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ORIGINAL RESEARCH ARTICLE

# Potential and actual evapotranspiration and Landsat-derived indices

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**ABSTRACT**

**BACKGROUND AND OBJECTIVES:** Evapotranspiration is an important component of water balance associated with the hydrological cycle and biological processes. Accurately estimating the rate of evapotranspiration is crucial for understanding fluctuations in water availability and effectively managing water resources in a sustainable manner. The study aims to examine the correlation between actual evapotranspiration and potential evapotranspiration by assessing the linkages with vegetation and snow cover in an ecologically fragile located in the northwestern Himalaya.
**METHODS:** The present study uses remote sensing Landsat satellite data series to map vegetation cover and snow cover in the area. Remote sensing data accessed from Moderate Resolution Imaging Radiometer evapotranspiration project data was used for calculating evapotranspiration and potential evaporation. The data from the Climatic Research Unit (2000–2022) was additionally utilized for the computation of potential evapotranspiration. The study investigates variances in evapotranspiration and explores correlations between normalized difference vegetation index and normalized difference snow index. It further examines the correlation between potential evapotranspiration and actual evapotranspiration.
**FINDINGS:** The study conducted from 1991 to 2021 demonstrates a notable rise in vegetation cover by 20.18 percent, showcasing spatial variations across the region. Conversely, there has been a significant decline in the extent of snow cover throughout this period. A positive correlation was identified between vegetation cover and evapotranspiration, whereas a negative correlation was observed between snow cover and evapotranspiration. Actual evapotranspiration is on the rise while potential evapotranspiration is declining throughout the region.
**CONCLUSION:** Hydrological cycle of a region is governed by many factors such as climate (precipitation, temperature), geohydrology, land use and land cover, socio-economic condition of habitants and institutions. Vegetation cover, snow cover, actual evapotranspiration and potential evapotranspiration and their relationship indicates changes in local and regional climate. An incremental rise in plant growth across the study site, coupled with spatial variability and a reduction in snow cover in the elevated mountainous zone, is influencing both actual evapotranspiration and potential evapotranspiration. Increase in actual evapotranspiration in the High Himalayan area of Himachal Pradesh attribute to substantial increase in vegetation cover in the dry cold desert region. The findings of the study will contribute to the comprehension of essential elements of water cycles and water budgets, facilitating improved resource allocation for climate-resilient sustainable initiatives.



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## INTRODUCTION

Climate change stands out as one of the most significant challenges confronting our planet in the contemporary era. The looming climate crisis has never been more pressing or apparent than it is in present time (WHO, 2003; EU, 2018). The accelerated pace of climate change has become another recent event that has attracted considerable attention. This phenomenon is unfolding at a rate that is even faster than what was previously anticipated, as emphasized in a report published by the United Nations (UN). The Intergovernmental Panel on Climate Change (IPCC) said that estimates suggest a possible rise in global temperature of between 1.4 and 5.8 degrees Celsius (°C) to a projected 20 percent (%) change in rainfall between 1990 and 2100 (IPCC, 2001). Despite uncertainties surrounding the precise magnitude of these changes, various studies and reports, including those by the United Nations Framework Convention on Climate Change (UNFCCC) in 2007, Alcamo *et al.* (1997); Allen *et al.* (1998); Clifton *et al.* (2010); Yang *et al.* (2011) converges on the overarching trend of climate change and its potential ramifications. According to the IPCC, Fifth Assessment Report (AR5) (Stocker *et al.*, 2013), natural and human factors have been causing changes in global and Indian sub-continental climates over the past century and the vulnerability is also increasing in western Himalaya (Kumar *et al.*, 2023a). The hydrological cycle is experiencing a rapid intensification due to substantial global warming, leading to adverse impacts on ecosystems, agriculture, and water resources world-wide. Modeling studies have revealed unprecedented changes in the region under investigation, with extreme fluctuations in surface air temperature, both at its maximum and minimum, as well as heavy and extremely heavy precipitation. Additionally, variations in the average daily value and trend have also been associated with these changes (Halder *et al.*, 2016). The runoff, evapotranspiration (ET), precipitation, soil moisture, and surface temperature are the key mechanisms that contribute to the variations observed across India. Gaining a more precise and comprehensive understanding of these mechanisms is crucial in order to develop an improved model projection of the future climate and current anthropogenic surface weather conditions in the region (Stocker *et al.*, 2013). High Mountain Asia is home to the largest ice mass besides the polar ice sheets (RGI Consortium, 2017). It is one of the most important and yet one of the most vulnerable mountain water towers in the world. These water towers serve as freshwater sources for downstream regions (Immerzeel *et al.*, 2020; Viviroli *et al.*, 2007; Yao *et al.*, 2022; Pritchard, 2019; Biemans *et al.*, 2019; Azam *et al.*, 2021). The accelerated transformation of snow (Lau *et al.*, 2010; Usha *et al.*, 2022) and ice (Brun *et al.*, 2017; Hugonnet *et al.*, 2021; Maurer *et al.*, 2020) will have a significant socioeconomic impact on upland and downstream populations (Azam *et al.*, 2021) as well as high mountain communities (McDowell *et al.*, 2022). The hydrologic response of high-mountain catchments is further complicated by climate change-induced alterations in precipitation patterns, permafrost thawing, subsurface water storage, and evapotranspiration. Most climate change studies predict that glacier runoff will peak in the coming decades, especially in the Indus and Ganges basins (Huss and Hock, 2018; Nie *et al.*, 2021). However the impact on the downstream water supply is remains uncertain, as a considerable portion could potentially be lost through evapotranspiration and atmospheric recycling this adds significantly to the uncertainty surrounding future estimates of the amount of water available in and coming from mountain regions. Given the context of climate change, it becomes crucial to investigate the potential evapotranspiration (PET) in order to effectively manage water resources (Zeng *et al.*, 2019; Lin *et al.*, 2018; Zhou *et al.*, 2017; Wang *et al.*, 2014; Lingling *et al.*, 2013). Evapotranspiration increases in response to changes in climatological parameters, like temperature (Chowdhury and Al-Zahrani, 2015). Consequently, the escalating temperatures, heightened evapotranspiration, and unpredictable rainfall patterns could potentially harm the water needs of crops and their overall water supply (Chowdhury *et al.*, 2016; Rotich and Mulungu, 2017; Salman *et al.*, 2020). This phenomenon may be caused by the expansion of plant leaves' stomata in response to high temperatures, allowing water vapor to escape (Onyutha, 2021; Urban *et al.*, 2017). Numerous studies have been carried out worldwide to investigate the characteristics and causes of differences between actual and potential evapotranspiration on a global scale. Various global research projects indicate that climate change greatly influences PET, with values differing depending on the region and the climate conditions considered when using various outputs from global climate models (GCM). Li *et al*., (2017) focusing on Qilian Mountains of China examined the effects of land use/ land cover and climate change on evapotranspiration and found that climate change had the greatest influence in China in between 2001 and 2013. Their findings suggest that future PET increases relative to the baseline period of 1960–2015. The same pattern was noted by Yadeta *et al*., (2020), who investigated the PET in the Kessem sub-watershed of Ethiopia in the light of climate change. Liambila and Kibret (2016) conducted a study on the Eastern region of Ethiopia to quantify the effects of climate change on the suitability of land for crop production in rain fed systems. The findings indicate that a rise in mean temperature, rainfall, and evapotranspiration resulted in the prolonged cyclic patterns of climate change. Onyutha (2016), in their study in Nile River countries observed that there has been a significant increasing trend in PET from 1985 to 2011. Numerous comparable studies have been conducted in nations such as the United States of America (USA), Iran, Egypt, Thailand, and Australia, among others, to measure the PET and AET, as well as their spatial variances, in correlation with diverse determining factors (Suwanlertcharoen *et al*., 2023; Wang *et al*., 2021; Hashem *et al*., 2020; Arast, 2020; Fawzy *et al*., 2021; Guerschman, 2022). The conducted studies have uncovered significant and extensive fluctuations in evapotranspiration, posing a threat to the stability of food production, people's livelihoods, and the overall sustainability of the environment. Few Indian studies have also investigated the features and reasons behind variation of ET over India so far. Bhimala *et al*., 2023 focusing on the entire Indian subcontinent studied the long-term trend (1980-2018) of actual evapotranspiration and its components like transpiration, bare soil evaporation, inception loss and open water evaporation etc. Their study revealed that there is an increasing trend (1.33 mm/y) in annual AET due to the rising trend in ET (1.91 mm/y) and canopy interception evaporation (Ei) (0.16 mm/y). Singh and Singh, 2023 conducted a study on impact of climate and land use and land cover change (LULCC) of evapotranspiration of Indian region suggest that changes in precipitation and LULCC across the Indian subcontinent have contributed significantly to changes in ET in different seasons. According to them the monsoon season increases precipitation, and soil evaporation is found to increase along with an increase in NDVI followed by canopy evaporation and transpiration. In their research on the trend analysis of evapotranspiration in India, Goroshi *et al.* (2017) discovered a rising trend in the average ET of 0.156 millimeters per season per year (mm/season/y) during the north east winter monsoon across the Indian subcontinent. Moreover, a significant increase (>4 mm/y) was noted in the arid and semi-arid regions. The Western Himalayan region, encompassing the picturesque landscapes of northern India, is a crucial ecological zone with diverse ecosystems and unique environmental challenges. The ongoing impact of climate change and land use on the delicate balance of this area underscores the importance of grasping essential processes like evapotranspiration for effective resource management and environmental preservation. Remote sensing technology, particularly satellite-based observations, offers a valuable tool for monitoring land surface conditions and understanding the dynamics of water movement within the environment. The integration of LANDSAT derived indices with evapotranspiration studies provides a comprehensive approach to analyze the spatiotemporal variations in vegetation, land surface temperature, and overall water dynamics in the Western Himalayan region. Various indices, such as the Normalized Difference Vegetation Index (NDVI), Normalized Difference Snow Index (NDSI), Soil Adjusted Vegetation Index (SAVI), and Land Surface Temperature (LST), derived from LANDSAT satellite data, offer insights into vegetation health, stress and land surface temperature variations. Several studies have emphasized the significance of integrating remote sensing techniques with hydrological modeling to improve the accuracy of evapotranspiration estimation (Senay *et al*., 2019; Bastiaanssen *et al*., 2005). Furthermore, study conducted in comparable mountainous areas has emphasized the significance of taking into account variances in topography and vegetation when studying evapotranspiration (ET) (Wang *et al*., 2015). Previous studies indicate an increase in the vegetation cover in the Himachal Himalaya. Studies depict that there is notable increase in vegetation cover in the Middle and Upper altitudinal zones (4000 m to 5000 m and above) in the Spiti valley of Himachal

