MAUSAM, **76**, 2 (April 2025), 417-430

MAUSAM

DOI : https://doi.org/10.54302/mausam.v76i2.6365
Homepage: https://mausamjournal.imd.gov.in/index.php/MAUSAM

UDC No. 551.583 : 631.445.5

Spatiotemporal changes in Indian land aridity : An assessment based on the CRU data and UNEP's aridity index

NITISH KUMAR SINGH*, VIJAY KUMAR BARAIK and MAHENDRA SINGH NATHAWAT

Discipline of Geography, Indira Gandhi National Open University, New Delhi – 110 068, India

(*Received 29 August 2023, Accepted 18 June 2024*)

e mails : *knack.008@gmail.com; vijaybaraik@ignou.ac.in; msnathawat@ignou.ac.in

सार – यह अध्ययन 1901 से 2021 तक भारतीय भूमि पर शुष्कता पैटर्न की सूक्ष्म गतिशीलता की पड़ताल करता है, जो बढ़ती मांगों और जलवायु अनिश्चितताओं के बीच सूचित भूमि और जल प्रबंधन के लिए महत्वपूर्ण है। सीआरयू डेटासेट और यूएनईपी के शुष्कता सूचकांक का उपयोग करते हुए, अनुसंधान पांच शुष्कता श्रेणियों की पहचान करता है और एक सावधानीपूर्वक स्थानिक-कालिक विश्लेषण करता है। एमके-ट्रेंड विश्लेषण पद्धति का उपयोग करते हुए, महत्वपूर्ण प्रवृत्तियों की पहचान की गई है, जो अति शुष्क, शुष्क, अर्ध-शुष्क, उप-आर्द्र और आर्द्र भूमि में बदलावों को स्पष्ट करती हैं। विशेष रूप से, अति शुष्क, शुष्क और आर्द्र क्षेत्रों में कम होती प्रवृत्ति देखी जाती है, जबकि अर्ध-शुष्क और उप-आर्द्र क्षेत्र विस्तार दर्शाते हैं। दिलचस्प बात यह है कि शुष्कता के प्रकारों के बीच परिवर्तन विकसित होते परिदृश्य को रेखांकित करते हैं ये निष्कर्ष भारत के शुष्क परिदृश्य को आकार देने वाले जलवायु कारकों के जटिल अंतर्संबन्ध को रेखांकित करते हैं, जिससे स्थानीय शुष्कता गतिशीलता की व्यापक समझ के लिए आगे अनुसंधान की आवश्यकता होती है।

ABSTRACT. This study delves into the nuanced dynamics of aridity patterns over Indian land from 1901 to 2021, crucial for informed land and water management amidst rising demands and climate uncertainties. Employing the CRU dataset and UNEP's aridity index, the research identifies five aridity categories and conducts a meticulous spatio-temporal analysis. Utilizing the MK-trend analysis method, significant trends are discerned, elucidating shifts in hyper-arid, arid, semi-arid, sub-humid, and humid lands. Notably, a diminishing trend is observed in hyper-arid, arid, and humid areas, while semi-arid and sub-humid areas exhibit expansion. Intriguingly, transformations between aridity types underscore the evolving landscape, with many formerly arid regions transitioning towards greater humidity and many humid regions experience heightened aridity, possibly influenced by changing temperature and rainfall patterns. These findings underscore the complex interplay of climate factors shaping India's aridity landscape, necessitating further research for a comprehensive understanding of localized aridity dynamics.

Key words – Aridity, CRU data, UNEP's Aridity Index, India.

1. Introduction

In recent years, increasing climatic aridity in the vastly populated continent like Asia has attracted increasing attention (Lioubimtseva and Henebry, 2009; Dai, 2011; Lioubimtseva *et al*., 2005; Lioubimtseva and Cole, 2006; An, 2014; Huang *et al*., 2017; Ramarao *et al*., 2019; Zheng *et al*., 2018; Luo, *et al*., 2023). This is being linked to the consequences of increasing global warming (Dai, 2011; Fu and Feng, 2014; Gao *et al*., 2015; Berg *et al*., 2016; Park *et al*., 2018; Greve *et al*., 2019; Lian *et al*., 2021). Reports suggest that over time Asia is warming faster than the global average. It was found that the present warming trend in Asia in 1991-2020 is larger than in 1961-1990 and the last 30 years (State of the climate in Asia, 2021). With increasing global warming, aridity is projected to increase over most parts of Asia (Greve and Seneviratne, 2015; Ramachandran *et al*., 2015; Zarch *et al*., 2017). Several scientific studies have shown increased regional-scale climatic aridity and associated dryland area in many Asian countries (Salvati *et al*., 2012; Salvati *et al*., 2013; Ghazanfari *et al*., 2013; Djebou, 2017; Huang *et al*., 2017; Prăvălie *et al*., 2019; Delgado-Baquerizo *et al*., 2020; Lian *et al*., 2021). The results of some studies show that there is a rapid increase in Potential Evapotranspiration (PET) due to global warming (Li *et al*., 2019; Fang *et al*., 2020; Ahmed *et al*., 2020; Pan *et al*., 2021; Chen and Wang, 2022). Along with this, the amount of rainfall is decreasing. Even if rainfall is increasing, its rate is much lower than the rate of PET increase. As a result, aridity is increasing in arid and semi-arid areas and it is expanding in other areas. With time, the threats related to aridity are taking more serious form in densely populated agricultural countries like India

(Paltasingh *et al*., 2012; Goparaju and Ahmad, 2019; Sarma and Singh, 2019; Pinjarla *et al*., 2021; Choudhary, *et al*., 2023). The net change in precipitation and temperature over India indicates decreasing precipitation and increasing temperature in most months and seasons of the year (Kumar *et al*., 2010; Jain and Kumar, 2012; Subash and Sikka, 2014; Mondal *et al*., 2015). The changing pattern of rainfall and temperature affects the pattern of land aridity significantly. Many old areas of arid and semi-arid lands in India may be increasing towards humidity. On the other hand, many sub-humid and humid lands are becoming arid and they are becoming arid faster than before.

The spatial extent and rate of arid lands are increasing, particularly in central India, the southern peninsula and northeastern India. Generally, aridity depends on the difference between mean annual rainfall and PET (Proutsos *et al*., 2021; Ullah *et al*., 2022; Zomer *et al*., 2022). Many aridity indices are currently used to monitor and map regional climate change. For example, the aridity index proposed by De Martonne (1923) measures the ratio of annual precipitation (in mm) to mean annual temperature, which is scaled by 10 (De Martonne, 1923). After this, Charles Warren Thornthwaite (1948) gave his index, in which he defined the aridity index as the ratio of potential evapotranspiration to actual evapotranspiration by estimating PET based on temperature (Thornthwaite, 1948). Then in 1949, Gaussen developed a more comprehensive index for estimating the aridity index, which is based on the concept that the difference between annual precipitation and PET determines the aridity of an area (Gaussen, 1949). Subsequently, Turc (1954) gave his aridity index, which was determined by the ratio between annual PET and annual rainfall (Turc, 1954). Further, in 1965, the Palmer Drought Severity Index was developed, which uses data on rainfall, temperature, and soil moisture to assess drought (Palmer, 1965). This index provides a measure of the deviation of the aridity of a place from the normal state of humidity. Later in 1974, M. Budyko developed the aridity index. In this index, Budyko used the ratio of actual evapotranspiration and potential evapotranspiration to assess the water balance and aridity of an area (Budyko, 1974). In addition, UNEP (1992) proposed an aridity index (UNEP, 1992). This index is defined as the ratio of rainfall (in mm) and PET (in mm) which is being used the most worldwide. Aridity is mainly the result of climatic conditions present on any land, and it deeply affects the vegetation, agricultural practices, and terrestrial ecosystem *etc*., of that land. Therefore, there is a need to prioritise research related to understanding various aspects of the dynamic pattern of aridity for the conservation and stability of land and water in India. However, there have been many works related to aridity in India. Still, many

