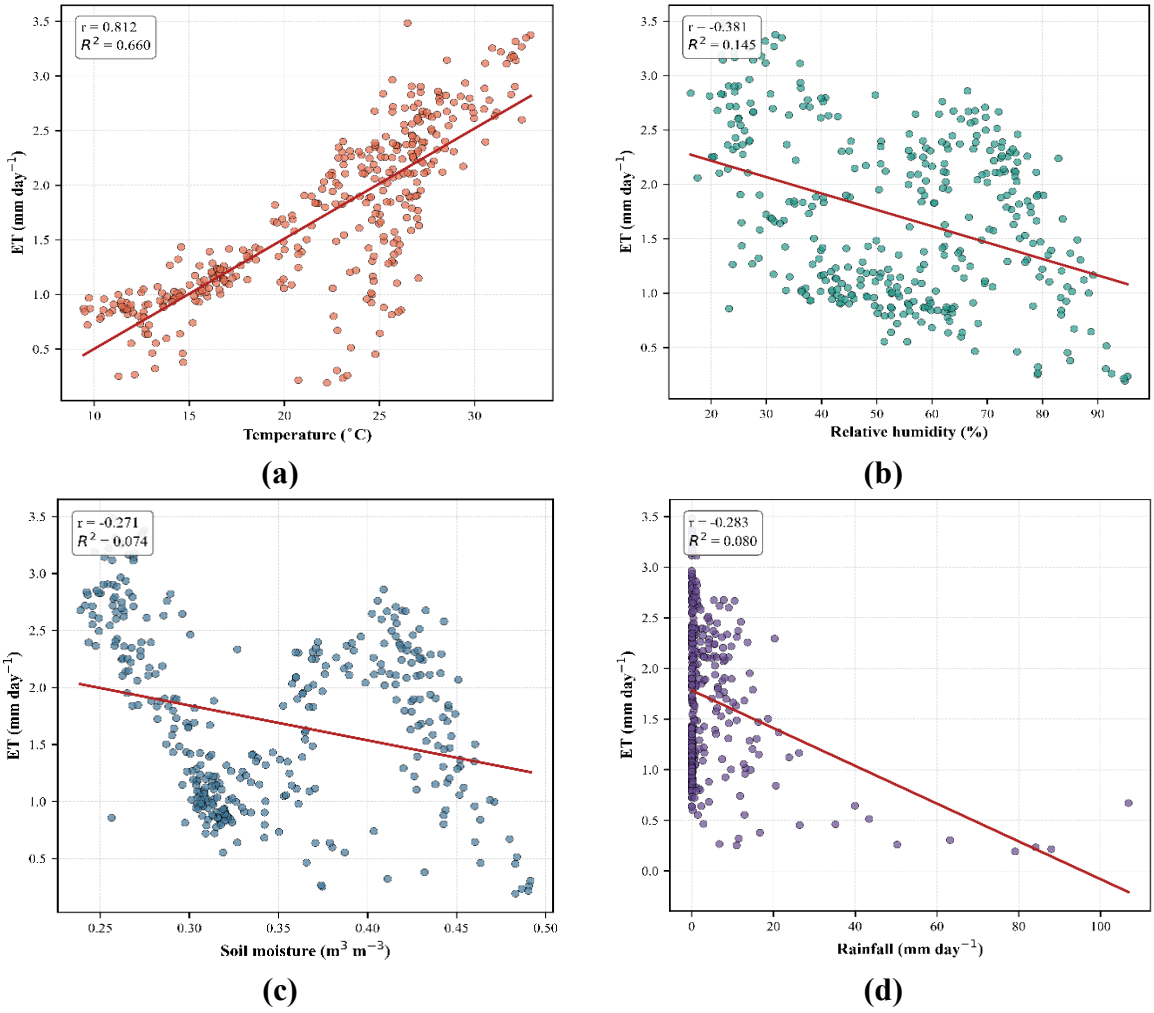