Himalaya (Kumar *et al.*, 2018). Land use land cover change analysis carried out in the Satluj river basin of Himachal Himalaya reveals a consistent pattern of vegetation cover growth in the upper elevations (3000m to 4500m and above) of Spiti and Hangrang valley from 1980 to 2020 (Kumar *et al.*, 2023b). Apple orchards are shifting towards higher altitude in the Himachal Himalaya in the last few decades (Sahu *et al.*, 2020) increasing vegetation cover in the region. Different climate scenarios have been projected to have a notable impact on the hydrological regime of the Manipur River basin, leading to significant changes in both runoff and evapotranspiration. The escalation of forest evapotranspiration in the Himalayan region as a result of climate change is contributing to the occurrence of extreme rainfall events (Singh *et al.*, 2021). The present study aims to bridge the gap in the studies establishing linkages between evapotranspiration dynamics and the information embedded in Landsat derived indices across the diverse landscapes of the Western Himalayan region. There is dearth of such type of studies performed in the Himalayan Mountain system. Investigating the relationships between these indices and evapotranspiration rates, authors seek to enhance the understanding of the complex interactions between land surface processes and climatic conditions in this ecologically sensitive area. The hypothesis derived from the aforementioned analysis suggests that as a result of climate change-induced snow cover melting and vegetation cover expansion in the upper Himachal Himalayan region, there have been spatial and temporal alterations in both actual and potential evapotranspiration (Fig. 1a).

The purpose of this research is to assess the spatial and temporal correlation between snow cover and vegetation dynamics on actual and potential evapotranspiration in the mountainous areas of Himachal Pradesh. Evapotranspiration plays a crucial role in the hydrological cycle by enabling the transfer of moisture and evaporation. Atmospheric conditions, such as temperature and humidity, play a significant role in determining the rate of this process, thereby shaping local and regional weather patterns. Given society's dependence on water, both the actions of society and the natural processes it interacts with are mutually influential. It becomes imperative to adopt thoughtful water resource management practices to ensure sustainable cohabitation (Fig. 1b). The study has been carried out in Himachal Pradesh, Western Himalayas in India, taking open-source remote sensing datasets for the period 2000 to 2022.

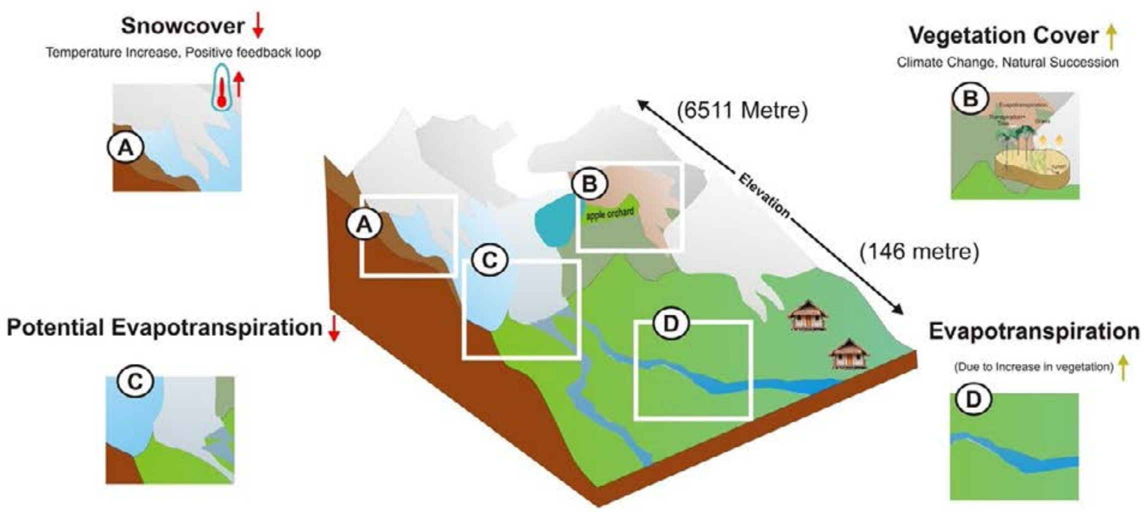


Fig. 1a: Graphical design of evapotranspiration and their outcomes

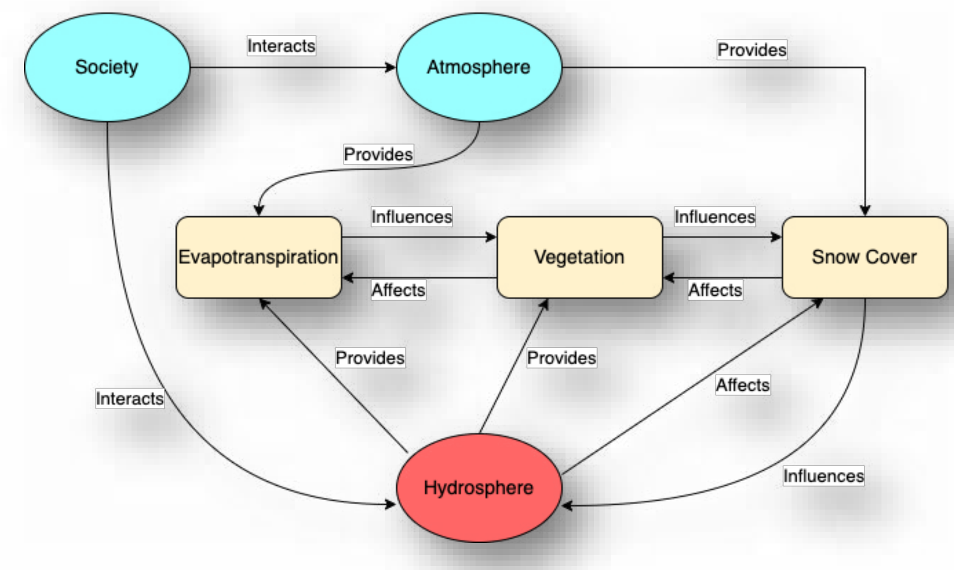


Fig. 1b: The cyclical relationship of evapotranspiration

## MATERIALS AND METHODS

*Study area*

Himachal Pradesh is a mountainous state in the Western Himalayas that shares borders with Jammu and Kashmir to the north, Uttarakhand to the southeast, Haryana to the south, Punjab to the west and Tibet (China) to the east. With a population of 6.8 million (as of the 2011 Census), Himachal Pradesh makes up 5.8% of all of India's land area, covering 55,673 square kilometer ($km^2$). Himachal Pradesh spans a land area of 5.57 million hectares and is situated between 30° 22' and 33° 12' north (N) and 75° 47' and 79° 04' east €. Its altitude varies from 146 to 6511meters (m) above mean sea level as shown in Fig. 2.

The varying population distributions across the state's districts can be attributed to the hilly topography and challenging agro-climatic conditions present in certain areas, rendering them unsuitable for human settlement. The quantity and uneven distribution of rainfall are crucial factors for a state such as Himachal Pradesh, where the geographical features hinder the establishment of irrigation systems. Nevertheless, the economy of the state continues to rely significantly on the agricultural and horticultural industries. From a geographical perspective, the state consists of three main regions: the greater Himalayas, the lesser Himalayas (middle Himalayas), and the Shiwaliks (outer Himalayas). Jaswal *et al.* (2015) stated that in the southern low tracts, the climate is hot and sub-humid tropical (altitude 450-900 m); in the northern and eastern high mountain ranges, it is warm and temperate (altitude 900-1800 m); cool and temperate (altitude 1900-2400 m); cold high mountain (altitude 2400-4000 m); and snowy frigid alpine (altitude > 4000 m). Himachal Pradesh experiences heavy snowfall in the winter due to the cold desert region, which receives minimal rainfall. The southwest monsoon and western disturbances from the Asian continental air mass play a crucial role in determining the weather patterns in the region. In the state, precipitation decreases from the south to the north and from the west to the east. The Kangra district receives the most rainfall in Himachal Pradesh, while the Lahaul-Spiti district receives the least. Increasing trend shows in both temperature and rainfall in study area from 2000 to 2021. The state is home to five major river systems, the Sutlej, Beas, Chenab, Yamuna, and Ravi that drain nearly 95% of the state's land area.

