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ORIGINAL PAPER

Spatiotemporal trends in extreme rainfall and temperature indices over Upper Tapi Basin, India

Priyank J. Sharma [1] · V. D. Loliyana [2] · Resmi S. R. [2] · P. V. Timbadiya [1] · P. L. Patel [1]

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Abstract

The flood risk across the globe is intensified due to global warming and subsequent increase in extreme temperature and precipitation. The long-term trends in extreme rainfall (1944–2013) and temperature (1969–2012) indices have been investigated at annual, seasonal, and monthly time scales using nonparametric Mann-Kendall (MK), modified Mann-Kendall (MMK), and Sen's slope estimator tests. The extreme rainfall and temperature indices, recommended by the Expert Team on Climate Change Detection Monitoring Indices (ETCCDMI), have been analyzed at finer spatial scales for trend detection. The results of trend analyses indicate decreasing trend in annual total rainfall, significant decreasing trend in rainy days, and increasing trend in rainfall intensity over the basin. The seasonal rainfall has been found to decrease for all the seasons except postmonsoon, which could affect the rain-fed agriculture in the basin. The 1- and 5-day annual maximum rainfalls exhibit mixed trends, wherein part of the basin experiences increasing trend, while other parts experience a decreasing trend. The increase in dry spells and concurrent decrease in wet spells are also observed over the basin. The extreme temperature indices revealed increasing trends in hottest and coldest days, while decreasing trends in coldest night are found over most parts of the basin. Further, the diurnal temperature range is also found to increase due to warming tendency in maximum temperature (T_{max}) at a faster rate compared to the minimum temperature (T_{min}). The increase in frequency and magnitude of extreme rainfall in the basin has been attributed to the increasing trend in maximum and minimum temperatures, reducing forest cover, rapid pace of urbanization, increase in human population, and thereby increase in the aerosol content in the atmosphere. The findings of the present study would significantly help in sustainable water resource planning, better decision-making for policy framework, and setting up infrastructure against flood disasters in Upper Tapi Basin, India.

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✉ P. V. Timbadiya
pvtimbadiya@ced.svnit.ac.in

Priyank J. Sharma
pjs230688@gmail.com

V. D. Loliyana
viraj_nishi@yahoo.com

Resmi S. R.
iiresmii@gmail.com

P. L. Patel
premlalpatel1966@gmail.com

[1] Department of Civil Engineering, Sardar Vallabhbhai National Institute of Technology (SVNIT), Surat, Gujarat 395007, India

[2] Centre of Excellence (CoE) on Water Resources and Flood Management, Department of Civil Engineering, Sardar Vallabhbhai National Institute of Technology (SVNIT), Surat, Gujarat 395007, India

1 Introduction

Rainfall is one of the key components of the hydrologic cycle, which exhibits diverse spatial and temporal variability across the globe. The Indian Summer Monsoon Rainfall (ISMR) is the major source of water availability for most parts of India (Dash et al. 2011). The agriculture sector in India is primarily dependent on ISMR for its water availability and sustainability. The variations in rainfall would have significant impacts on the agricultural production in the country. The stability of ISMR over the past century has been a riddle against the backdrop of rising global surface temperature (Goswami et al. 2006). The global mean precipitation was projected to increase; however, nonuniformity was observed in its pattern at regional scales (Stocker et al. 2013). Also, the globally averaged land and ocean surface temperatures were found to increase during the period 1880–2012 (IPCC 2014). The increase in temperature and reduction in rainfall may lead to shortage of crop water and subsequent reduction in agricultural production (Riha et al. 1996). The climate models predict an increasing trend in extreme precipitation under greenhouse warming conditions over large parts of the globe (Kharin and Zwiers 2000; Wehner 2004; Goswami et al. 2006; Rajeevan et al. 2008). Based on Clausius-Clapeyron relation, surface warming is expected to cause increase in water vapor concentration by about 6–7% per °C change in temperature (Trenberth 2011). As a consequence, the magnitude and frequency of precipitation extremes were found to increase under global warming condition (IPCC 2014). As a result, the frequency of great floods (having return periods greater than 100 years) was found to significantly increase during the twentieth century (Milly et al. 2002). Such extreme rainfall often results in flash floods; landslides; damage to buildings, infrastructure, and crops; and loss of lives which have major social, economic, and environmental consequences (Goswami et al. 2006; Soro et al. 2016). The detection of long-term trends and variability in extreme rainfall and temperature would facilitate sustainable water resources planning and management, assessment of the impact of climate changes on water resources, and setting up of infrastructure for disaster preparedness (Goswami et al. 2006; Rahmat et al. 2015).