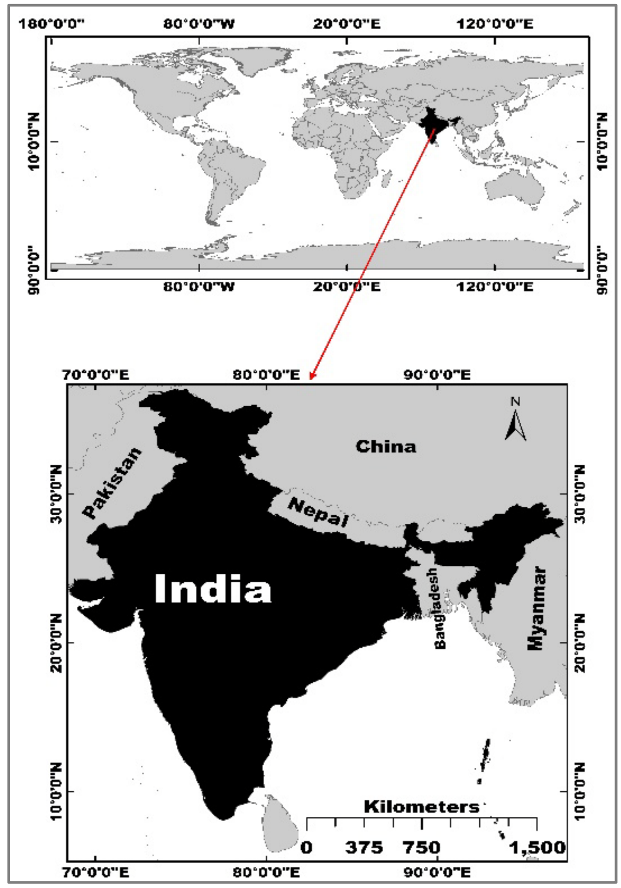

Fig. 1. Location of India

aspects are absent in it, such as analysis of annual aridity patterns and main types of aridity (like- Hyper-arid, Arid, Semi-arid, Sub-humid and Humid). How is the transformation happening over time, and what is its spatio-temporal pattern? What kind of transformation is taking place among the types of aridity?.

Therefore, an attempt has been made to do the present study considering the above aspects of aridity, which are as follows - (*i*) to analyse the pattern of aridity and its types on Indian land. (*ii*) to assess the pattern of transformation of different types of aridity into each other on Indian land. (*iii*) Finally, to analyse the monotonic linear trend of aridity and its types.

2. Methodology

2.1. *Study area*

India, officially known as the Republic of India (37°6′N to 8°4′N and 68°7′E to 97°25′E), is the largest country in South Asia (Fig. 1). It is bordered by Pakistan and Afghanistan in the northwest, Tibet (China) and Nepal in the north, Bhutan in the northeast and Bangladesh and Myanmar in the east. It also shares maritime borders with Sri Lanka to the south and Maldives to the southwest. Geographically, the area of India is 3287261 square kilometres, which makes it the seventh largest country in the world. India is a country of diverse landscapes that includes the Himalayan Mountain range, the fertile Indus-Gangetic-Brahmaputra plain, the arid Thar Desert in the northwest, the Arabian Sea in the west and the Bay of Bengal coast and islands in the east. Apart from its diverse geography, India is also known for its diverse climate. It experiences tropical monsoon climate. In which there are different seasons of summer, monsoon (rain) and winter. Different parts of India also have different climate patterns which are influenced by factors like latitude, altitude and proximity to water bodies. Overall, India's geography presents a mixed landscape of mountains, fertile plains, arid deserts, diverse forests, and picturesque sea coasts. This diverse landscape contributes to the development of India's rich natural resources, cultural heritage, and vibrant ecosystems.

2.2. *Dataset*

This study uses gridded time series datasets of precipitation and potential evapotranspiration (PET) to calculate the aridity index developed by UNEP (*Data Source* : https://crudata.uea.ac.uk/cru/data/hrg/). These datasets are being compiled and maintained by the Climate Research Unit (CRU) of the University of East Anglia. These datasets of rainfall and PET cover the entire land at 0.5-degree resolution. These datasets are constructed by interpolating *in-situ* climatological data obtained by weather stations. CRU puts these datasets through rigorous quality control procedures to ensure data accuracy and reliability. These processes include checking for errors in the datasets, correcting anomalies, checking for data gaps, and resolving them (Harris *et al., 2020*). The main goal behind doing this is to maintain homogeneity and consistency across datasets. The main focus is implementing adjustments and correction procedures to account for factors such as changes in measurement methods, station relocation, equipment bias, *etc* (Harris *et al., 2020*). The above features make these datasets widely useful and reliable for various purposes, including climate research, climate modelling, weather forecasts, impact assessment and policy-making. Hence, they have been used in the present study. The present study is based on datasets from 1901-2021.

2.3. *Data processing procedures and analysis methods*

In this study, the gridded datasets of rainfall and PET have been processed with the help of ArcGIS v10.8.2 software (Fig. 2). The precipitation and PET data processing usually involve the following steps: Firstly, the gridded datasets were obtained in NetCDF format. The NetCDF Raster Layer tool was then used to visualize these datasets as a map and time series plot. The raster layer of the desired study area is clipped by converting rainfall and PET-gridded datasets to raster format using this tool. Ahead, monthly layers for each year are composited separately from this raster layer of precipitation and PET using the Composite band tool. After that, raster layers with mean annual values were generated using the cell statistics tool to obtain the climate values of these annual layers. Raster layers with 0.5-degree resolution obtained after this process were converted into point data. Further, this annual point data was transformed into layers of 100 m resolution using the IDW interpolation tool. The final raster layers obtained after the above procedures are used to derive the annual pattern of the aridity index which UNEP develops. UNEP's aridity index is a measure used to assess the dryness of an area based on rainfall and PET data (UNEP, 1992; Thomas, 1997). The derivation of this aridity index involves calculating the PET and comparing it to the amount of rainfall. The equation of this index is:

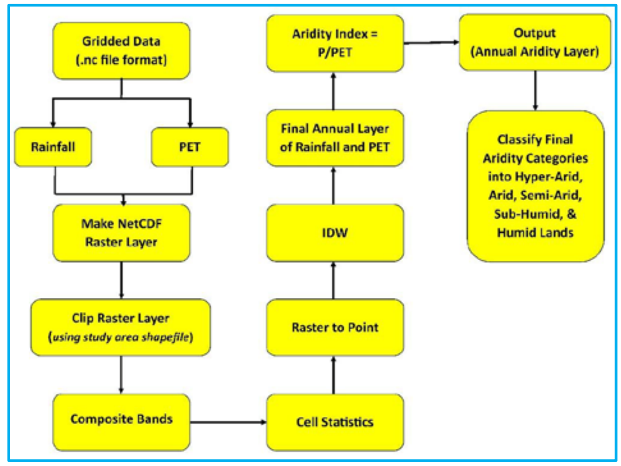

Fig. 2. Methodology of the study

UNEP's Aridity Index = P/PET

where P is the Precipitation in mm and PET is potential evapotranspiration in mm. This index is categorised into following categories with reference to India (Table 1):

After determining and mapping the different types of aridity, their transformations over time have been analysed. The overlay analysis method has been used to analyze the transformations of aridity types into each other. At last, MK-trend test has been applied.

TABLE 1

UNEP aridity index categories

Aridity Types	Index
Hyper-Arid Land	AI < 0.05
Arid Land	0.05 ≤ AI < 0.2
Semi-Arid Land	0.2 ≤ AI < 0.5
Sub-Humid Land	0.5 ≤ AI < 0.65
Humid Land	AI ≥ 0.65

The Mann-Kendall trend test is a non-parametric method for detecting trends in time-series data. It is useful in trend analysis because it does not make any assumptions about the distribution of time-series data. Hence it handles non-normal and non-linear data easily. The MK trend test is robust to outliers or extreme values, which are common in any climatic data series. To avoid extreme values in the data series, the MK trend test focuses on the order or rank of the data rather than the actual values present in the table. In addition, the MK trend test can be applied to any time series, making it a flexible method for analyzing climate data spanning different periods. The MK trend test is monotonic in nature, so it can easily determine the statistically significant trend present in the time series, whether the trend is increasing or decreasing. Hence, being monotonic in nature, the MK trend test is more capable than others in detecting both linear and non-linear trends. The MK trend test is also useful because it is insensitive to missing data in the time series, so it handles missing or irregularly spaced data points smoothly and error-free. In addition, the MK trend test calculates Kendall's Tau to determine the strength of the trend present in the time series. Here Kendall's Tau represents the strength and direction of the trend in the time series. Kendall's Tau is calculated by:

Kendall's tau (τ) = (number of concordant pairs - number of discordant pairs) / (n*(n-1)/2),

where n is the number of data points.