*Methodology*

The development of potential evapotranspiration takes several decades. Thornthwaite (1948)

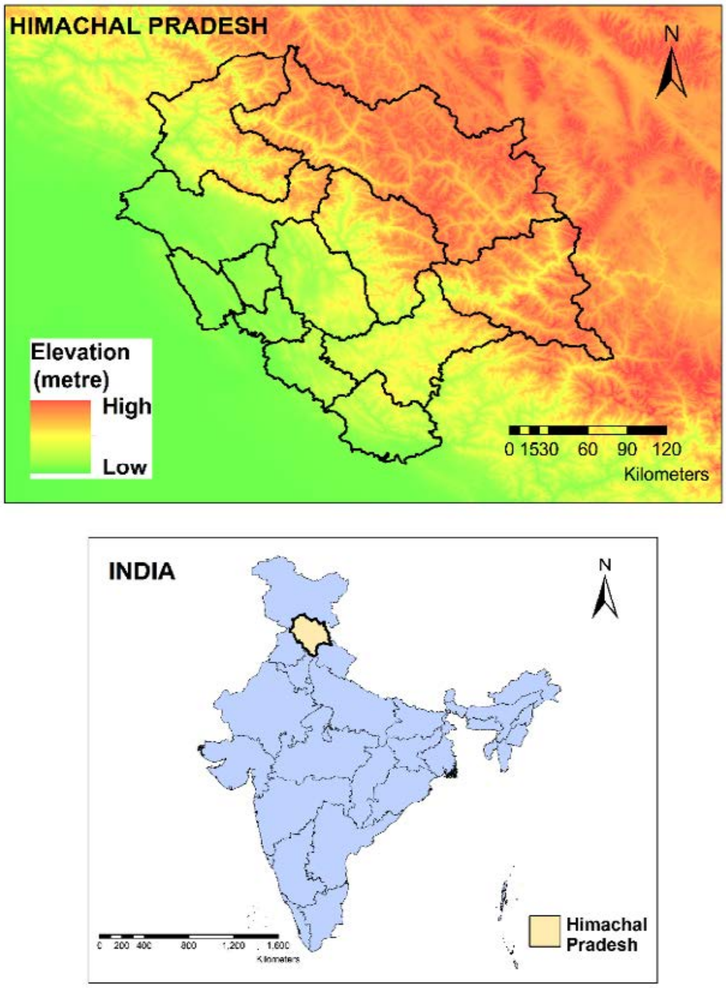


Fig. 2: Geographic location of the study area in Himachal Pradesh, Western Himalayas in India with altitude gradient

differentiated it from ET by introducing the term "potential evapotranspiration" after analyzing rainfall and water utilization across US states. The amount of water that can be transferred from land or water to the atmosphere is known as atmospheric evaporation demand. Thornthwaite (1948) defined PET as "the combined evaporation from the soil surface and transpiration from plants, represents the transport of water from the earth back to the atmosphere, the reverse of precipitation". The Earth Observing System (EOS) project by the National Aeronautics and Space Administration (NASA) incorporates the Moderate Resolution Imaging Radiometer (MODIS) ET project. This initiative utilizes satellite remote sensing data to calculate global terrestrial ET from the Earth's surface. The primary data source for this study was MOD16A2GF.061 which was obtained from the Application for Extracting and Exploring Analysis Ready Samples (AppEEARS) of National Aeronautics and Space Administration (NASA). The monthly AET and PET datasets are primarily synthesized using MOD16A2, an 8-day synthetic dataset with a spatial resolution of 500 m, which is part of the ET product. The data format projection and conversion were carried out using Microsoft Excel, while the GIS environment was utilized for the transformation and mapping processes. The monthly and annual PET and AET data for the study area were obtained following data processing steps. The data on potential evapotranspiration was obtained from the Climate

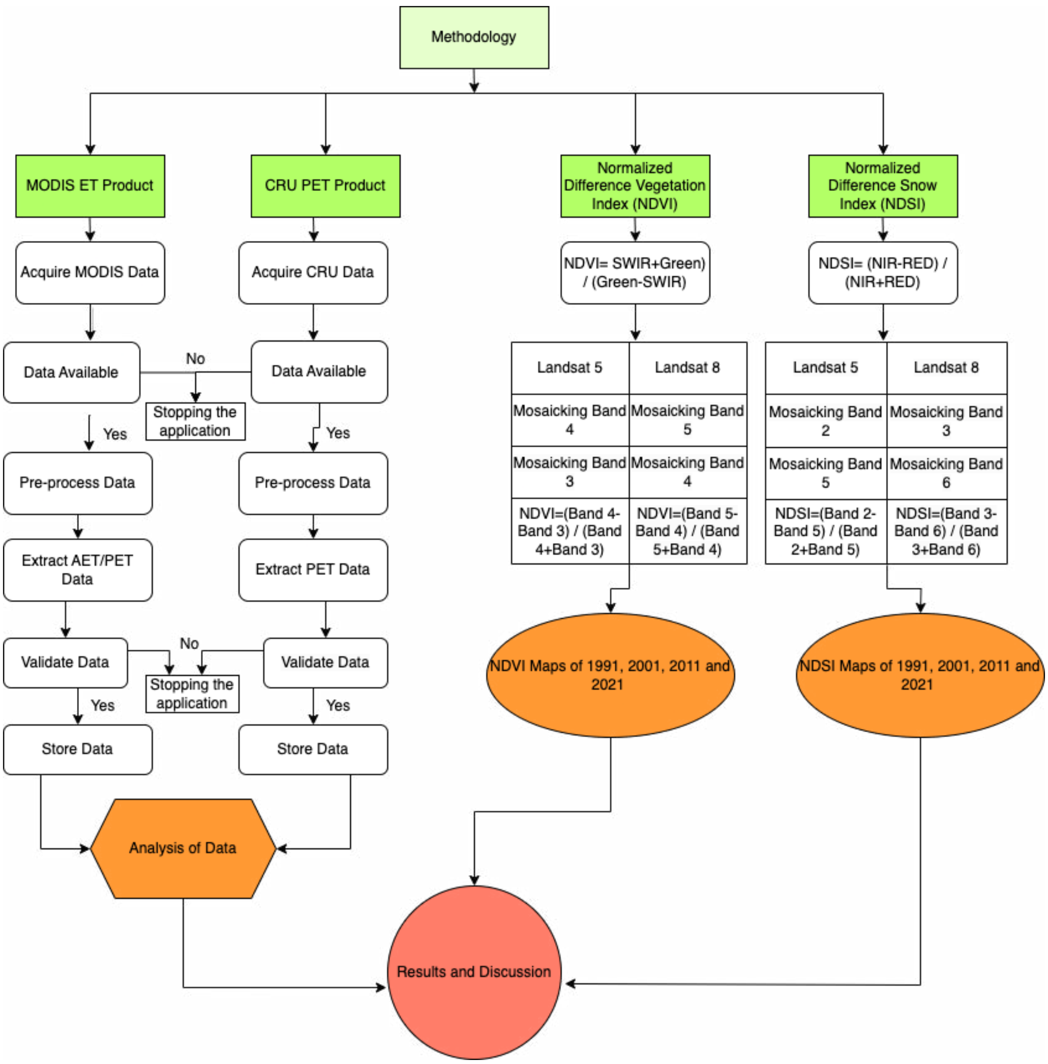


Fig. 3: Methodological flowchart of this study

Research Unit (CRU) (Harris *et al.*, 2020) for the period 2000 to 2022. (Fig. 3). The study employed statistical technique correlation to determine the extent of the relationship among AET, PET, NDVI and NDSI.

*The Normalized Difference Vegetation Index (NDVI)*

This index is mainly focused on monitoring vegetation throughout the world. Healthy vegetation is recorded high in Near Infrared (NIR) spectrum and low in red light spectrum. NDVI is calculated subtracting red band from the NIR band. The value of the NDVI ranges between -1 to 1 having distinct interpretation for different values. Positive values (0.2 to 1) represent healthy and green vegetation, the higher the value, the denser and healthier the vegetation. Values near zero (0 to 0.2) values often indicate bare soil or sparse vegetation. Negative values (-1 to 0): Typically represent water bodies or surfaces with little or no vegetation, and Landsat 8 data for 2021 using Eq. 1 (Lata and Ghosh, 2022).

$$NDVI = (Red + NIR)/(NIR - Red) \quad (1)$$

Where,

The *NIR* is the reflectance in the infrared spectrum,

In the red spectrum, the reflectance is *Red*.

In the case of Landsat 8 data, the NIR band is represented by band 5 and the Red band is band 4. In contrast, for Landsat 5 and 7, the NIR band is band 4 and the Red band is band 3. Here, the raster calculator in ArcGIS 10.3.1 has been used to calculate the NDVI values for 1991, 2001, 2011, and 2021 using Landsat 5, 7 and 8.

*The normalized difference snow index (NDSI)*

NDSI is a parameter used in hydrological study to map the area covered by snow. Green band of the visible part of electromagnetic spectrum reflects snow more while Short Wave Infrared (SWIR) is highly absorbent. Due to the fact that snow absorbs a significant amount of the incoming radiation in the SWIR spectrum, whereas clouds do not, the Normalized Difference Snow Index (NDSI) can effectively differentiate between snow and clouds. An NDSI value, larger than 0.4, usually indicates a snow-filled area. The Himachal Pradesh NDSI values for 1991, 2001, 2011 and 2021 has been derived using Eq. 2 (Lata and Ghosh, 2022).

$$NDSI = (SWIR + Green)/(Green - SWIR) \quad (2)$$

Where,

*Green* is the reflectance in the green spectrum.

*SWIR* is the reflectance in the shortwave infrared spectrum.

Green band is band 3 and SWIR is band 6 in the Landsat 8 data. Band 2 is green and band 5 is SWIR in Landsat 5 and 7.