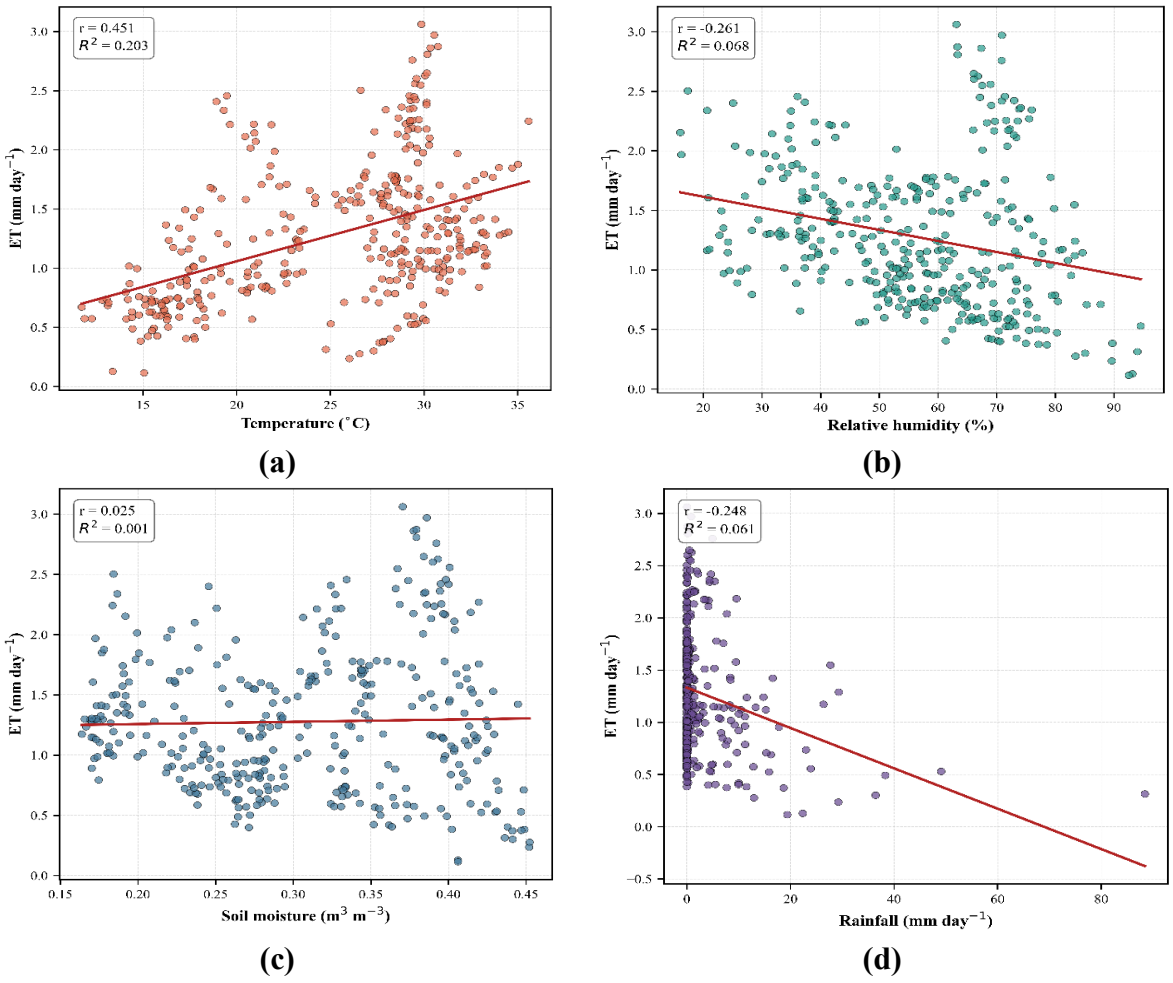