The changes in extremes of climatic variables (precipitation and temperature) and their impacts such as heat waves, droughts, floods, cyclones, and wildfires have attracted much attention in recent years. In the recent past, a number of researchers analyzed the trends in mean and extreme precipitation as well as temperature (Zhai et al. 2005; Alexander et al. 2006; Martinez et al. 2012; Zhang et al. 2012; Boccolari and Malmusi 2013; Song et al. 2014; Sharma and Babel 2014; Soltani et al. 2016; Soro et al. 2016; Liu et al. 2016; Xiao et al. 2016; He et al. 2017; Caloiero 2017; Ye and Li 2017) and largely reported their increasing trends across the globe. Moreover, trends and variability in extreme precipitation and temperature, at country, regional, and basin scales, play an important role in hydrologic assessments. The studies reported by different researchers (Parthasarathy et al. 1994; Sen Roy and Balling 2004; Guhathakurta and Rajeevan 2008; Rajeevan et al. 2008; Krishnamurthy et al. 2009; Kothawale et al. 2010; Kumar et al. 2010; Kumar and Jain 2011; Pal and Al-Tabbaa 2011; Revadekar et al. 2011; Guhathakurta et al. 2011; Jain and Kumar 2012; Kharol et al. 2013; Jhajharia et al. 2014; Pingale et al. 2014; Taxak et al. 2014; Sonali and Kumar 2016; Meshram et al. 2016; Panda et al. 2016; Chandniha et al. 2016, Deshpande et al. 2016; Bisht et al. 2017; Guhathakurta et al. 2017) provide insight about long-term trends and variability of extreme precipitation and temperature in the Indian context. Sen Roy and Balling (2004) investigated linear trends in seven extreme precipitation indices (total precipitation; maximum 1-, 5-, and 30-day total rainfall; 90th, 95th, and 97.5th percentile rainfall values) across 129 stations in India over the period 1910–2000. Their study revealed an increasing trend in frequency of extreme precipitation in the region extending from northwestern Himalayas to most of the Deccan Plateau in the southern peninsular region of India. Goswami et al. (2006) found a significant increase in frequency and magnitude of extreme rainfall over central India during 1951–2000, which may likely enhance the associated flood risks in the coming decades. Rajeevan et al. (2008) also reported an increase in frequency of extreme events over India at about 6% per decade during the period 1901–2004. The results of Ghosh et al. (2009) contradict with that of Goswami et al. (2006) for some places over central India, wherein the presence of increasing trend in heavy rainfall and decreasing trend in moderate rainfall was reported by the latter. The study analyzed the data at a finer scale, demonstrating high spatial variability in rainfall due to local level changes (in terms of population and urbanization), which contradicts with the results analyzed at larger scales. Kumar et al. (2010) found a decreasing trend in annual total rainfall at the rate of −2.8% of mean rainfall per 100 years over west central India. Kishtawal et al. (2010) pointed out that increasing trends in extreme rainfall events over urban areas were larger and more statistically significant than those over rural areas. Further, increasing trend in frequency of extreme rainfall events was observed over India in the regions with extensive urbanization. Vittal et al. (2013) highlighted the changes in pattern of extreme rainfall over India due to intense urbanization after the year 1950. Ali et al. (2014) also reported a significant increase in extreme rainfall at the urban areas located in west-central India, which could be due to large-scale climatic variability in the region. Mondal et al. (2015) reported overall decreasing trend in annual rainfall and increase in maximum and mean temperatures over India. Guhathakurta et al. (2017) reported 50% increase in rainstorms while 80% increase in duration of rainstorms during the period 1951–2000 over India.

Singh et al. (2005) reported a westward shift, larger variability, and declining tendency in the rainfall across the river basins of India, especially the basins of central India (viz., Sabarmati, Mahi, Narmada, Tapi, Godavari, and Mahanadi). Kumar and Jain (2011) also reported similar findings and found decreasing trends in annual rainfall and rainy days over the Tapi Basin with percentage changes of −18.1 and −23.5% of their respective means of 100 years. The decreasing trends in annual precipitation (post-1950) were also observed over Chhattisgarh State (Meshram et al. 2016), Madhya Pradesh State (Duhan and Pandey 2013; Kundu et al. 2015), Wainganga Basin (Taxak et al. 2014), Jharkhand State (Chandniha et al. 2016), and Purna Basin (Sharma et al. 2017). Kundu et al. (2016) found a decreasing trend of rainfall and an increasing trend in minimum and maximum temperatures and annual reference evapotranspiration over Madhya Pradesh State for the period 1901–2005. Bisht et al. (2017) indicated downward trends in seasonal and annual rainfalls while upward trends in extreme rainfall (post-1970 period) across major river basins of India and emphasized the need to carry out analysis at subbasin scale for larger basins to capture the intrabasin spatial variability for better decision-making in water resources management.