## RESULTS AND DISCUSSION

*The trend of spatiotemporal variation in AET and PET*

Jensen and Alen, (2016) investigate that the weather, vegetation, soil, waterbodies, management, and other factors influencing the AET rate. The spatiotemporal dynamics of actual evapotranspiration and potential evapotranspiration (PET) are influenced by various factors. The trends in evapotranspiration for different land-use types are associated with the biophysical attributes and variables that control evapotranspiration. Forest regions exhibit resilience to water stress during the typical dry season as a result of the adequate water storage found in the topsoil, supporting a continuous ET rate. (Khand *et al.*, 2017). Moreover, the height of the vegetation affected the AET peak rate which has been reflected in the value of range of AET during monsoon and winter season. Compared to other land-use categories, forests have higher ET values because they have more stomatal control than agricultural plants (Jensen and Alen, 2016).

The examination of real evapotranspiration and potential evapotranspiration through the utilization of MODIS data sets uncovers a significant spatial disparity within the designated research region. The relationship between PET and AET revealed a negative correlation, characterized by a high-magnitude

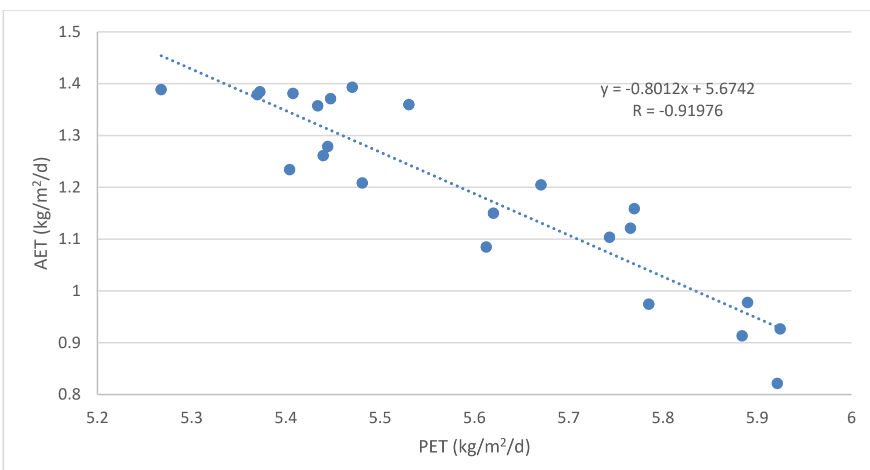


Fig. 4a: Relationship of AET with PET

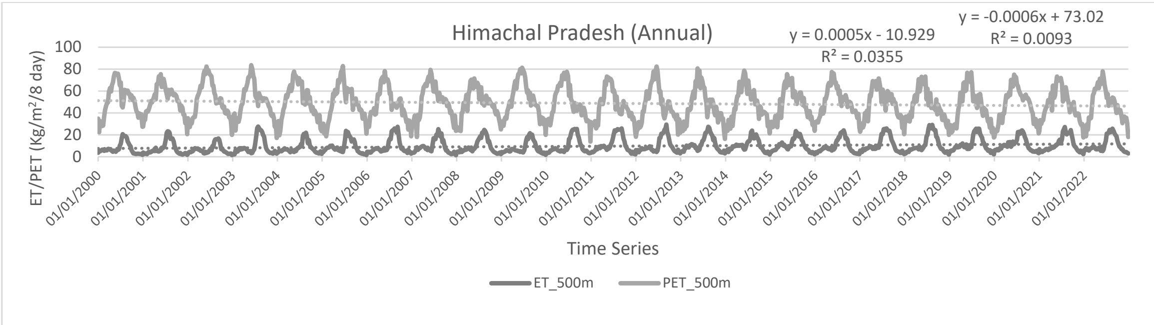


Fig. 4b: Temporal Distribution of AET/PET

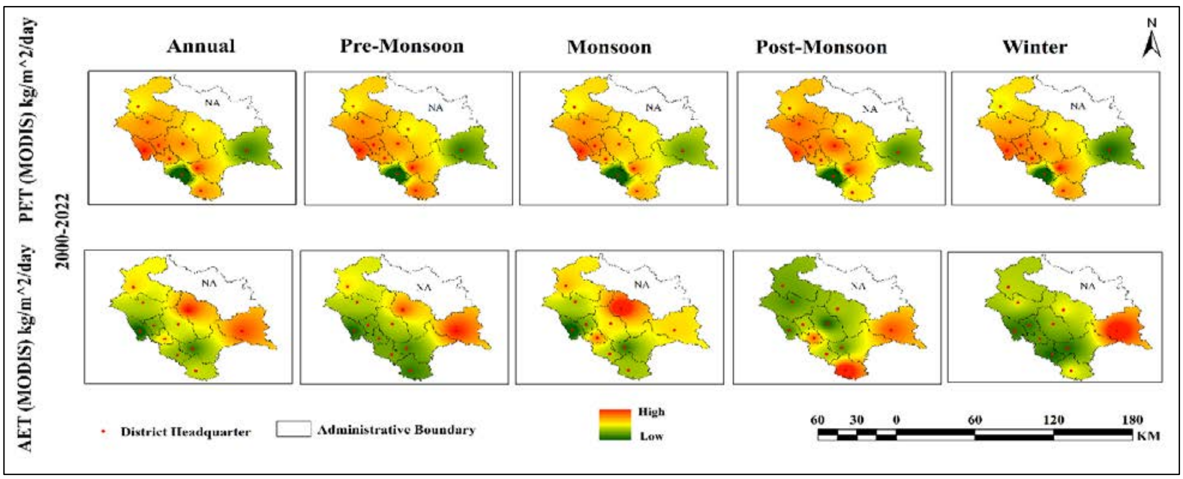


Fig. 4c: Spatial distribution of AET/PET

correlation coefficient of -0.91976 (Fig. 4a). Between 2000 and 2022, there was a variation in the yearly actual evapotranspiration of 0.640149 to 1.80571 kg/m²/d where 1.192768 kg/m²/d was determined to be the average annual AET (Fig. 4b and Table 1). It is worth noting that Kinnaur, located in the eastern region, stands out due to its high altitude and recorded the second-highest actual evapotranspiration (1.69632 kg/m²/d) among all regions. Surpassing Kinnaur, Kullu in Himachal Pradesh recorded the highest actual evapotranspiration (1.80571 kg/m²/d). Conversely, Una in the southwest exhibited the lowest actual evapotranspiration (0.640149 kg/m²/d), closely followed by Shimla in the south (0.829982 kg/m²/d) (Fig. 4c).

In contrast the average annual potential evapotranspiration for the same period was 5.593707 kg/m$^2$/d, whereas the minimum and maximum values were 1.041972 and 7.108779 kg/m$^2$/d, respectively. Una in the Southeast had the highest PET recorded, with Shimla in the South coming in second; on the other hand, Solan had the lowest PET recorded, followed by Kinnaur in the East.

The annual trendline of AET for Himachal Pradesh as a whole demonstrates an upward trajectory with a positive slope of 0.0005. On the other hand, the PET yearly trendline shows a declining trend with a -0.0006 negative slope. All stations display the identical AET/PET ratios pattern, aligning with the overall trend observed in Himachal Pradesh. Still, there are several noteworthy differences: The southernmost region, Sirmaur, has a significant increase in AET (trendline slope: 0.0018), while Kullu, in the central part, has a slope of 0.0007. Shimla and Chamba, conversely, exhibit a significant downward trajectory for PET, both with a slope of -0.0008. The

Table 1: Actual evapotranspiration (kg/m$^2$/d)

| District name | Annual | Pre-Monsoon | Monsoon | Post-monsoon | Winter |
|---|---|---|---|---|---|
| Bilaspur | 1.345965 | 0.713255 | 2.574185 | 1.086141 | 0.514266 |
| Chamba | 1.348373 | 1.217482 | 2.377106 | 0.558379 | 0.634284 |
| Hamirpur | 0.975883 | 0.721543 | 1.706046 | 0.688881 | 0.448007 |
| Kinnaur | 1.69632 | 1.901404 | 2.261583 | 1.153736 | 1.099275 |
| Kangra | 1.11019 | 0.948762 | 1.875408 | 0.478351 | 0.672554 |
| Kullu | 1.80571 | 1.727023 | 3.260972 | 0.660983 | 0.707201 |
| Mandi | 1.171675 | 0.936655 | 2.194395 | 0.359918 | 0.584239 |
| Shimla | 0.829982 | 0.610809 | 1.459239 | 0.512455 | 0.42183 |
| Sirmaur | 1.154231 | 0.539176 | 1.841474 | 1.38279 | 0.700589 |
| Solan | 1.041972 | 0.765066 | 1.917221 | 0.666395 | 0.402264 |
| Una | 0.640149 | 0.410598 | 1.04769 | 0.469905 | 0.43981 |