After this variance of Kendall's tau is calculated. The variance of Kendall's tau takes into account the ties in the data and is calculated as:

$$\mathrm{Var}(\tau) = (n*(n-1)*(2n+5)-\sum t_i*(t_i-1)*(2t_i+5))/18,$$

where t_i is the number of tied data values for the i-th group.

After this the standardized test statistic is calculated. The test statistic is calculated as:

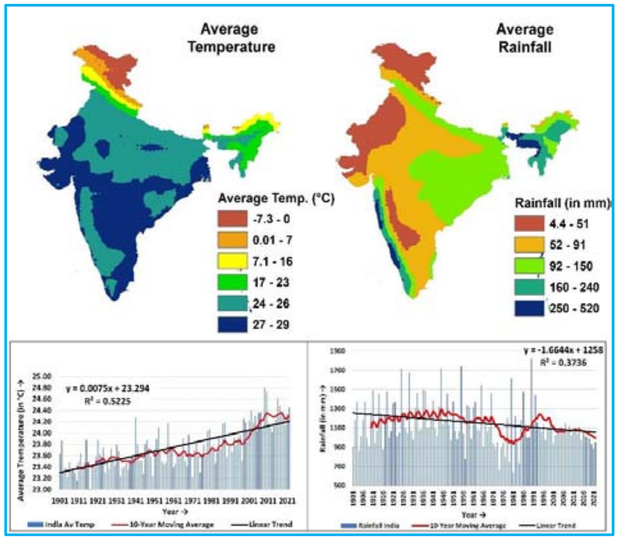

Fig. 3. Long-term average temperature and rainfall pattern in India (1901-2021)

$$Z = (\tau-1) / \mathrm{sqrt}\,[\mathrm{Var}(\tau)],$$

which follows a standard normal distribution under the null hypothesis.

Finally, the significance test is performed. In this, compare the absolute value of the test statistic (|Z|) against the critical values of the standard normal distribution at the desired significance level (*e.g.*, 0.05 or 0.01). If |Z| exceeds the critical value, reject the null hypothesis, and conclude that there is a statistically significant trend in the data. Otherwise, fail to reject the null hypothesis and conclude that no statistically significant trend exists in the data.

Overall, the MK test is suitable for climatic analyses because it is a robust and flexible method that comfortably handles climate data's complex and non-linear nature. MK trend test gives reliable results even when the data does not meet the assumptions of parametric tests.

3. Result

3.1. *Temperature and precipitation status of India*

There have been considerable changes in rainfall and temperature patterns over time. Available temperature and rainfall data show that India's average temperature is 22.95 °C. It has increased by 0.85 °C since 1901. The average rate of temperature increase in India has been 0.007 °C/year. Similarly, the average annual rainfall of India is 91.59 mm. The average rainfall in 1901 was 81.84 mm, which has increased to 104.56 mm at the rate of 0.19 mm/year.