The ISMR has been found to exhibit wide spatial and temporal variability across India which may be, apart from global warming, due to many local-scale changes like population growth, rapid urbanization, industrialization, and deforestation (Ghosh et al. 2009). The results on variability of climatic parameters could be misleading, if local-scale changes are not given due consideration. The analysis of the results of extreme climatic indices at larger scales (countrywide, regional, or basin level) may neutralize the variability at finer scales (subbasin level) (Thomas et al. 2015). Therefore, analysis of extreme climatic indices at a finer scale would be of utmost importance and reliable in hydrological applications and water resources management (Ghosh et al. 2009; Bisht et al. 2017) of respective subbasins. The Tapi Basin is one of the major river basins in west central India, spread over an area of 65,145 km^2, covering Madhya Pradesh, Maharashtra, and Gujarat states. The average annual rainfall for the three subbasins of Tapi Basin, viz., Upper, Middle, and Lower, were observed to be 935.6, 631.5, and 1042.3 mm, respectively (Jain et al. 2007). Keeping in view considerable variability in rainfall across the basin and the importance of water resource management and flooding at local levels, the present study emphasizes on the assessment of spatial and temporal variations in trends of extreme rainfall and temperature indices at finer scale (subbasin level) for Upper Tapi Basin (area ≈ 29,430 km^2). The present study has been aimed to fulfill the following objectives: (i) analyze the long-term trends and variability in annual, seasonal, and monthly total rainfall using nonparametric Mann-Kendall (MK), modified Mann-Kendall (MMK), and Sen's slope estimator tests; (ii) analyze the trends and variability in frequency and magnitude of extreme rainfall indices; (iii) analyze the spatial variability in extreme temperature indices at different temporal scales; and (iv) establish the linkages between changes in extreme climatic indices with anthropogenic influences such as changes in land use-land cover and human population and their associated effects in Upper Tapi Basin.

2 Materials and methods

2.1 Study area

The Tapi River originates from Multai in Betul District, Madhya Pradesh, India. The Tapi River is one of the largest rivers draining into the Arabian Sea in the western part of the country. The Tapi Basin is delineated into three subbasins, i.e., Upper Tapi Basin from origin to Hathnur dam (29,430 km^2), Middle Tapi Basin from Hathnur dam to Ukai dam (31,767 km^2), and Lower Tapi Basin from Ukai dam to the Arabian Sea in the Gulf of Khambhat (3948 km^2) (CWC 2014). The annual average rainfall in the Tapi Basin is about 835 mm, the maximum being 2550 mm. About 90% of the total rainfall is received during the monsoon months (June to September), of which 50% is received during July and August months. The Upper Tapi Basin covers Amravati, Akola, and Buldana districts of Maharashtra state and Betul and Khandwa districts of Madhya Pradesh state. There are two major rivers, viz. Tapi (length ≈ 363 km) and Purna (length ≈ 353 km), which meets the former just at upstream of Hathnur dam. The basin is located in the zone of severe rainstorms, wherein maximum 1-, 2-, and 3-day point rainfalls were reported to be equal to or more than 200, 250, or 300 mm, respectively (Dhar and Nandargi 1995). The southwest monsoon is the principal rainfall season in the basin which traditionally sets in by the middle of June and withdraws by mid-October. The index map of the Upper Tapi Basin with locations of rain gauge and weather stations and the digital elevation model (DEM) is included in Fig. 1.

2.2 Data used

The daily rainfall data of 24 rain gauge stations were collected from India Meteorological Department (IMD), Pune and Central Water Commission (CWC), Surat for the Upper Tapi Basin. Further, twice-daily maximum and minimum temperatures recorded at five weather stations, one in each district, were collected from IMD Pune. The geographical attributes of the rain gauge and weather stations including their elevations and data availability are listed in Table 1. The Betul and Khandwa weather stations are located outside the basin boundary; however, a considerable portion of these districts falls in the basin and, hence, considered for analysis in the present study. The land use-land cover (LULC) for the year 2010 was classified based on supervised classification in ERDAS® Imagine 10.0. The five scenes of Indian Remote Sensing (IRS) P6 LISS-III imagery, 23.5-m horizontal resolution, were obtained from the National Remote Sensing Centre (NRSC), Hyderabad, and classified into five Food and Agriculture Organization (FAO)-based classes (see Fig. 2). It is found that agriculture land (about 63%) is the predominant land use, followed by deciduous forest (about 28%) in the Upper Tapi Basin. The major urban centers located in the basin are Amravati, Akola, Buldana, and Burhanpur which have been found to expand rapidly in the recent decades.