Table 2: Potential evapotranspiration (kg/m$^2$/d)

| District name | Annual | Pre-monsoon | Monsoon | Post-monsoon | Winter |
|---|---|---|---|---|---|
| Bilaspur | 6.249943 | 7.688512 | 7.284851 | 5.055752 | 4.227627 |
| Chamba | 5.297434 | 6.378397 | 6.426325 | 4.654371 | 3.139991 |
| Hamirpur | 6.606005 | 8.076631 | 7.734715 | 5.52577 | 4.350589 |
| Kinnaur | 3.912085 | 4.382171 | 5.426053 | 3.264946 | 1.854801 |
| Kangra | 6.312745 | 7.700257 | 7.459749 | 5.676223 | 3.820245 |
| Kullu | 5.325593 | 6.236474 | 6.563689 | 4.543614 | 3.285236 |
| Mandi | 6.303446 | 7.710719 | 7.159103 | 5.920969 | 4.010281 |
| Shimla | 6.999291 | 8.655586 | 7.899083 | 6.070924 | 4.762183 |
| Sirmaur | 6.373483 | 8.232141 | 7.444294 | 4.774751 | 4.152899 |
| Solan | 1.041972 | 0.765066 | 1.917221 | 0.666395 | 0.402264 |
| Una | 7.108779 | 8.790957 | 8.303159 | 5.956929 | 4.601993 |

analysis of season-wise spatiotemporal variation in AET reveal a rising trendline during the pre-monsoon, monsoon, and post-monsoon seasons. Pre-monsoon AET readings for Kinnaur in the Eastern area and Una in the Southwest were, respectively, 1.901404 kg/m$^2$/d and 0.410598 kg/m$^2$/d at their maximum and minimum. Highest AET range (2.213282 kg/m2/d) has been recorded in the monsoon season indicative of increase in greenery in the Himachal Himalaya. The lowest range of AET was during winter season (0.677445 kg/m$^2$/d). The highest and lowest AET values during the monsoon season were 3.260972 kg/m$^2$/d for Kullu and 1.04769 kg/m$^2$/d for Una in the southwest. Sirmaur's actual evapotranspiration has a notable rising trend (trendline slope 0.1144) during the monsoon season. In the study area, there is a noticeable upward trendline during the post-monsoon season, with minimal fluctuations. Specifically, the Sirmaur district experiences a significant rise in actual evapotranspiration during this period, as indicated by a trendline slope of 0.1031. AET values range from 1.38279 kg/m$^2$/d for Sirmaur to 0.359918 kg/m$^2$/d for Mandi, with Una coming in second at 0.469905 kg/m$^2$/d. With the exception of Kangra, Kinnaur, and Mandi (trendline slopes of -0.0034, -0.0017, and -0.0028, respectively), which exhibit a negligible downward trend, the trendline is upward over the majority of the region throughout the winter. According to Table 2, the highest and lowest AET values were 1.099275 kg/m$^2$/d for Kinnaur and 0.402264 kg/m$^2$/d for Solan in the South. Highest AET has been recorded in Kinnaur district in the winter season (1.099275 kg/m$^2$/d) indicate increase of vegetation in the last 22 years in this higher Himalayan region. Lowest AET has been recorded in Shimla district.

Season-wise spatio-temporal study conducted during the same timeframe indicates that PET typically exhibits a decreasing pattern throughout all seasons, with the exception of Solan, where it demonstrates an increasing trend during pre-monsoon, monsoon, post-monsoon, and winter periods. The pre-monsoon, monsoon, post-monsoon, and winter trendline slopes for Solan are 0.0271, 0.0268, 0.0084, and 0.0091, respectively. There are seasonal variations in the PET maximum and minimum values. Una has the greatest PET value of 8.710957 kg/m²/d during the pre-monsoon season, while Solan has the lowest PET value of 0.765066 kg/m²/d. Una has the greatest PET value of 8.303159 kg/m²/d during the monsoon season, while Solan has the lowest PET value of 1.917221 kg/m²/d. As we move into the post-monsoon season, Solan continues to have the lowest PET value at 0.666395 kg/m²/d, while Shimla has the highest PET value at 6.070924 kg/m²/d. With a winter PET value of 4.762183 kg/m²/d, Shimla has the highest value, while Solan has the lowest at 0.402264 kg/m²/d.

*The trend of spatiotemporal variation in PET (mm/d)*

Potential evapotranspiration plays important role in evaluating atmospheric demands of water for a region. The analysis of PET trends utilizing data from CRU for the same 22-year period spanning from 2000 to 2022 reveals that the annual PET values ranged from 2.166304 to 3.994565 mm/d, with an average annual PET of 3.427053 mm/d (Fig. 5a). The range of PET is 1.828261, 3.11884, 1.653261, 1.339131, 1.097101 and the standard deviation is 0.57459, 0.925696, 0.629455, 0.394705 and 0.298499 for annual, pre-monsoon, monsoon, post-monsoon and winter season respectively. The spatial pattern analysis reveals a notable contrast in PET levels between the North-eastern region, which exhibits low PET, and the rest of the region, where PET is relatively high. Moreover, within the Himachal Himalaya, the higher region experiences lower PET compared to the middle and lower regions.

Sirmaur, situated in southern Himachal Pradesh, exhibited the highest PET, followed by Solan in the south. In contrast, Lahaul and Spiti, positioned in the northern part characterized by high altitude and a cold desert climate, displayed the lowest PET values.

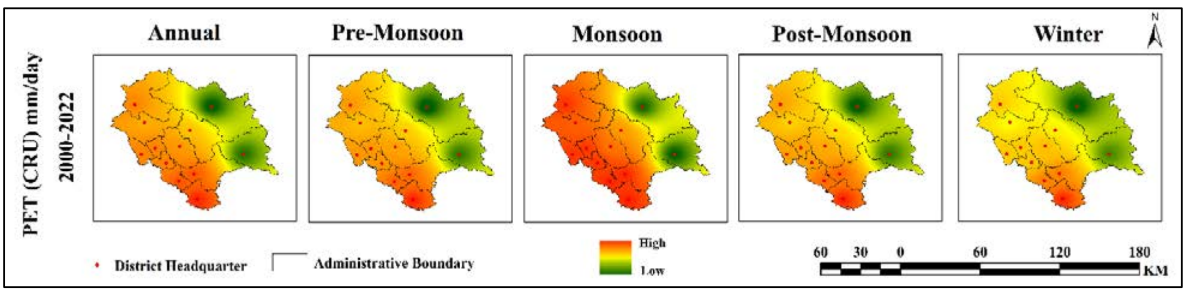


Fig. 5a: Spatial distribution of PET

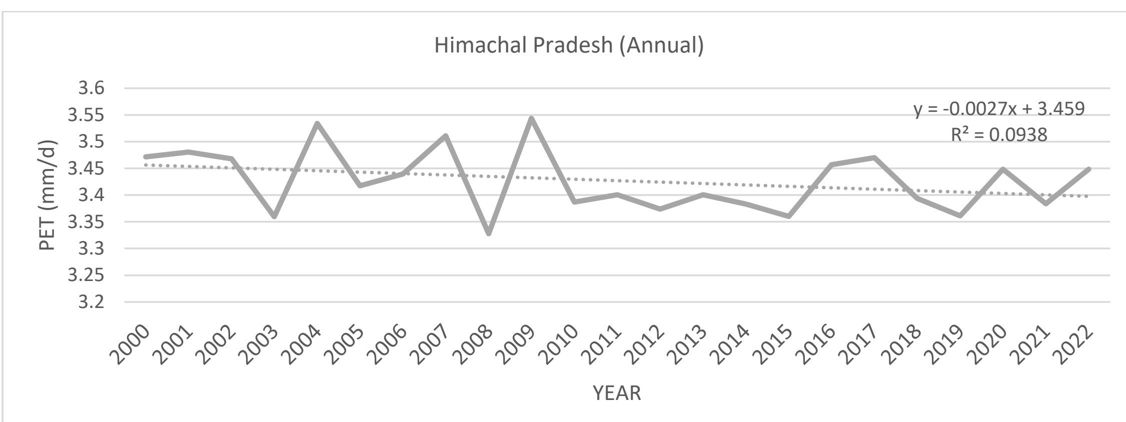


Fig. 5b: Temporal distribution of PET

The annual PET trendline in the study region shows a decrease with a negative slope of -0.0027. This consistent negative trend is observed at all stations, indicating a moderate intensity (Fig. 5b). Throughout the seasonal analysis, the data indicates a decrease in trendlines for the pre-monsoon, monsoon, post-monsoon, and winter seasons across the region. However, an interesting anomaly is observed in Sirmaur, the southernmost region, where there is a noticeable increase in trend specifically during the pre-monsoon season.

In the pre-monsoon season, Sirmaur experienced a maximum PET value of 5.643478 mm/d, while Lahaul and Spiti had a minimum PET value of 2.524638 mm/d. Moving on to the monsoon season, Sirmaur recorded a maximum PET value of 4.727134 mm/d, whereas Lahaul and Spiti had a slightly lower value of 3.073913 mm/d. As for the post-monsoon season, Sirmaur's PET value dropped to 2.958696 mm/d, while Lahaul and Spiti had a minimum value of 1.619565 mm/d. Finally, during winter, Sirmaur experienced a PET value of 2.05942 mm/d, while Lahaul and Spiti had the lowest value of 0.962319 mm/d (Table 3).

*NDVI time series*

In recent decades, there has been a notable rise in vegetation cover, particularly forest cover, in the upper Himalayan region (Kumar *et al.*, 2018). As forest grow (as indicated by higher NDVI), contributes to increase ET. Lush vegetation enhances transpiration, releasing water vapor into the atmosphere. This process plays a vital role in regional and local water cycles, affecting climate and hydrology. A statistical analysis of the time series distribution using NDVI was conducted to assess the patterns of vegetation growth in the area (Table 4). The average NDVI ranges from 0 to 0.97, with the highest NDVI values observed for the southern and southeastern regions, while the lowest NDVI values are recorded in the northern and northeastern parts (Fig. 6).

In 1991, the predominant land cover in the study area was forest, covering 35,835.43 square kilometers (km²), which accounted for 64.37% of the total area. By 2021, the NDVI map indicate that approximately 77.36% of the study area, equivalent to 43,067.28 km², was covered by forests. The total percentage change in forest cover between 1991 and 2021 amounts to 20.18%. Visual interpretation of the NDVI map of year 1991, 2001, 2011 and 2021 depicts increase of sparse and moderate vegetation in the three upper districts Kinnaur, Lahaul and Spiti and Chamba between 1991 to 2021. The rise in the sparse and moderate vegetation categories will have a direct impact on the region's overall AET and PET values.