Figure 7. The daily scatter plots of ET with T, RH, R, and SM with LULC class trees for the year 2024 are shown in Figure 7(a), (b), (c), and (d), respectively.

Relationships between daily ET and T, RH, R, and SM for 2024 are shown in **Figure 7**. ET is strongly related to T, with an R^2 of 0.66, which indicates that more energy is available for evaporation and transpiration and that more vegetation is available. ET was moderately correlated with RH (0.14 R^2), weakly correlated with R, and weakly negatively correlated with SM, indicating the need for other parameters to be evaluated for a more effective calculation of ET.



Figures 8(a-d). Represent daily scatter plots of ET with T, RH, R, and SM for the LULC class crops for the year 2017.

Relationships of ET with the factors T, RH, R, and SM for the LULC class crop for the year 2017. ET has a moderate relationship with T (R2 = 0.203) and explains about 20% of the daily variation in ET for the crop in 2017. In contrast, the RH is weakly negatively correlated and indicates reduced atmospheric evaporative demand under humid conditions. R was weakly negatively correlated; perhaps R is associated with cloud cover and season. SM is weakly positively related; this is an important factor, but in basin-wide studies, major factors such as T and RH dominate at the basin scale (**Figure 8**).

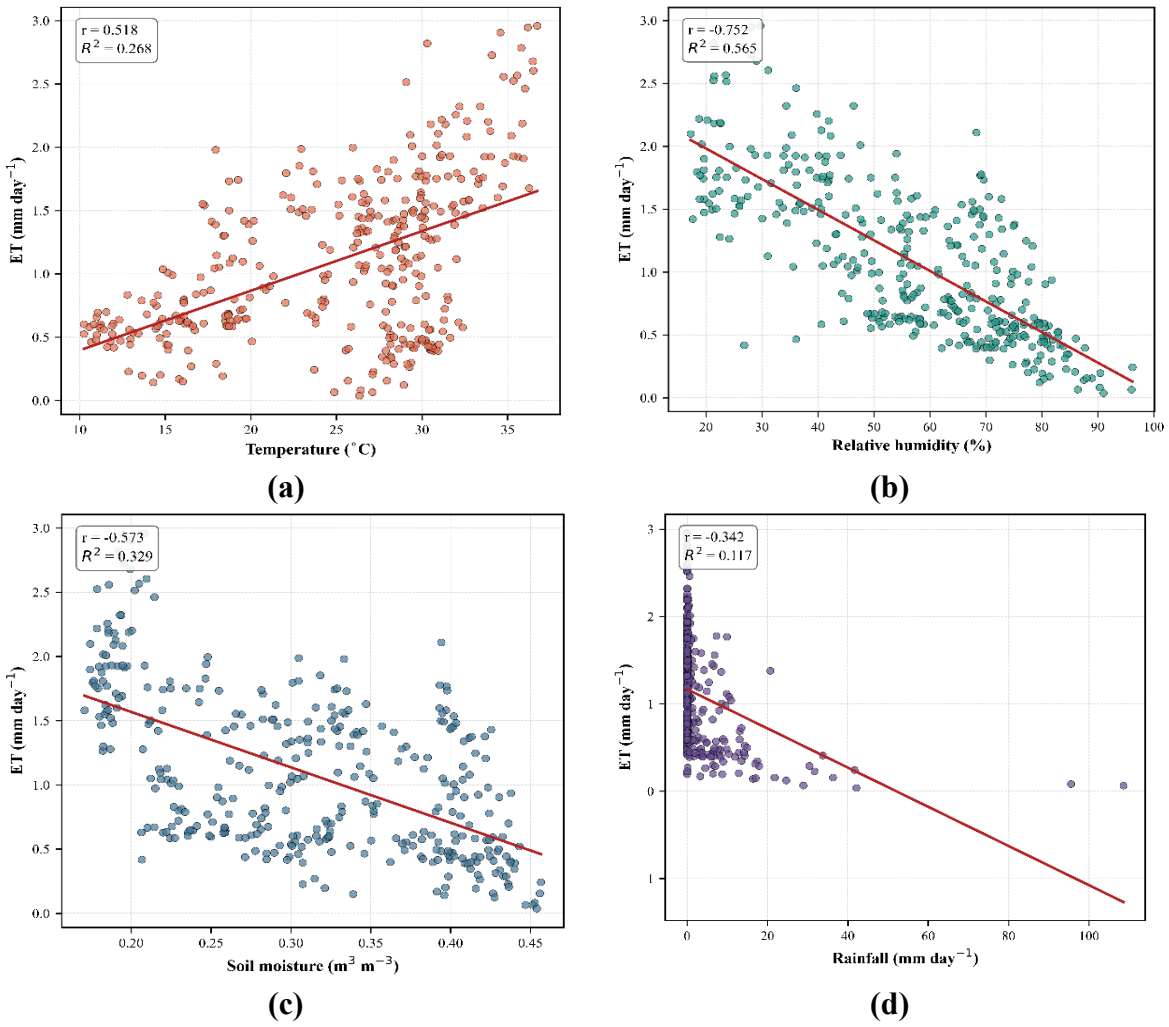


Figure 9. The daily scatter plots of ET with T, RH, R, and SM for the LULC class crops for the year 2024 are shown in Figure 9(a), (b), (c), and (d), respectively.