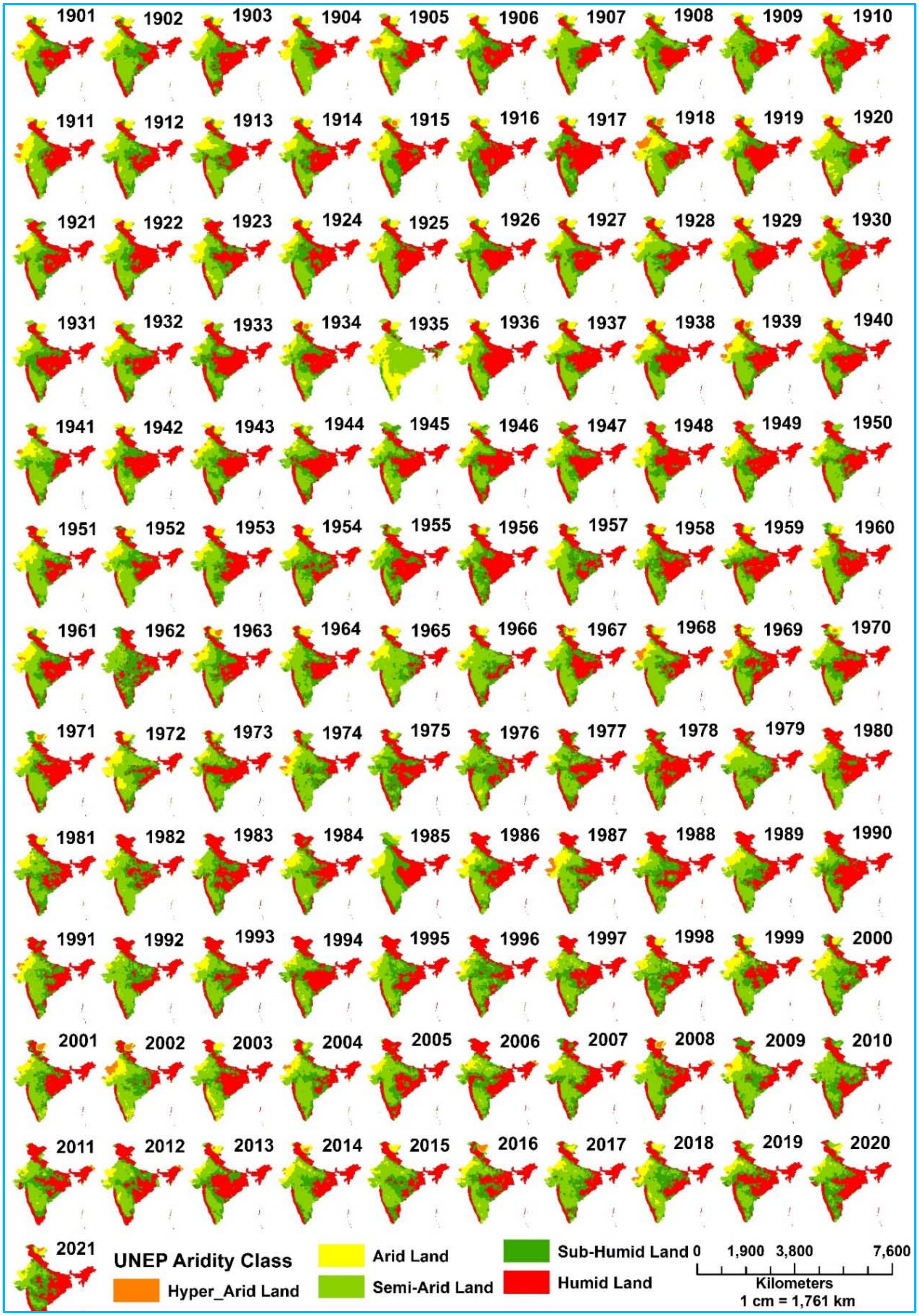

Fig. 2. Long-term annual pattern of different types of aridity in India

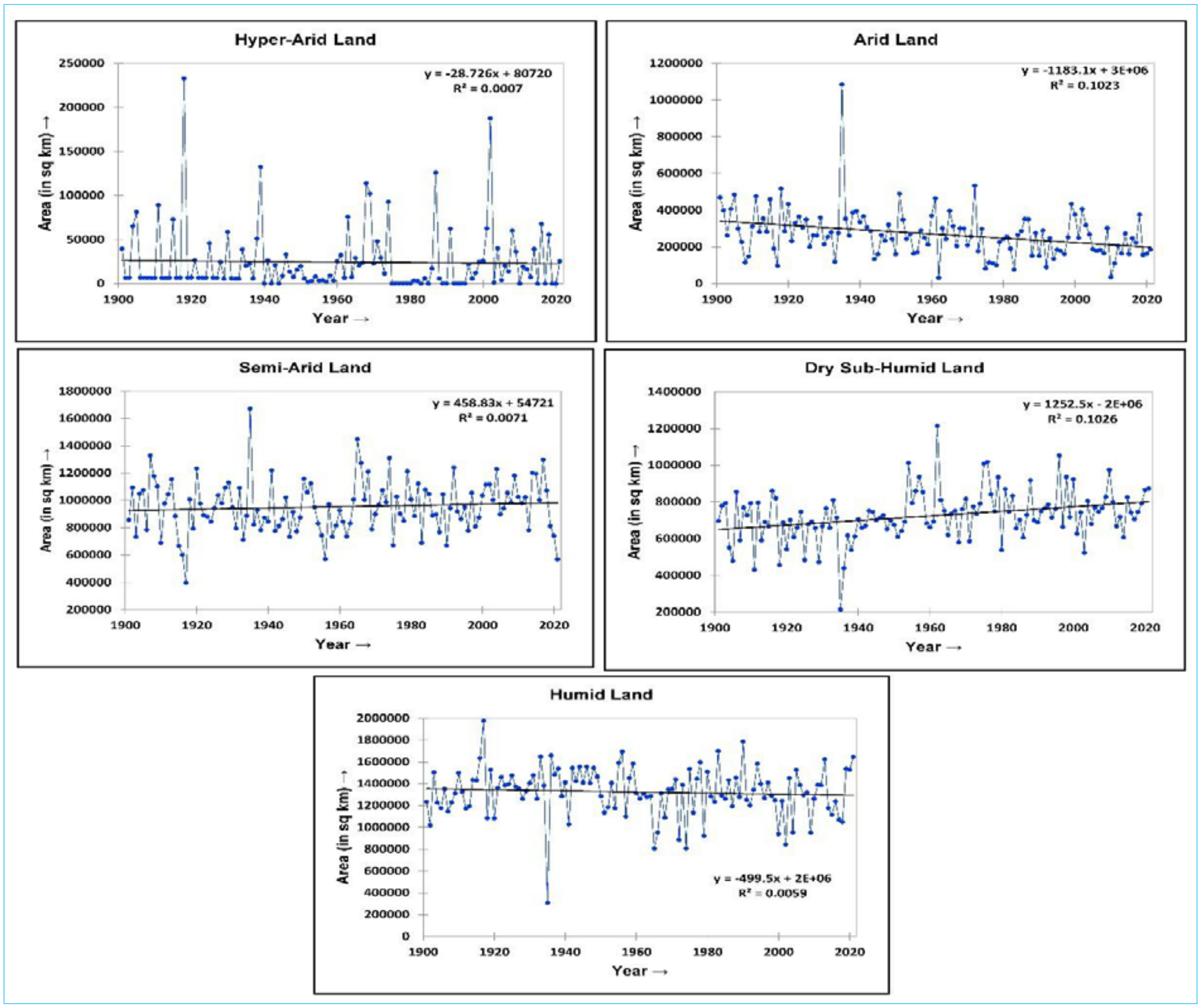

Fig. 3. Temporal trend of different types of aridity

In this way, it was found that since 1901 till now there has been an increase in the temperature and rainfall of India. The long-term spatial pattern of temperature and precipitation over India shows considerable spatial variation exists in the pattern of temperature and precipitation (Fig. 3). A significant effect of these variations is visible in the aridity pattern here because temperature and rainfall are the two main factors that determine the aridity of the concerned area. On a spatial basis, the average temperature of 31.26 per cent of the country's land has been 25 °C. Similarly, mean temperatures of 26 °C and 27 °C spread over 22.47 per cent and 11.14 per cent of the country's land area, respectively. Thus, the average temperature of about 65 per cent of India's land area is about 26 °C.

According to the annual long-term average rainfall pattern, the annual average rainfall in India is 91.59 mm. About 36 per cent of the country's land area comes under the low rainfall category (53-93 mm/year). Similarly, 30 per cent of the land area comes under moderate annual average rainfall (94-154 mm/year), and 24 per cent of the land area comes under very-low average annual rainfall (4-52 mm/year). Thus, about 90 per cent of India's land area receives rainfall ranging from 5 to 155 mm/year. In contrast, 7 per cent of India's land area receives high rainfall (154-240 mm/year), and 3 per cent of land receives very high rainfall (241-517 mm/year).

3.2. *Aridity types and pattern in India*

The above variations in rainfall and temperature play an important role in determining the aridity pattern of the country. Due to this, there is considerable spatio-temporal variation in the pattern of aridity in India. In the present research paper, this aridity pattern has been studied on an annual basis (Fig. 4) which is as follows:

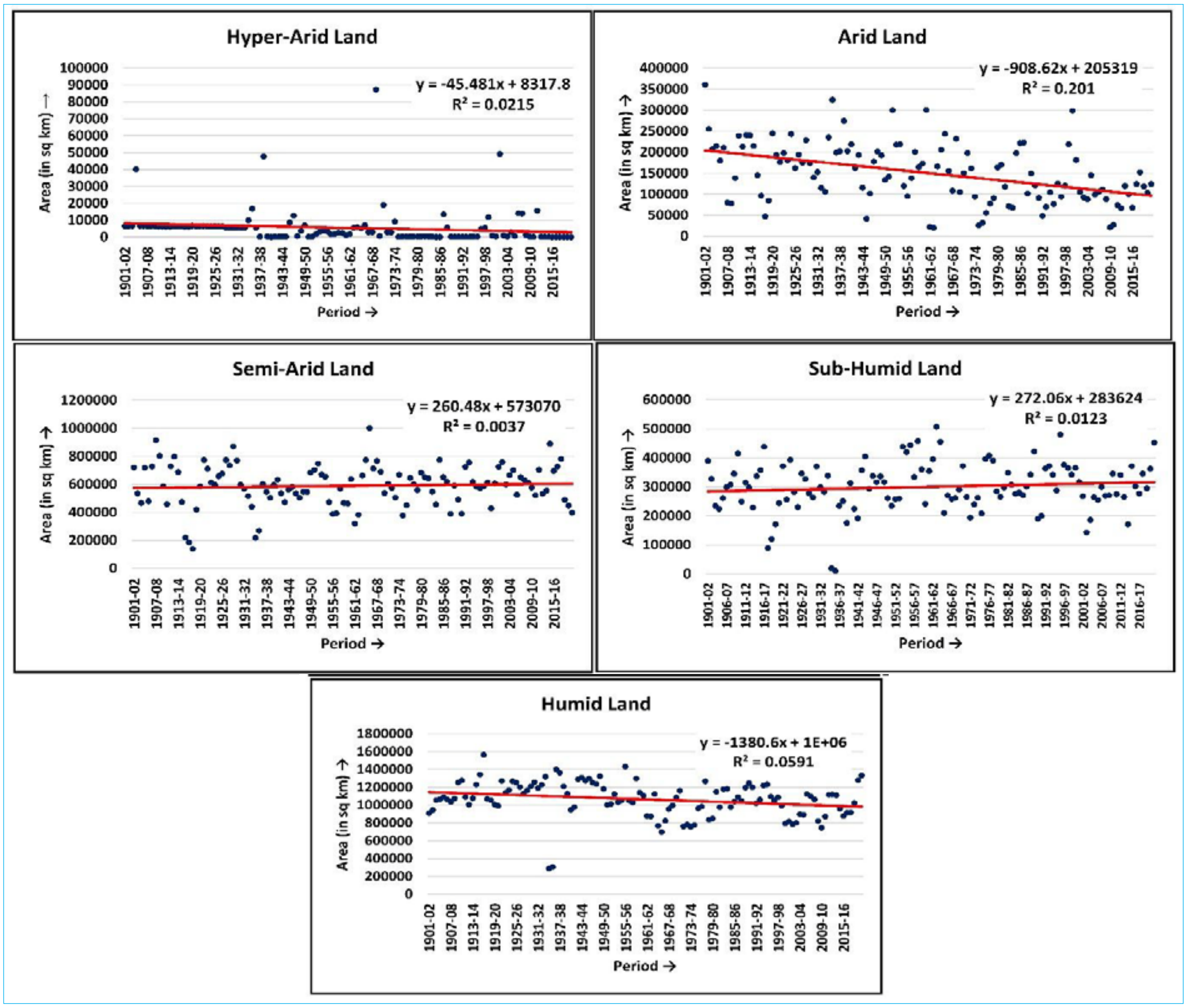

Fig. 4. Temporal trend of non-converted lands under different aridity types

TABLE 1

Long-term average statistics of different aridity types in India

Variable	Minimum Area	Maximum Area	Mean Area	Kendall's tau	p-value
Hyper-Arid Land	0	232763	24388	-0.094	0.1254
Arid Land	31211	1084189	268766	-0.239	0.0001
Semi-Arid Land	397479	1671676	954489	0.066	0.2852
Sub-Humid Land	213585	1213912	725119	0.218	0.0004
Humid Land	306690	1976115	1323590	-0.048	0.4343