*NDSI time series*

The presence of snow cover in mountainous regions plays a significant role in shaping the albedo pattern. During the winter season, the upper part of Himachal Pradesh is predominantly covered in snow. Various recent research studies and reports of international and national research organization such as IPCC, International Centre for Integrated Mountain Development (ICIMOD), World Meteorological Organization (WMO), Indian Institute of Remote Sensing (IIRS) and others published on snow cover and glacier monitoring of Hindu Kush Himalaya clearly indicate decreasing trend of snow cover in the region in last few decades. With the reduction of snow cover,

Table 3: Potential evapotranspiration (mm/d)

| District name | Annual | Pre-Monsoon | Monsoon | Post-Monsoon | Winter |
|---|---|---|---|---|---|
| Bilaspur | 3.648188 | 4.924638 | 4.681522 | 2.626087 | 1.675362 |
| Chamba | 3.648188 | 4.924638 | 4.681522 | 2.626087 | 1.675362 |
| Hamirpur | 3.648188 | 4.924638 | 4.681522 | 2.626087 | 1.675362 |
| Kinnaur | 2.336957 | 2.975362 | 2.998913 | 1.802174 | 1.172464 |
| Kangra | 3.463406 | 4.63913 | 4.531522 | 2.458696 | 1.533333 |
| Kullu | 3.363768 | 4.531884 | 4.291304 | 2.430435 | 1.581159 |
| Lahaul and Spiti | 2.166304 | 2.524638 | 3.073913 | 1.619565 | 0.962319 |
| Mandi | 3.561957 | 4.872464 | 4.45 | 2.595652 | 1.711594 |
| Shimla | 3.822464 | 5.268116 | 4.721739 | 2.784783 | 1.869565 |
| Sirmaur | 3.994565 | 5.643478 | 4.727174 | 2.958696 | 2.05942 |
| Solan | 3.822464 | 5.268116 | 4.721739 | 2.784783 | 1.869565 |
| Una | 3.648188 | 4.924638 | 4.681522 | 2.626087 | 1.675362 |

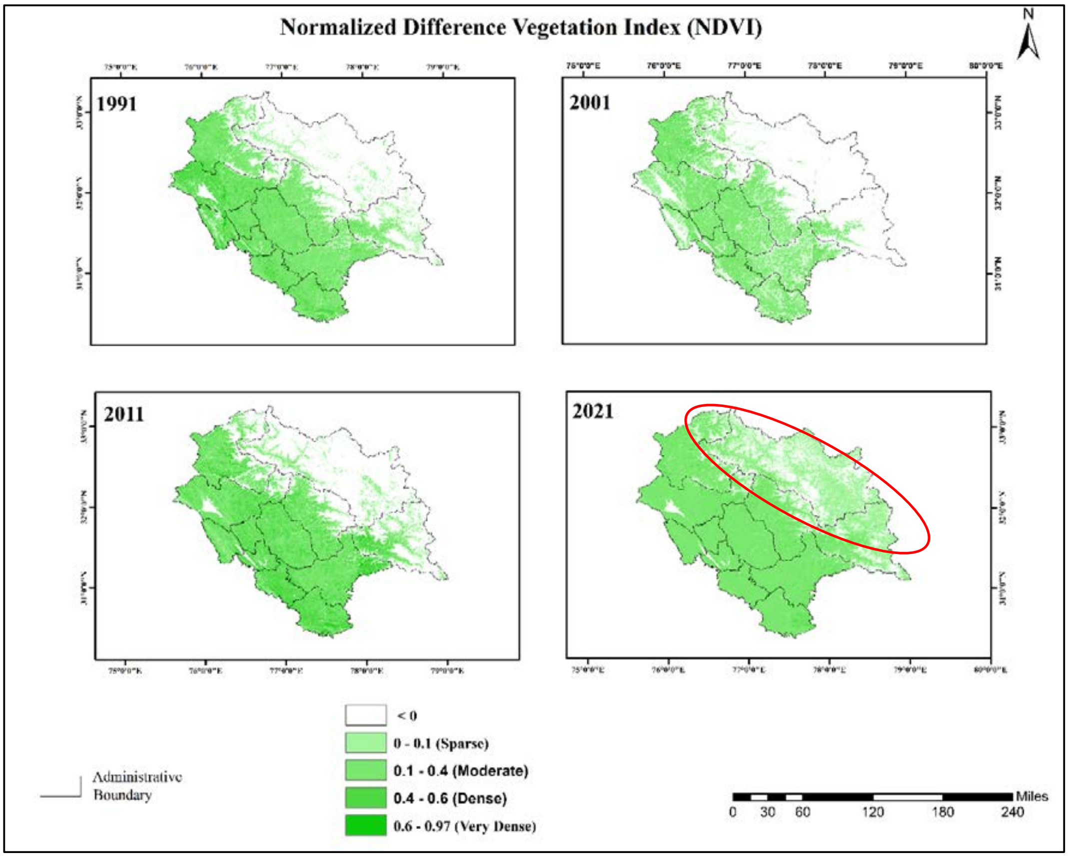


Fig. 6: NDVI map of Himachal Pradesh

Table 4. Areal coverage of vegetation and snow cover

| LULC | 1991 (Km$^2$) | Area (%) | 2001 (Km$^2$) | Area (%) | 2011 (km$^2$) | Area (%) | 2021 (Km$^2$) | Area (%) | % of change between 1991 to 2021 |
|---|---|---|---|---|---|---|---|---|---|
| Forest Cover | 35835.43 | 64.37 | 30334.76 | 54.49 | 36383.52 | 65.35 | 43067.28 | 77.36 | 20.18 |
| Snow Cover | 3333.849 | 6 | 7566.193 | 13.59 | 6426.477 | 11.54 | 1648.581 | 2.96 | -50.55 |

the land that is now exposed absorbs additional solar energy, resulting in elevated temperatures. Increased temperatures enhance evaporation from soil and vegetation, contributing to higher ET. The Fig. 7 illustrates the long-term trend in snow cover for Himachal Pradesh spanning from 1991 to 2021. Snow cover maps from 1991, 2001, 2011, and 2021 were employed in this study. The chart presented offers a statistical evaluation of the snow-covered area between 1991 and 2021.

The decadal analysis of snow cover, derived from the Landsat dataset, clearly indicates a decline in snow cover within the study area. The analysis reveals that, on average, there was snow cover over 3333.849 km², 7566.193 km², 6426.477 km², and 1648.581 km² in 1991, 2001, 2011, and 2021, respectively. The amount of snow cover has been consistently decreasing from 1991 to 2021, with a percentage change of -50.55% over the course of these years. Spatial snow cover reduction in the Himachal Himalaya is particularly noticeable in the northwestern and northeastern regions (Fig. 7).

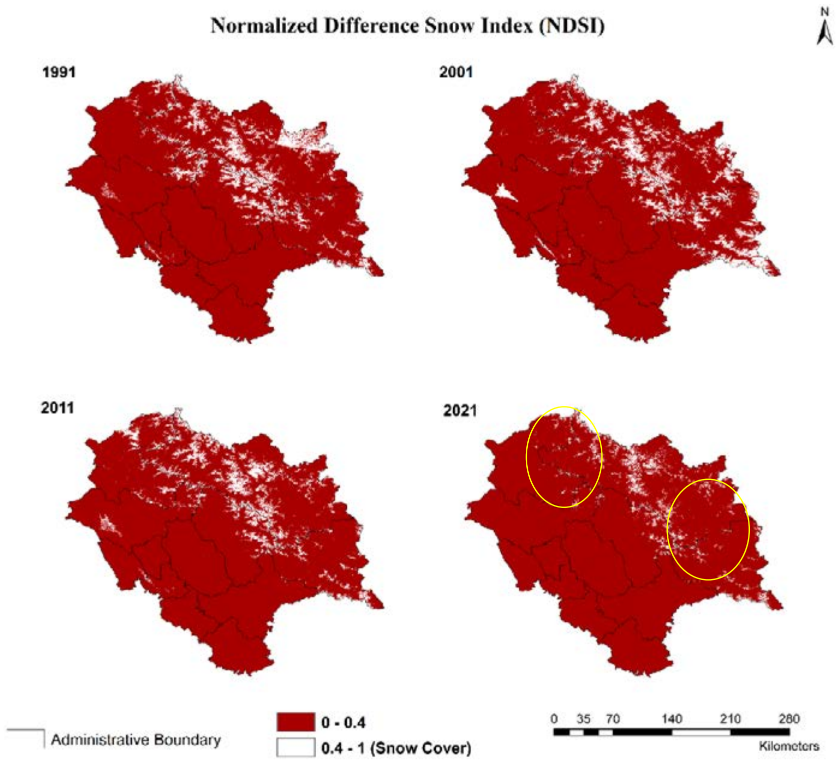


Fig. 7: NDSI map of Himachal Pradesh

*Monitoring the relationship of actual evapotranspiration with NDVI and NDSI*

The relationship between AET and PET with NDVI and NDSI has been established taking data for the year 1990, 2010 and 2021.

The study demonstrated a significant link between annual AET and NDVI, indicated by a high correlation coefficient of 0.984801 (Fig. 8a). The strong correlation coefficient observed between AET and NDVI can be attributed to the rise in vegetation cover and its influence on evapotranspiration within the region. Increase in AET will contribute to more moisture availability in the atmosphere. This finding has been corroborated with result of positive correlation with strong correlation coefficients for pre-monsoon, monsoon, post-monsoon and winter season measuring 0.998394, 0.962967, 0.955263, and 0.997981, respectively.