Correlation of ET with the factors T, RH, R, and SM for the LULC class crops in 2024. ET is moderately correlated with T (0.26) and R^2, and in 2024, RH and SM also become strongly controlling factors (R^2 values of 0.56 and 0.32, respectively). As above, the LULC changes reveal that the crop area increases over the years from 2017 to 2024 across the basin. These factors partly contribute to the basin in the year 2024, indicating that crop ET is more sensitive to hydrodynamic conditions, whereas tree ET remains T-controlled (**Figure 9**).

4. DISCUSSION

Analysis of the ET trends over the long-term period in the RGRB (1995–2024) revealed the results of four independent analysis methods, which all indicated a clear change in the water balance in the basin after the mid-2000s, with the change being due mainly to intensified

agricultural activity. For instance, the Mann–Kendall test indicates a statistically significant upwards trend in annual ET ($\tau = 0.430$, $Z = 3.31$, $p = 0.000905$). This is a simple but strong nonparametric method that is applicable regardless of whether we can assume that the data are normally distributed (Mann, 1945). The mean annual ET is 766.74 ± 38.95 mm/year (median 766.98 mm/year; CV = 5.08%), with a variation over the years from 692.08 mm/year in 1998 to 888.84 mm/year in 2024. This trend is consistent with the ET trends established for the wider Ganga Basin, which reported an average annual increase of approximately 2.72 mm/year from 1982 to 2014 (Soni & Syed, 2021).

The Pettitt change-point test yields time-related accuracy that is not possible with the monotonic trend test. The test revealed that the year 2005 was a significant break point ($p = 0.0148$; Pettitt, 1979) and clearly divided the period of mostly negative ET anomaly (1995–2004) from the predominantly positive period (2006–2024), a duration that resulted in the extreme spike in 2024. The sudden shift that took place, rather than a gradual drift, occurred at the same time as the low-ET phases (1998 and 2003) that occurred before the break and high-ET periods (2009, 2012, 2024) thereafter, indicating that the water balance of the basin indeed reorganised around the mid-2000s instead of just varying. Although reduced monsoon rainfall during known national drought years (2002, 2004, 2009, 2014, and 2015) is likely to account for some low-ET events before 2005, 2010, and 2013, having been close to normal monsoon years proves that it is not only national monsoon failure affecting ET practices in the basin after the break point.

The LULC change for the period (2017–2024) led to the formation of a reasonable view of the structural mechanism underlying the change that occurred after 2005. The area of arable land increased by 1922.36 square km (which signifies an increase of 11.17%), while the area of pastures increased by 507.815 square km (i.e., approximately 21.85%). However, the area of forestland decreased sharply by 2746.63 square km (which signifies a 29.12% decrease), while the area of developed-up land increased by 344.745 square km (i.e., by approximately 14.49%). Land use change in the Ganga River Basin has shown that the adoption of agriculture and increased agricultural support have contributed to the increase in ET at the basin level (Anand et al. 2018; Patidar and Behera, 2019). Thus, although it is theoretically possible that forest loss contributes to reducing ET in the basin because of reduced soil moisture and decreased interception by the leaves of trees, the large agricultural areas cultivated by irrigated agriculture have led to greater ET (which reflects the findings of other researchers that in this situation, the increase in ET due to irrigation exceeds the decrease in ET caused by deforestation) (Huang et al. 2025). This land use evidence has filled a crucial void that the analysis of trends and change points alone would not have filled.

This finding points toward agricultural intensification and irrigation with groundwater as the probable cause of the shift in the ET regime in the mid-2000s, with the 2017–2024 LULC window indicating that the transitional phase of this process is in an accelerated state (Raghavendra et al., 2023; Kumar et al., 2023; McCabe et al., 2013).

From the analysis of the daily ET-driver relationships within tree and crop classes, it can further be argued that such land use interpretation has strong mechanistic support. When examined across 2017 and 2024, while the ET for the tree class continues to show strong, stable, and temperature-controlled behavior, with the temperature explaining more than 50% of the daily ET variability, this highlights the idea that temperature is the driving force behind the energy available for the process of latent heat exchange, while deep-rooted natural plants are persistently decoupled from variations in soil moisture over short periods of time (Young et al.