2.3 Preliminary statistical analysis

The analysis of daily precipitation values indicated that, at some stations, few rainfall records were missing which were

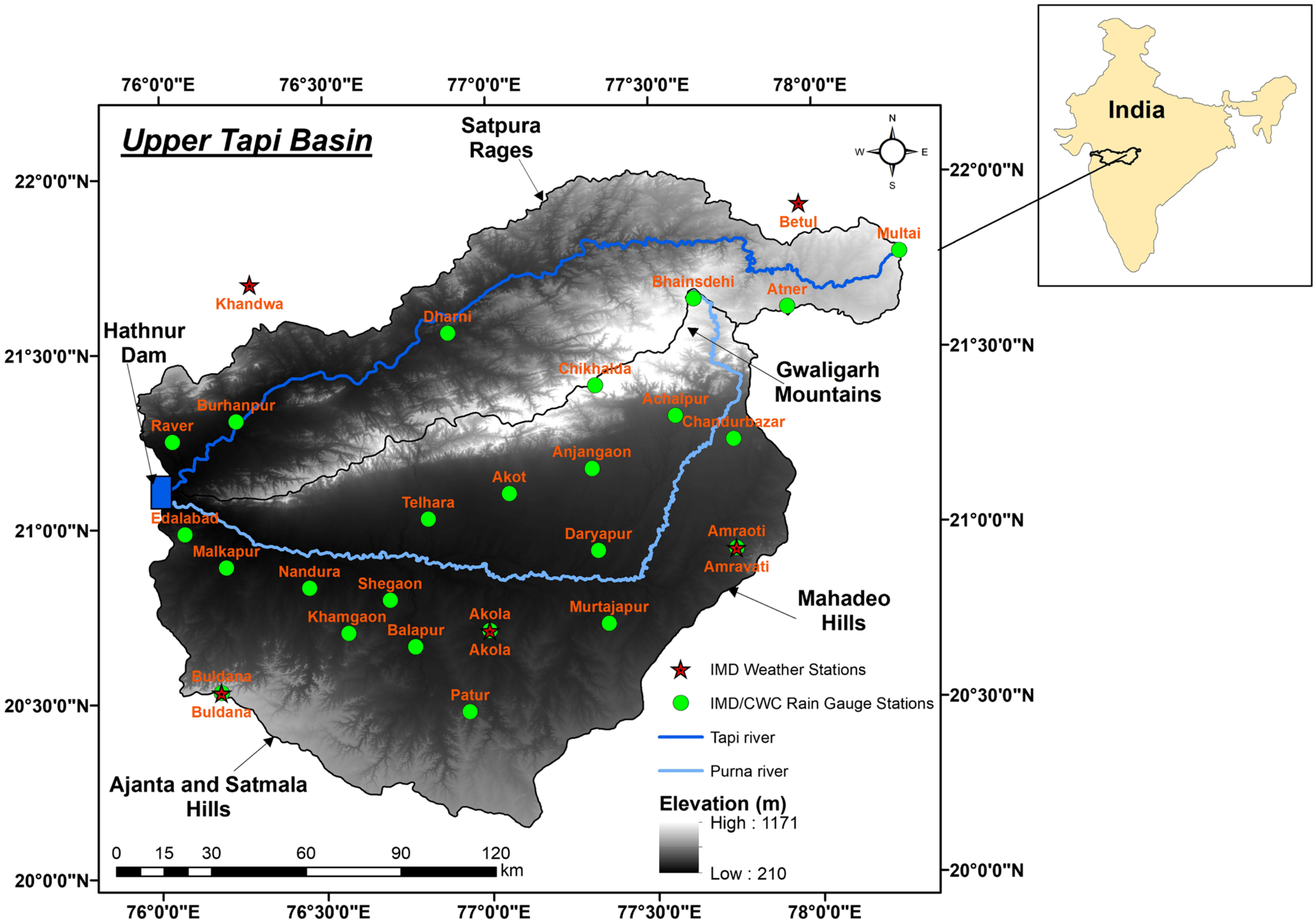

Fig. 1 Index map showing the location of rain gauge and weather stations in Upper Tapi Basin

filled using the inverse distance weighting (IDW) method (Chen and Liu 2012) (see Eq. 1).