The relationship between annual AET and NDSI exhibits a strong negative correlation (Fig. 8b), with a correlation coefficient of -0.8838. The robust negative correlation coefficient between AET and NDSI suggests a rise in transpiration and evaporation from the ground. Similar negative correlation coefficients are seen across different seasons, with values of -0.96751 for winter, -0.83355 for post-monsoon, -0.81819 for pre-monsoon, and -0.9302 for monsoon.

*Monitoring the relationship of potential evapotranspiration with NDVI and NDSI*

The computation of the coefficient of correlation reveals a negative correlation, characterized with a high-magnitude correlation coefficient of -0.98859 between PET and NDVI (Fig. 8c). Strong negative correlations were found across different seasons, with correlation coefficients of -0.93264, -0.88804, -0.99904, and -0.92395 for pre-monsoon, monsoon, post-monsoon, and winter, indicating a consistent seasonal pattern. PET and NDSI exhibit a positive correlation, with an annual PET strong correlation coefficient of 0.894486 (Fig. 8d), similar correlation coefficients of significant magnitude are also seen in the seasonal analysis.

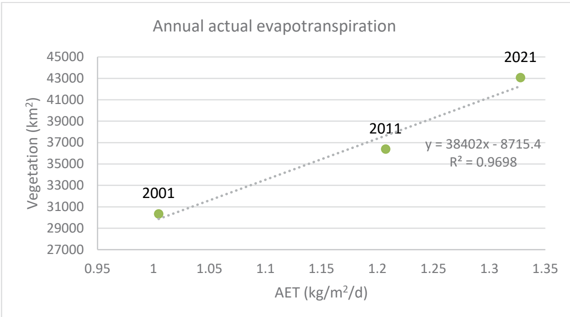


Fig. 8a: Relationship of AET with vegetation (NDVI)

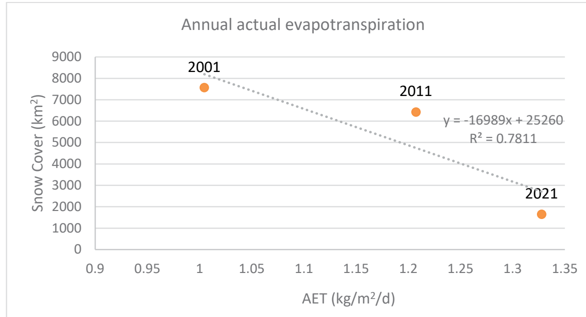


Fig. 8b: Relationship of AET with snow cover (NDSI)

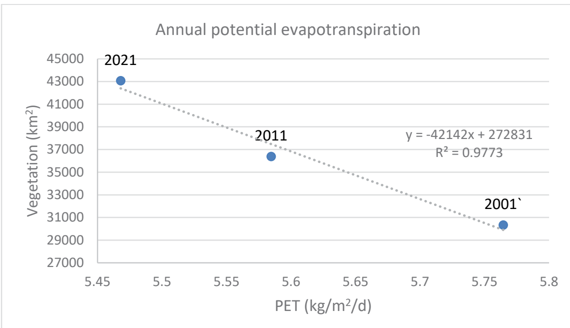


Fig. 8c: Relationship of PET with vegetation (NDVI)

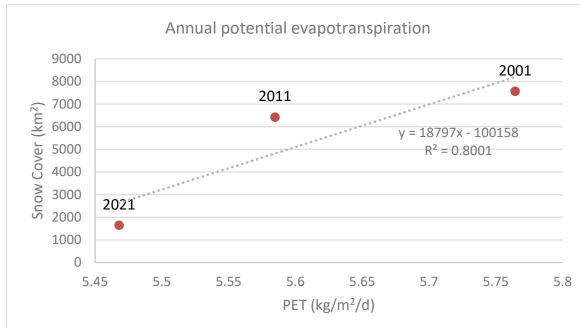


Fig. 8d: Relationship of PET with snow cover (NDSI)

*Monitoring the relationship of CRU data derived potential evapotranspiration with NDVI and NDSI*

The CRU data for the years 2001, 2011, and 2021 was analyzed to investigate the association between PET and NDVI. The findings indicate a strong negative correlation, with an impressive correlation coefficient of -0.93978 for annual PET (Fig. 9a). The findings from the previous section have been confirmed through the use of CRU data sets. The correlation between PET and NDVI as well as NDSI matches the results obtained in the previous section utilizing MODIS data sets.

The results of the previous section are further validated by the strong correlation coefficients observed for the pre-monsoon, monsoon, post-monsoon, and winter seasons, which exhibit a negative correlation of -0.51268, -0.87227, -0.99078, and -0.56812 respectively. With an annual PET correlation coefficient of 0.78931, the relationship between PET and NDSI is observed to be positively correlated (Fig. 9b). The correlation coefficients for pre-monsoon, monsoon, post-monsoon, and winter exhibit a consistent seasonal pattern, indicating a robust positive correlation in each respective season.

*Relationship between snow cover (NDSI) and vegetation cover (NDVI)*

In the Western Himalayan region, a complex relationship exists between vegetation and snow cover, influenced by different variables. Decreased snow cover often corresponds with increased temperatures. Higher temperatures have the potential to extend the growing period for plants, promoting growth and expanding plant coverage. This effect is particularly notable in high-altitude regions, where the duration of the growing season is primarily dictated by temperature conditions.

The correlation between NDVI and NDSI was analyzed by calculating the correlation coefficient over a span of 30 years (1991-2021), as illustrated in Fig. 10. The results revealed a significant correlation coefficient of -0.86601, suggesting a robust negative relationship. In the study area, a rise in vegetation was noted between 1991 and 2021 (20.16%) whereas, there was a drop in the amount of snow cover (-50.55%). There are many factors but climate change can lead to

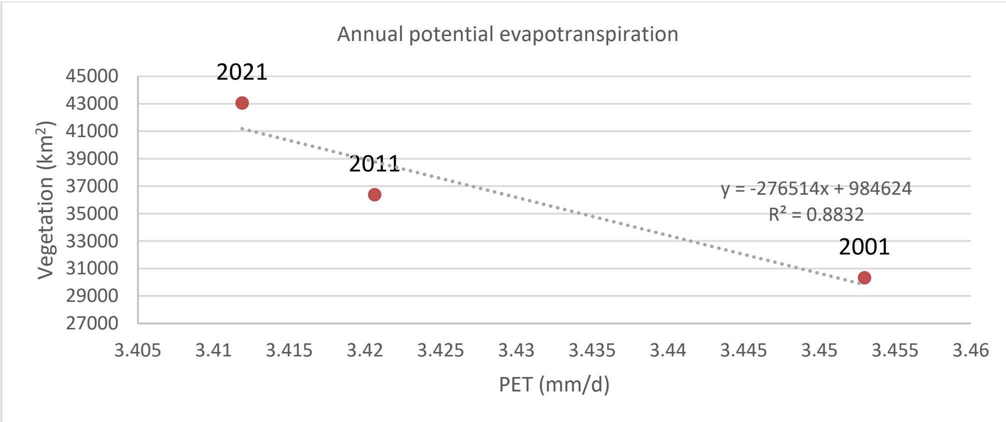


Fig. 9a: Relationship of PET with vegetation (NDVI)

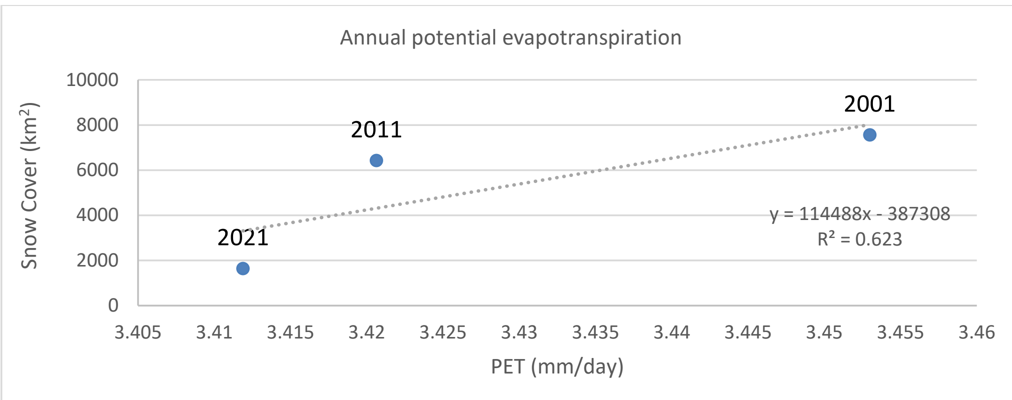


Fig. 9b: Relationship of PET with snow cover (NDSI)

alterations in temperature and precipitation patterns. In hilly areas, increasing temperatures may result in higher rates of evaporation. Shifts in precipitation patterns impact the water supply for plants, which may result in higher transpiration rates as vegetation adjusts to the evolving environment (2000-2022). With the mean AETs for annual, pre-monsoon, monsoon, post-monsoon, and winter season has shown a rising trend in actual evapotranspiration due to increase in vegetation cover. In contrast, the study area experienced an annual and seasonal decline in potential evapotranspiration; throughout the course of the time, mean PET values were 5.593707, 6.783355, 6.692567, 4.737331, and 3.509828 kg/$m^2$/d for annual, pre-monsoon, monsoon, post-monsoon and winter respectively. The mentioned findings are in consistent with prior research findings, such as Bhimala *et al.* (2023) and Goroshi *et al.* (2017) who have estimated an increasing trend of 1.33 mm/y and 0.156 mm season-1 year-1 of AET respectively in the Indian subcontinent over a longer period of time. Recent study by Singh and Singh, (2023) have also concluded that there lies an inter-seasonal variations and trends in ET over India during three seasons over 30 years (1981-2010) and especially ET increases during the northeast winter monsoon season. The study area has exhibited a three-fold rise in actual evapotranspiration from winter to monsoon season, owing to a positive correlation between vegetation and actual evapotranspiration. The NDVI analysis reveals that approximately 20.18 % of forest cover has been increased during 1991-2021 which is in consistence