2022). In contrast, the crop class displays a significantly altered driver pattern over the same period, as temperature accounted for approximately 20% of the daily ET variability in 2017, whereas RH, precipitation, and soil moisture were weakly correlated drivers; however, by 2024, RH and SM became strong drivers with increasing temperature. By comparison, this increase in the hydrodynamic sensitivity of the crop class aligns strongly with the increase in cropland area (Ahmadpour et al., 2025; Huang et al., 2025, Maina, et al., 2024).

An increase in basin ET indicates a shift in land surface use from natural landscapes to agricultural areas rather than a direct effect of climate change. The original ET regime of forests, controlled mainly by temperature, is now being replaced by an irrigation-dependent regime related to crops. The 29.12% reduction in tree cover not only signifies a change in vegetation but is also related to one of the most hydrologically stable land covers in the basin (Huang et al., 2025). Moreover, the 21.85% increase in the area of the rangelands suggests that the tree-covered areas are being replaced by degraded or shrubland regions, which have lower ecological value. This shift toward more water-dependent and less stable land cover types is likely to increase ET fluctuations. The link between ET sensitivity across different land cover types and various hydroclimatic factors significantly influences agricultural and environmental research in the Indo-Gangetic and Himalayan foothill basins. This finding offers a possible explanation for how agricultural growth affects long-term water balance changes, highlighting the need for land use awareness in terms of irrigation, groundwater management, and climate adaptation strategies (Bhagat et al., 2022; Raghavendra et al., 2023; Rajouria et al., 2025).

5. CONCLUSIONS

This study has scrutinised the long-term changes in ET for the Ramganga Basin (1995–2024) related to land use/land cover (LULC) changes and the influence of meteorological and hydrological factors on ET for tree and crop classes that have taken place in the basin and how these processes have affected the water balance in the basin. The Mann–Kendall test confirmed that there is a trend toward an increase in the annual ET ($p = 0.000036$). The mean annual ET is equal to 766.74 ± 38.95 mm/year and varies from 692.08 mm/year in 1998 to 888.84 mm/year in 2024. The Pettitt test for the detection of the change point allowed us to determine the beginning of the change precisely; the year 2005 was identified as the year in which the change in the ET regime changed from mainly negative (1995–2004) to mostly positive (2006–2024) ($p = 0.0148$). The LULC change analysis conducted for the period from 2017 to 2024 provides a possible structural explanation for this transition.

The cropland area increased, while there was a significant decrease in tree coverage, and the developed-up area also increased in size by nearly 14.49%. The expansion of agricultural and urban areas at the expense of natural areas explains the increase in ET observed and is in line with the increase in ET values corresponding to the timing of and results detected in the research, as the increase in ET should be connected to the intensification of cropland irrigation. In addition, the analysis of daily ET drivers helped us better understand the processes behind this transition. ET in the tree class was strongly temperature controlled in 2017 and 2024, which shows that energy-limited processes prevailed and were not strongly affected by soil-related factors.

Conversely, the ET of the crop class significantly increased from a weak temperature-control reference in 2017 to strong relationships between ET and temperature, RH, and SM,

which proves that compared with natural forests, irrigated agriculture is more sensitive to hydrology.

The RGRB has experienced pronounced changes in hydroclimatic conditions since the middle of the past decade, caused not only by the increase in temperature but also largely by the intensification of agriculture, characterised by the shift from natural forests to irrigation-dependent croplands; the increase in the scale and impact of ET in turn affects irrigation water use, groundwater recharge, and water flow to the Ganga River. Thus, it is important to emphasise the necessity of integrating land use into water resource management, especially considering the different sensitivities of the evaporative processes of forestland and agricultural land under the conditions of continuing agricultural expansion.

For future studies, it will be essential to go beyond the impressions that have already been presented during discussions of related research and incorporate area-related data on rainfall, groundwater and irrigable lands specific to the basins to achieve more reliable conclusions regarding the observed changes in ET; the Sen's slope estimator for establishing the pace of ET growth should be used, and LULC and driver connection analysis beyond the timeframe used in this study should be performed to assess whether the alteration regarding sensitivity to crop-ET identified in the present research during the years 2017–2024 continues to develop or stabilise considering the ongoing process of agricultural intensification. Such developments would further prove the connection between agricultural land use changes and the hydrometeorological shifts identified in this study.

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