3.2.1. *Hyper-Aridity*

According to the study, the average area of hyper-arid land in India has been 24388 sq km (Table 2). Hyper-aridity expansion is mainly found in southwest Rajasthan, north-western Gujarat, Ladakh and western parts of Haryana and Punjab regions. The highest expansion of hyper-aridity was observed in the year 1918, while the lowest expansion was in the year 2019. Apart from these, in 1985 and 2020, India was free from the effects of

TABLE 3

MK-trend test of different types of aridity transformations

Series\Test	Kendall's tau	p-value
HA to HA	-0.426	**< 0.0001**
HA to A	-0.021	0.730
HA to SA	0.188	**0.005**
HA to SH	0.222	**0.002**
HA to H	0.226	**0.001**
A to HA	0.040	0.518
A to A	-0.313	**< 0.0001**
A to SA	-0.058	0.347
A to SH	0.140	**0.026**
A to H	0.287	**< 0.0001**
SA to HA	0.110	0.104
SA to A	0.007	0.915
SA to SA	0.010	0.876
SA to SH	0.075	0.225
SA to H	0.195	**0.002**
SH to HA	0.162	**0.023**
SH to A	0.144	**0.022**
SH to SA	0.087	0.159
SH to SH	0.077	0.213
SH to H	0.114	0.065
H to HA	0.156	**0.028**
H to A	0.182	**0.006**
H to SA	0.175	**0.005**
H to SH	0.131	**0.034**
H to H	-0.181	**0.003**

hyper-aridity. A very weak negative association has been observed between the area of hyper-aridity and time, which means that the size of the lands under the influence of hyper-aridity has decreased with time compared to the past (Fig. 5). Still, this long-term trend is not statistically significant because p-value is higher than 0.05 (Table 2).

Land transformation analysis shows that lands under hyper-aridity that have not been transformed into any other aridity type have a statistically significant decreasing trend due to the less p-value (p-value $\leq$ 0.05) (Table 3), *i.e.*, stable areas of hyper-aridity decrease over time because there is a moderate type of negative association between stable areas of hyper-aridity and time (Fig. 6).

The shift observed in lands transitioning from hyper-arid to arid conditions over time lacks statistical significance, primarily attributed to a low p-value (p-value $\leq$ 0.05) (Table 3) and a very weak type of negative association has been observed between it and time. It has been found that the hyper-arid to arid land transformation has decreased over time (Fig. 7).

A very weak positive association has been observed between hyper-arid to semi-arid land transformation and time which shows that the lands under hyper-arid to semi-arid land transformation have increased with time (Fig. 7). The statistically significant positive trend in the transformation from hyper-arid to semi-arid land is indicated by a p-value of 0.005, which is below the significance threshold of 0.05. (Table 3).

Analysis indicates a transformation of certain hyper-arid regions into sub-humid conditions every year, with this shift being statistically significant, as evidenced by a p-value of 0.002, falling below the established significance threshold of 0.05 (Table 3). There has been a weak but positive association between the dynamics of hyper-arid to sub-humid land transformation land and time, *i.e.*, the land area under hyper-arid to sub-humid land transformation has increased with time (Fig. 7).

The transformation trend from hyper-arid to humid land in this study is noteworthy, given its significant p-value of 0.001, which falls below the 0.05 level of significance (Table 3). It was also found that the dynamics of the areas under hyper-arid to humid land transformation and the time has been a weak type of positive association, which shows that the areas under hyper-arid to humid land transformation over time have increased (Fig. 7).

3.2.2. *Arid Land*

The country's average land area affected by aridity is 268766 sq km (Table 2). The main areas affected by aridity include most of the land in the states of Rajasthan, Gujarat, Haryana, and Punjab. Apart from this, the expansion of aridity has also been observed in the central parts of South India. The maximum extent of land affected by aridity in the country was in 1935 and the least in 1962. A weak negative association has existed between the area dynamics and the time of aridity-affected lands. Over time, the arid region has shown a diminishing trend compared to previous periods. The long-term decline has been found statistically significant, with a p-value of 0.0001, which is less than the 0.05 level of significance (Table 3).

The pattern of land transformation shows that arid lands have shrunk over time. They have been transformed

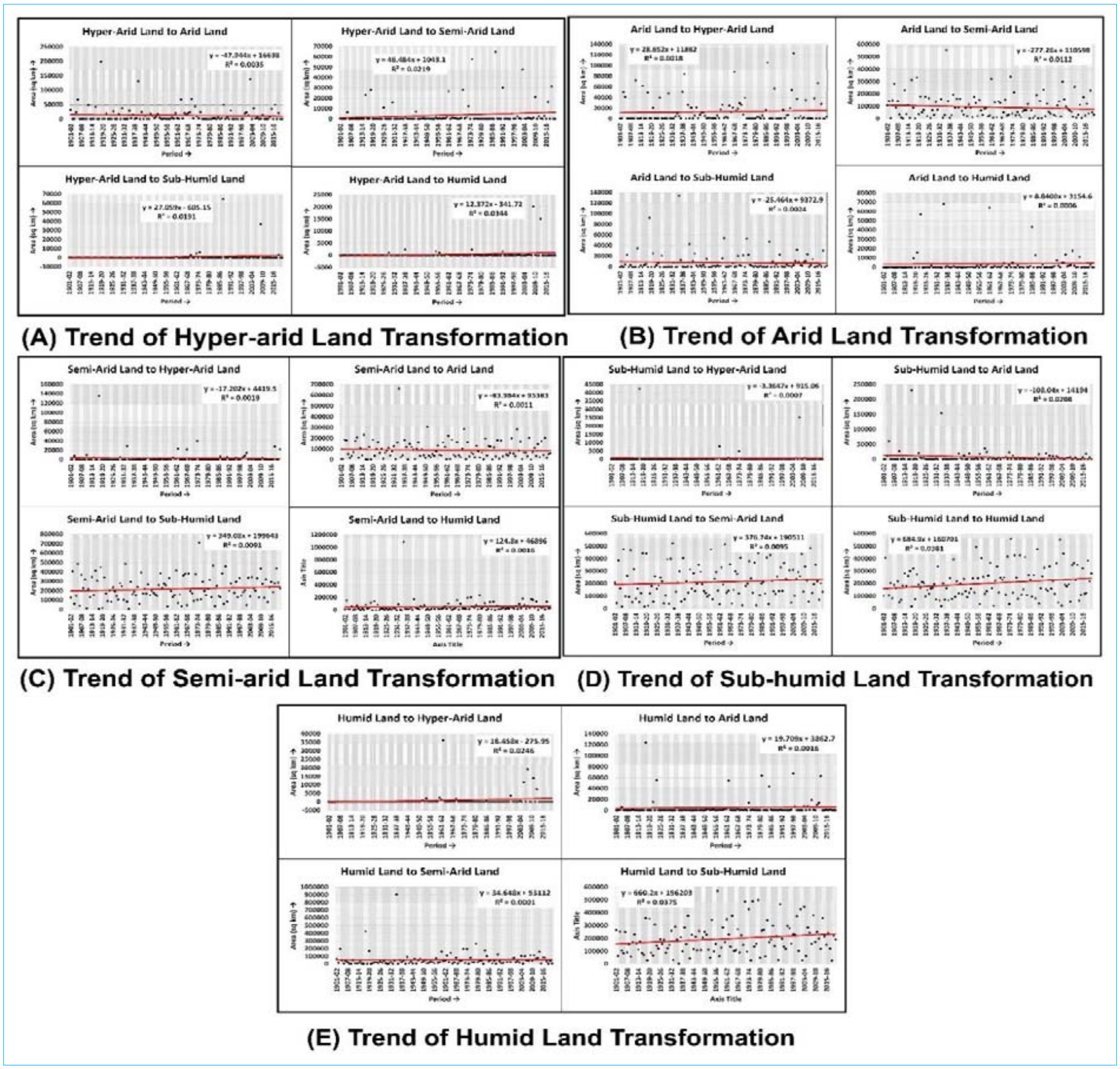

Fig. 5. Trend of different types of arid land transformations in India

into other types and their size has become smaller than before. The statistical analysis observed that arid lands that have not undergone any transformation have a weak negative association with time, which corroborates the decrease in the former area of arid land (Fig. 6). Furthermore, it was noted that the diminishing stable aridity area trend is statistically significant, supported by a p-value (<0.0001), which is below the threshold of 0.05 (Table 3).