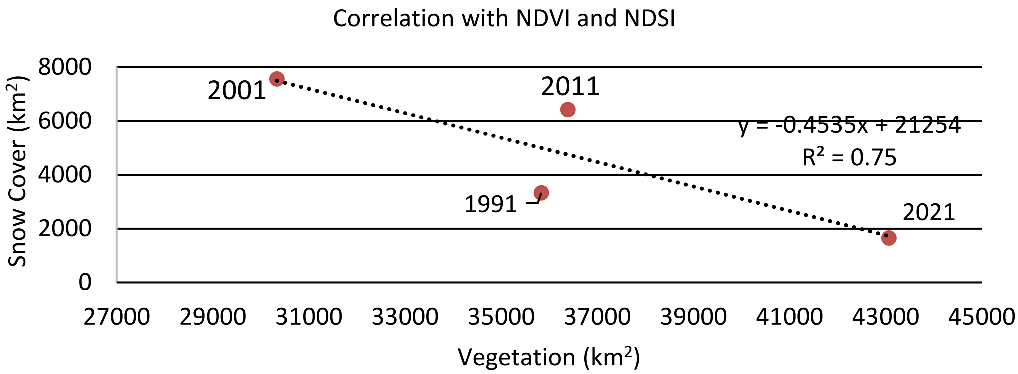


Fig. 10: Relationship between snow index (NDSI) and vegetation index (NDVI)

with previous studies (Kumar *et al.*, 2023). The seasonal coefficient of correlation reveals a significant rise in the dense forest cover in the lower and middle regions of the Himachal Himalaya, while the upper Himachal Himalaya exhibits vegetation ranging from sparse to moderately dense. The spatial increase in vegetation cover will have positive bearing on availability of moisture in the atmosphere in the all season. The correlation between the NDSI and NDVI is largely negative with a correlation coefficient of -0.86601. The findings of the study depicts negative association between AET and NDSI, with correlation coefficients for annual, pre-monsoon monsoon, post monsoon, and winter measuring 0.96751, -0.83355, -0.81819, and -0.9302 respectively. The seasonal dynamics of NDSI is very much linked with mean temperature and precipitation in the form of snow in different season. An increase in mean temperature in the region is associated with decrease in snow cover. The decline in snow cover facilitates the growth of vegetation, particularly horticulture in the higher elevations of the Himalayas, leading to a rise in the area's Actual Evapotranspiration (AET). The relationship between PET and vegetation reveals a negative correlation with a correlation coefficient of -0.98859. Increase in AET and subsequent decrease in PET as evident from the results, points towards change in local and regional climate of the region due to more moisture availability in the atmosphere having bearing on hydrological cycle. From the year 2000 to 2022, there was a noticeable rise in vegetation, a decline in snow cover, a significant increase in actual evapotranspiration, and a decrease in potential evapotranspiration. These changes, which varied spatially and seasonally, indicate a shift in the hydrological cycle components of the area. Increased moisture availability in the Himachal Himalaya will influence spatial distribution of precipitation depending on altitudinal variations. Alteration in the hydrological cycle will further result in change in seasonal water budget of the region. Better understanding of seasonal water budget of the Himachal Pradesh will help in recalibrating sustainable regional development policy keeping demand and supply balanced.

## CONCLUSIONS

Spatio-temporal pattern of actual and potential evapotranspiration depends on nature of land use and land cover in the area. Vegetaion cover, snow cover and other land cover categories regulates regulates evaporation and transpiration. Availability of moisture in the atmosphere influence local weather behaviour. Previous studies published on vegetation cover and snow cover of Himachal Himalaya depicts altitudinal shift of vegetation cover from temperate to dry cold regions of higher altitude. The present study investigated nature and pattern of changes in vegetation and snow cover and how these changes are associated with change in actual and potential evapotranspiration in the region. Study of spatio temporal change in AET and PET will help modelling local weather phenomena with acceptable accuracy.

Open-source Landsat, MODIS and CRU satellite data has been collected for mapping and analysis purposes. The datasets were used to explore the relationship between Actual and Potential

Evapotranspiration (AET and PET) and Landsat-derived indices (NDVI and NDSI) in Himachal Pradesh of India. The average annual and seasonal AET and PET values generated from the MODIS dataset along with processed PET values acquired from CRU dataset (pixel values). Maps of NDVI and NDSI were used to analyze the relationship between AET and PET, between AET and NDVI, AET and NDSI, PET and NDVI, PET and NDSI and between NDVI and NDSI. Marked spatio-temporal variations were observed among the stations considered. This negative trend is consistent across all stations, showing moderate intensity. Results clearly depicts increase of vegetation cover and decrease of snow cover in the Himachal Himalaya with varying magnitude during the period of investigation. The decrease in snow cover and increase in vegetation cover is mostly attributed to average increase in the temperature in the area. Rising temperatures globally have led to the melting of snow and the formation of lakes, leading to further absorption of heat and the formation of the positive feedback loop, accelerating the melting of snow. When snow cover decreases, the darker surface underneath absorbs more sunlight (because of different albedo) leading to further warming and acceleration of the melting process. Vegetation growth, on the other side, is affected by the availability of water, among various other factors. Actual evapotranspiration and vegetation have a strong positive correlation. When AET is higher, it represents that there is more water available for plants, which can lead to increased vegetation growth, assuming other conditions such as nutrients and sunlight are also favorable. An increase in forest cover in the area has led to higher AET as forests typically have a higher transpiration rate as compared to non-forest cover. The analyzed results show that the annual trendline of AET using MODIS data for the study area indicates an upward trajectory whereas the PET yearly trendline shows a declining trend. The annual trend line of PET across the study area as per the CRU data also indicates a downward trajectory.. It means that the AET is inversely proportional to PET in the study area characterized by a high-magnitude correlation coefficient. The findings of CRU datasets also corroborate results derived using MODIS data sets. Actual evapotranspiration and snow cover have a negative correlation because of various factors such as climate, season and geographical location etc. During winter season, when snow cover is high, evapotranspiration rates are typically low due to cold temperature and less availability of liquid water for plants to transpire. As the snow melts in the summer and spring, evapotranspiration rates tend to increase as more liquid water becomes available for plants to transpire and for evaporation to occur from the soil surface. Potential evapotranspiration is negatively correlated with vegetation and positively correlated with snow cover as PET decreases humidity increases. These findings of the study underscore the intricate relationships between climate, land cover, and hydrological processes in Himachal Pradesh, highlighting the impacts of climate change on regional ecosystems and long-term water budget. Open-source remote sensing data sets and open Geographical Information System (GIS) environment play pivotal role in investigating different dimensions of mountain environment. The datasets and methodologies used in the current study can be used to do similar type of study for any region in consideration. The findings of the present study sheds lights on the importance of looking impacts of land use land cover change on actual and potential evaporation of hydrological cycle. The findings of the study will help orienting short term and long-term regional water policies and budget.

## AUTHOR CONTRIBUTIONS

A. Yadav was responsible for conceptualizing and designing the experiments, analyzing and interpreting the data as well as preparing and editing the manuscript. Ashwani conducted the literature review, carried out experimental procedures, compiled data, drafting manuscript and performed data analysis. P. Kumar drafted the manuscript, add important intellectual content, reviewed its final version and contributed to the development of the experimental design. D. Deka contributed to data collection, assisted in the literature review and participated in manuscript preparation. J.P. Das helped in the material support and reviewing the manuscript. A. Singh played a role in data analysis and manuscript preparation. M. Kumar supervised the results. A. Gurjar reviewed and approved the final version of the manuscript.

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## CONFLICT OF INTEREST

The authors declare that there are no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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## ABBREVIATIONS

| | |
|---|---|
| *%* | Per cent |
| *°C* | Degree Celsius |
| *AET* | Actual evapotranspiration |
| *AppEEARS* | Application for extracting and exploring analysis ready samples |
| *AR5* | Fifth assessment report |
| *CRU* | Climatic Research Unit |
| *Ei* | canopy interception evaporation |
| *EOS* | Earth observing system |
| *Eq* | Equation |
| *ET* | Evapotranspiration |
| *ICIMOD* | International Centre for Integrated Mountain Development |
| *IIRS* | Indian Institute of Remote Sensing |
| *IPCC* | Intergovernmental Panel on Climate Change |
| *GCM* | Global climate models |
| *GIS* | Geographical information system |
| *$Kg/m^2/d$* | Kilogram/meter square/day |
| *$Km^2$* | Kilometer square |
| *LST* | Land surface temperature |
| *LULCC* | Land use land cover change |
| *mm* | Millimeter |
| *mm/d* | Millimeter/day |
| *mm/ season/y* | Millimeter *season per year* |
| *mm/y* | Millimeter/year |
| *MODIS* | Moderate resolution imaging spectroradiometer |
| NASA | National Aeronautics and Space Administration |
| *NDSI* | Normalized difference snow index |
| NDVI | Normalized Difference Vegetation Index |
| *NIR* | Near Infrared |
| *PET* | Potential evapotranspiration |
| *SAVI* | Soil adjusted vegetation index |
| *Sq. Km* | Square kilometer |
| *SWIR* | Shortwave infrared |

| | |
|---|---|
| *TM* | Thematic Mapper |
| *UNFCC* | United Nations Framework Convention on Climate Change |
| *USA* | United States of America |
| *WHO* | World Health Organization |
| *WMO* | World Meteorological Organization |

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