A very weak positive association has been found between arid to hyper-arid type of land transformation and time (Fig. 7), This indicates that the transition from arid to hyper-arid conditions is occurring at a sluggish pace over time. The non-significant p-value of 0.518 suggests that the trend is not statistically significant (Table 3)

There is a negative correlation observed between the conversion of arid to semi-arid land and time. This suggests a decreasing trend in the transformation of arid land to semi-arid land over time (Fig. 7), and the p-value of 0.347 indicates that this trend lacks statistical significance (Table 3).

The research revealed a slower growth in the conversion of arid to sub-humid land areas, as depicted in Fig. 7. The trend analysis indicates a relatively weak positive correlation between the transformation of arid to sub-humid land and time. Notably, the statistical significance of this trend is supported by a p-value of 0.026, as presented in Table 3, which is less than the 0.05 level of significance.

The arid-to-humid land transformation has increased over time (Fig. 7) because a weak type of positive association has been found between these two, and the arid-to-humid land transformation trend has been determined to be highly significant, with a p-value of <0.0001, surpassing the 0.05 level of significance (Table 3).

3.2.3. *Semi-arid land*

The average size of lands affected by semi-aridity in the country has been 954489 sq. km (Table 2). Expansion of semi-aridity is observed over most parts of Punjab, Haryana, eastern Rajasthan, eastern Gujarat, western Uttar Pradesh, western Madhya Pradesh, and central parts of South India. The greatest extent of semi-aridity was observed on the lands in 1935 and the least in 1917. Because of the minimal positive correlation, the average size of semi-aridity-affected lands has seen a slight increase over time. However, the long-term trend is not statistically significant, as indicated by the non-significant p-value of 0.2852, which is below the 0.05 level of significance (Table 2).

The pattern of arid land transformation shows that the stable areas under arid land have shrunk over time because a weak negative association has been observed between the areas of arid land and time, which shows a significant decreasing trend confirming the reduction in its area (Fig. 6). The analysis found that there is a very weak type of positive association between the area of non-transformed semi-arid lands and time, which indicates a slow increase in the area of non-transformed semi-arid lands, and with a p-value of 0.876 exceeding the 0.05 significance level, the observed trend is deemed statistically non-significant (Table 3).

A very weak positive association was found in semi-arid to hyper-arid transformation and time, showing its slow increase (Fig. 7). The statistical significance of the semi-arid to hyper-arid transformation trend is not substantial, given its p-value of 0.104, which exceeds the 0.05 level of significance (Table 3).

The transformation from semi-arid to arid land did not exhibit statistical significance, as indicated by a p-value of 0.915, which is below the 0.05 level of significance (Table 3). The semi-arid to arid transformation has a very slow positive association with time, showing that the semi-arid to arid transformation is increasing slowly (Fig. 7).

The increasing trend of transformation from semi-arid to sub-humid land is also not statistically significant as it has a p-value of 0.225, which is higher than the 0.05 level of significance (Table 3).

There exists a subtle yet discernible positive correlation between the conversion of semi-arid to humid land and the passage of time. The transformation from semi-arid to humid land exhibits a rising pattern over time, and this trend holds statistical significance with a p-value of 0.002. The p-value's significance, being below the 0.05 threshold, confirms the statistical significance of the observed transformation trend from semi-arid to humid land (Table 3).

3.2.4. *Sub-Humid Land*

The average area of land affected by sub-humidity is 725119 sq km (Table 2). The extent of lands affected by sub-humidity is mainly in the valleys of the Narmada-Tapti Rivers, Tarai areas in north-eastern Himalayan foothills, eastern Madhya Pradesh, eastern Maharashtra, eastern Bihar and eastern coastal parts of India. In India, the maximum expansion of sub-humidity land was in 1962 and the lowest in 1935. Due to a weak positive association, the area of sub-humidity increased with time compared to the former (Fig. 5), which was statistically significant because it has a p-value of 0.0004, which is less than the level of significance of 0.05 (Table 2).

There has been a very weak positive association between the areas of sub-humid lands and time, due to which the sub-humid lands have increased very slowly over time. The non-transformed sub-humid land trend lacks statistical significance, as evidenced by its p-value of 0.213, exceeding the threshold of 0.05 (Table 3). The non-transformed sub-humid land comprised 41 per cent of the total sub-humid lands.

About 0.1 per cent of the sub-humid lands have been transformed into hyper-arid lands, and a very weak type of positive association was found with time (Table 3). This implies that the sub-humid to hyper-arid land transformation has occurred very slowly in the long term (Fig. 7), which has been found to be statistically significant, because its p-value (0.023) is less than the 0.05 level of significance.

About 1.1 per cent of the sub-humid land has been converted into arid land, and it has a very weak negative association with time (Table 3), *i.e.*, sub-humid to arid land transformation gradually decreases with time (Fig. 7). The statistically significant rise in the transformation of sub-humid to arid land is evident, as indicated by a p-value of 0.022, which is below the 0.05 level of significance (Table 3).

From 1901-2021, about 29 per cent of the sub-humid land has been transformed into semi-arid land. A very weak positive association was observed between areas under sub-humid to semi-arid land transformation and time (Table 3); therefore, sub-humid to semi-arid land transformation has been increasing slowly (Fig. 7) with statistically non-significant trend because it has a p-value of 0.159 which is higher than the level of significance (Table 3).

Since 1901, about 28 per cent of the sub-humid land has been transformed into humid land. A very weak positive association was observed between areas under sub-humid to humid land transformation and time, so sub-humid to humid land transformation has been increasing slowly (Fig. 7) with a non-significant trend over time (Table 3).

3.2.5. *Humid Land*

The long-term pattern shows that the average land area under the influence of humidity has been 1323590 sq km (Table 2). The humid land is mainly spread over the western coastal areas, north-eastern India, Himachal Pradesh, Uttarakhand and Jammu and Kashmir. The highest expansion of humid land was observed in 1917 and the lowest was in 1935. The finding of a very weak negative association shows that the size of the lands with the effect of humidity has shrunk compared to the previous sizes (Fig. 5), but the decline in humid lands is not deemed statistically significant, as the p-value associated with the humid land trend is determined to be 0.43, which is higher than the level of significance 0.05 (Table 2).

On a long-term average basis, it was found that about 81% of the wetland area has remained intact in its original form with minor changes. There is a very weak negative association between non-transformed humid land and time, due to which the area of old non-transformed humid land has been decreasing very slowly (Fig. 6). The decreasing trend of non-transformed humid areas is statistically highly significant because it has a p-value of 0.003 (Table 3).

There is a noteworthy favourable trend (p-value-0.028) in the transformation from humid to hyper-arid land, indicating a minimal positive correlation between this transformation and time (Table 3). 0.06 per cent of the areas have been affected by humid to hyper-arid land transformation.

There has been a statistically significant upward trend in the transformation of humid to arid land, as indicated by a p-value of 0.006, which is below the 0.05

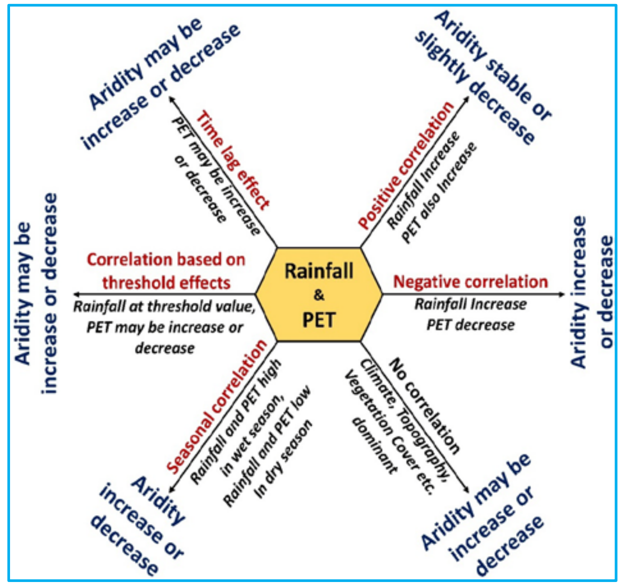

Fig. 6. Rainfall and PET relationship

significance level (Table 3). The humid to arid land transformation has increased over time (Fig. 7) because it has a very weak positive association with time. The long-term average size of the land area undergoing humid to arid land transformation has been 5055 km².

Statistically, the humid to semi-arid land transformation showed a significant increase because its p-value is found 0.005, which is below the 0.05 (Table 3). In the long run, 4 per cent of the humid land has been converted into semi-arid land.

The transition from a humid to a sub-humid environment demonstrated a significant rise, suggesting a positive correlation with the passage of time. This shift is well-supported by a p-value of 0.035, indicating statistical significance (Table 3). About 15 per cent of the humid land was converted to sub-humid land in 1901-2021.

4. Discussion

The study observed that aridity hinges on a delicate correlation between precipitation and potential evapotranspiration (Fig. 8). Due to the changes in these two, there is a change in the spatio-temporal pattern of the existing aridity of any region. The relationship between precipitation and PET is also influenced to a large extent by many other geographic factors, such as climate zones, topography, and vegetation cover. This study mainly observed 6 types of possible relationships between rainfall and PET (Fig. 8).

In some regions, there is a positive relationship between rainfall and PET; that is, as rainfall increases, PET also increases. This relationship typically develops in areas of high temperature due to abundant erratic rainfall receipts where increased precipitation provides more moisture than ever before to evaporate. Along with the rain, the value of PET also becomes high. Due to the formation of a positive correlation between rainfall and PET, the region's aridity either remains constant or decreases at a slower rate. Due to the formation of a positive correlation, the areas of the lands affected by hyper-aridity, aridity, and semi-aridity start shrinking, and their transformation starts taking place in the lands with higher humidity than before.

On the other hand, a negative correlation exists between precipitation and PET in some regions. In such cases, as the rainfall increases, the PET starts decreasing compared to the rainfall. This correlation is usually seen in regions with cold or moderate temperatures, such as Ladakh and other mountainous regions. The increased rainfall in these areas reduces the effect of PET, as a result of which the PET becomes less in the aridity index, and the rainfall becomes more. As a result, there is a decrease in aridity and the land there starts to look more humid than before.

Like above, there are some areas where no significant relationship between rainfall and PET is observed. The relationship between precipitation and PET in these regions cannot be clearly defined because the correlation between precipitation and PET in these regions is highly influenced by topography, vegetation cover, and local climate. In such cases, more influence of the other four is seen on PET. In such a situation, the dryness of the concerned area may increase or decrease.

It is observed that the correlation between rainfall and PET may vary seasonally. For example, there is a positive correlation between rainfall and PET during the monsoon when both rainfall and PET are high. On the other hand, there is a negative correlation between precipitation and PET in the dry season because higher temperatures lead to higher PET while precipitation remains low or non-existent.

Similarly, there may be a threshold effect between precipitation and PET in some cases. In these, PET dominates the water balance below a certain threshold of rainfall, and any increase in rainfall may increase PET. However, after a certain threshold, the effect of precipitation on PET becomes more significant, and increased precipitation can reduce the effect of PET. Due to such threshold-based correlation, the aridity of the concerned area may increase or decrease.

Apart from all the above, the time lag effect can also have an effect on the correlation between rainfall and PET. PET may not respond immediately after a precipitation event. It will react only when the temperature increases or decreases. The time lag effect assumes that precipitation and PET do not respond to each other simultaneously. This correlation type can be seen in studies with shorter periods like daily or weekly.

Finally, it is worth noting that the correlation between precipitation and PET is complex and strongly influenced by local geographic and climatological conditions. The specific relationship between precipitation and PET can vary greatly from region to region.

5. Conclusion

This study estimates the spatio-temporal changes of aridity over Indian land from 1901-2021 using the CRU dataset (rainfall and PET) and UNEP's aridity index. The study also analyzed the transformations in aridity types (hyper-arid, arid, semi-arid, sub-humid and humid). Under this, it was seen to what extent the dry land of hyper-arid, arid, semi-arid, sub-humid and humid types have transformed into each other and their trend. Finally, the trend of hyper-arid, arid, semi-arid, sub-humid and humid lands and their transformation has been analyzed statistically with the help of the MK trend test. The results of this study show that aridity in India is spreading from northwest to east and southeast. The main reason for this spread is the increasing temperature and increasing PET in these parts. The study found that the area of land with hyper-arid, arid, and humid nature decreases over time, while the area of land with semi-arid and sub-humid nature increases with time. It was also found that many areas of hyper-arid, arid, and semi-arid nature lands have changed due to changes in rainfall patterns. There is a decrease in dryness. Such results are visible in the northwestern parts, the central plateau, and the Gangetic plains. On the other hand, the humidity level in the plains, some parts of the northeast, and many parts of eastern India has decreased over time, so the prevalence of aridity is gradually increasing in these parts. It was observed in the study that the aridity pattern in India is changing with great rapidity. Therefore, there is a need to emphasize studying various aspects of increasing aridity in more depth. The present study demonstrates the spatio-temporal patterns of different types of aridity as accurately as possible, which can be used to make robust aridity estimates and better implement projects related to sustainable agriculture and water resources management. Moreover, there is a need to emphasize determining the role of other variables related to the spatio-temporal variability of aridity present in different parts of India so that further studies related to aridity will prove to be more accurate and useful for us.

Acknowledgement

The authors are grateful to the India Meteorological Department and the Climate Research Unit of the University of East Anglia for providing free gridded climatic data.

Disclaimer : The contents and views expressed in this study are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

References

Ahmed, K., Shahid, S., Chung, E. S., Nawaz, N., Khan, N. and Rasheed, B., 2020, "Divergence of potential evapotranspiration trends over Pakistan during 1967-2016", *Theoretical and Applied Climatology*, **141**, 215-227.

An, Z. (Ed.), 2014, Late Cenozoic climate change in Asia : loess, monsoon and monsoon-arid environment evolution.

Berg, A., Findell, K., Lintner, B., Giannini, A., Seneviratne, S. I., Van Den Hurk, B., ... and Milly, P. C., 2016, "Land-atmosphere feedbacks amplify aridity increase over land under global warming", *Nature Climate Change*, **6**, 9, 869-874.

Budyko, M. I., 1974, "Climate and Life", New York, NY: Academic Press p508.

Chen, H., and Wang, S., 2022, "Accelerated transition between dry and wet periods in a warming climate", *Geophysical Research Letters*, **49**, 19, e2022GL099766.

Choudhary, A., Mahato, S., Roy, P. S., Pandey, D. N., and Joshi, P. K., 2023, "Analyzing the long-term variability and trend of aridity in India using non-parametric approach", *Stochastic Environmental Research and Risk Assessment*, 1-18.

Dai, A., 2011, "Drought under global warming: a review", *Wiley Interdisciplinary Reviews : Climate Change*, **2**, 1, 45-65.

De Martonne, E., 1923, "Aridité et indices d'aridité. Académie des Sciences", Comptes Rendus, **182**, 23, 1935-1938.

Delgado-Baquerizo, M., Doulcier, G., Eldridge, D. J., Stouffer, D. B., Maestre, F. T., Wang, J., ... and Singh, B. K., 2020, "Increases in aridity lead to drastic shifts in the assembly of dryland complex microbial networks", *Land Degradation & Development*, **31**, 3, 346-355.

Djebou, D. C. S., 2017, "Bridging drought and climate aridity", *Journal of Arid Environments*, **144**, 170-180.

Fang, D., Hao, L., Cao, Z., Huang, X., Qin, M., Hu, J., ... & Sun, G., 2020, "Combined effects of urbanization and climate change on watershed evapotranspiration at multiple spatial scales", *Journal of Hydrology*, **587**, 124-869.

Fu, Q. and Feng, S., 2014, "Responses of terrestrial aridity to global warming", *Journal of Geophysical Research : Atmospheres*, **119**, 13, 7863-7875.

Gao, Y., Li, X., Leung, L. R., Chen, D. and Xu, J., 2015, "Aridity changes in the Tibetan Plateau in a warming climate", *Environmental Research Letters*, **10**, 3, 034013.

Gaussen, H., 1949, "L'étage sub-alpin-Ecologie et reboisement", *Revue forestière française*, (7), 324.

Ghazanfari, S., Pande, S., Hashemy, M. and Sonneveld, B., 2013, "Diagnosis of GLDAS LSM based aridity index and dryland identification", *Journal of environmental management*, **119**, 162-172.

Goparaju, L. and Ahmad, F., 2019, "Analysis of seasonal precipitation, potential evapotranspiration, aridity, future precipitation anomaly and major crops at district level of India", *KN-Journal of Cartography and Geographic Information*, **69**, 2, 143-154.

Greve, P. and Seneviratne, S. I., 2015, "Assessment of future changes in water availability and aridity", *Geophysical research letters*, **42**, 13, 5493-5499.

Greve, P., Roderick, M. L., Ukkola, A. M. and Wada, Y., 2019, "The aridity index under global warming", *Environmental Research Letters*, **14**, 12, 124006.

Harris, I., Osborn, T. J., Jones, P. and Lister, D., 2020, "Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset", *Scientific data*, **7**, 1, 109.

Huang, J., Li, Y., Fu, C., Chen, F., Fu, Q., Dai, A., ... & Wang, G., 2017, "Dryland climate change : Recent progress and challenges", *Reviews of Geophysics*, **55**, 3, 719-778.

Jain, S. K. and Kumar, V., 2012, "Trend analysis of rainfall and temperature data for India", *Current Science*, 37-49.

Kumar, V., Jain, S. K. and Singh, Y., 2010, "Analysis of long-term rainfall trends in India", *Hydrological Sciences Journal-Journal des Sciences Hydrologiques*, **55**, 4, 484-496.

Li, Y., Chen, Y. and Li, Z., 2019, "Dry/wet pattern changes in global dryland areas over the past six decades", *Global and Planetary Change*, **178**, 184-192.

Lian, X., Piao, S., Chen, A., Huntingford, C., Fu, B., Li, L. Z., ... & Roderick, M. L., 2021, "Multifaceted characteristics of dryland aridity changes in a warming world", *Nature Reviews Earth & Environment*, **2**, 4, 232-250.

Lian, X., Piao, S., Chen, A., Huntingford, C., Fu, B., Li, L. Z., ... & Roderick, M. L., 2021, "Multifaceted characteristics of dryland aridity changes in a warming world", *Nature Reviews Earth & Environment*, **2**, 4, 232-250.

Lioubimtseva, E. and Cole, R., 2006, "Uncertainties of climate change in arid environments of Central Asia", *Reviews in Fisheries Science*, **14**, 1-2, 29-49.

Lioubimtseva, E. and Henebry, G. M., 2009, "Climate and environmental change in arid Central Asia : Impacts, vulnerability, and adaptations", *Journal of Arid Environments*, **73**, 11, 963-977.

Lioubimtseva, E., Cole, R., Adams, J. M. and Kapustin, G., 2005, "Impacts of climate and land-cover changes in arid lands of Central Asia", *Journal of Arid Environments*, **62**, 2, 285-308.

Luo, D., Hu, Z., Dai, L., Hou, G., Di, K., Liang, M., ... & Zeng, X., 2023, "An overall consistent increase of global aridity in 1970-2018", *Journal of Geographical Sciences*, **33**, 3, 449-463.

Mondal, A., Khare, D. and Kundu, S., 2015, "Spatial and temporal analysis of rainfall and temperature trend of India", *Theoretical and applied climatology*, **122**, 143-158.

Palmer, W. C., 1965, Meteorological drought (Vol. 30). US Department of Commerce, Weather Bureau.

Paltasingh, K. R., Goyari, P. and Mishra, R. K., 2012, "Measuring weather impact on crop yield using aridity index : Evidence from Odisha", *Agricultural Economics Research Review*, 25(347-2016-17010), 205-216.

Pan, N., Wang, S., Liu, Y., Li, Y., Xue, F., Wei, F., ... & Fu, B., 2021, "Rapid increase of potential evapotranspiration weakens the effect of precipitation on aridity in global drylands", *Journal of Arid Environments*, **186**, 104414.

Park, C. E., Jeong, S. J., Joshi, M., Osborn, T. J., Ho, C. H., Piao, S., ... & Feng, S., 2018, "Keeping global warming within 1.5 C constrains emergence of aridification", *Nature Climate Change*, **8**, 1, 70-74.

Pinjarla, B., Joshi, P. K. and Roy, P. S., 2021, "Long term spatio-temporal variations of seasonal and decadal aridity in India", *Journal of Atmospheric Science Research*, **4**, 3, 29-45.

Prăvălie, R., Bandoc, G., Patriche, C. and Sternberg, T., 2019, "Recent changes in global drylands: Evidences from two major aridity databases", *Catena*, **178**, 209-231.

Proutsos, N. D., Tsiros, I. X., Nastos, P. and Tsaousidis, A., 2021, "A note on some uncertainties associated with Thornthwaite's aridity index introduced by using different potential evapotranspiration methods", *Atmospheric Research*, **260**, 105727.

Ramachandran, A., Praveen, D., Jaganathan, R. and Palanivelu, K., 2015, "Projected and observed aridity and climate change in the east coast of south India under RCP 4.5.", *The Scientific World Journal*, 2015.

Ramarao, M. V. S., Sanjay, J., Krishnan, R., Mujumdar, M., Bazaz, A., & Revi, A., 2019, "On observed aridity changes over the semiarid regions of India in a warming climate", *Theoretical and applied climatology*, **136**, 693-702.

Salvati, L., Mancino, G., De Zuliani, E., Sateriano, A., Zitti, M. & Ferrara, A., 2013, "An expert system to evaluate environmental sensitivity: A local-scale approach to desertification risk", *Appl. Ecol. Environ. Res.*, **11**, 4, 611-627.

Salvati, L., Perini, L., Sabbi, A. and Bajocco, S., 2012, "Climate aridity and land use changes : A regional-scale analysis", *Geographical Research*, **50**, 2, 193-203.

Sarma, R. and Singh, D. K., 2019, "Spatio-temporal analysis of drought and aridity in Gomti basin", *Current Science*, **116**, 6, 919-925.

State of the climate in Asia, 2021, World Meteorological Organization. https://public.wmo.int/en/our-mandate/climate/wmo-statement-state-of-global-climate/asia

Subash, N. and Sikka, A. K., 2014, "Trend analysis of rainfall and temperature and its relationship over India", *Theoretical and applied climatology*, **117**, 449-462.

Thomas, D. S., 1997, World atlas of desertification (Vol. 182). N. Middleton (Ed.). London: Arnold.

Thornthwaite, C. W., 1948, "An approach toward a rational classification of climate", *Geographical review*, **38**, 1, 55-94.

Turc, L., 1954, Le bilan d'eau des sols: Relation entre la precipitations, l'evaporation et l'ecoulement. Annales Agronomiques, Série A, 5, 491.

Ullah, S., You, Q., Sachindra, D. A., Nowosad, M., Ullah, W., Bhatti, A. S., ... & Ali, A., 2022, "Spatiotemporal changes in global aridity in terms of multiple aridity indices : An assessment based on the CRU data", *Atmospheric Research*, **268**, 105998.

United Nations Environment Programme (UNEP), 1992, World Atlas of Desertification.

Zarch, M. A. A., Sivakumar, B., Malekinezhad, H. and Sharma, A., 2017, "Future aridity under conditions of global climate change", *Journal of Hydrology*, **554**, 451-469.

Zheng, H., Chiew, F. H., Charles, S. and Podger, G., 2018, "Future climate and runoff projections across South Asia from CMIP5 global climate models and hydrological modelling", *Journal of Hydrology : Regional Studies*, **18**, 92-109.

Zomer, R. J., Xu, J. and Trabucco, A., 2022, "Version 3 of the global aridity index and potential evapotranspiration database", *Scientific Data*, **9**, 1, 409.