$$P_{\mathrm{o}} = \frac{\sum_{i=1}^{n} \frac{R_i}{d_i^2}}{\sum_{i=1}^{n} \frac{1}{d_i^2}} \tag{1}$$

Here, P_{o} = the rainfall value at missing rain gauge station (mm), R_i = the known rainfall value at i^{th} surrounding rain gauge station (mm), n = the number of observations, and d_i = the distance between missing rain gauge station and i^{th} surrounding rain gauge station (km). The statistical parameters such as arithmetic mean, median, range, standard deviation, coefficient of variation (C_{v}), skewness, and kurtosis of rainfall data are also computed for different stations. It is observed that overall mean and standard deviation of total annual rainfall in the Upper Tapi Basin are 835.1 and 258.8 mm, respectively. The average temperature in the basin varies from 18 to 32 °C during the entire year, while the highest and lowest temperatures are recorded in the months of May and January, respectively. The least variation in the average temperature is found during monsoon ($C_{\mathrm{v}} = 9.6\%$), whereas the variability during the winter ($C_{\mathrm{v}} = 11.5\%$) is a bit higher. The spatial distribution of historical annual and seasonal total rainfall as well as average temperature over Upper Tapi Basin is shown in Figs. 3 and 4, respectively. In order to compute the spatial distribution from the point values, spatially interpolated maps are prepared. The topo to raster tool of ArcGIS® 10.4, an interpolation tool specifically designed for the creation of hydrologically correct DEMs (Hutchinson and Dowling 1991), is adopted, in the present study, to generate maps showing spatial distribution of climatic variables. In present study, 12 months were grouped into four different seasons, viz., premonsoon (March–May), monsoon (June–September), postmonsoon (October–November), and winter (December–February). From available historical data (1944–2013), the rainfall distribution in premonsoon, monsoon, postmonsoon, and winter seasons are found to be 1.93, 88.20, 7.72, and 2.14%, respectively, of annual total rainfall (see Fig. 3). This clearly indicates that the southwest monsoon is the principal rainy season in the basin, whereas the basin receives very less rainfall during the retreating monsoon. From Fig. 3, it can be seen that

Table 1 Description of rain gauge and weather stations in the study area

Station ID	Rain gauge/weather stations	Latitude	Longitude	Elevation (m)**	Data availability	No. of years
Rain gauge stations						
1	Achalpur	21° 18′ N	77° 34′ E	377	1944–2013	70
2	Akola	20° 42′ N	77° 00′ E	285	1944–2013	70
3	Akot	21° 05′ N	77° 04′ E	314	1951–2013	63
4	Amravati	20° 55′ N	77° 45′ E	366	1944–2013	70
5	Anjangaon	21° 09′ N	77° 19′ E	339	1944–2013	70
6	Atner	21° 37′ N	77° 56′ E	665	1944–2004#	61
7	Balapur	20° 39′ N	76° 47′ E	277	1944–2013	70
8	Bhainsdehi	21° 38′ N	77° 38′ E	767	1944–2013	70
9	Buldana	20° 31′ N	76° 11′ E	565	1944–2013	70
10	Burhanpur	20° 18′ N	76° 14′ E	252	1945–2013	69
11	Chandurbazar	21° 14′ N	77° 44′ E	373	1944–2013	70
12	Chikhalda	21° 38′ N	77° 19′ E	1084	1976–2013	38
13	Daryapur	20° 55′ N	77° 20′ E	285	1976–2013	38
14	Dharni	20° 33′ N	76° 53′ E	323	1944–2013	70
15	Edalabad	20° 59′ N	76° 04′ E	235	1951–2013	63
16	Khamgaon	20° 41′ N	76° 34′ E	305	1944–2013	70
17	Malkapur	20° 53′ N	76° 14′ E	252	1944–2013	70
18	Multai	21° 46′ N	78° 15′ E	770	1944–2013	70
19	Murtajapur	20° 43′ N	77° 22′ E	307	1944–2013	70
20	Nandura	20° 49′ N	76° 28′ E	271	1944–2013	70
21	Patur	20° 27′ N	76° 56′ E	348	1944–2013	70
22	Raver	21° 14′ N	76° 02′ E	248	1944–2013	70
23	Shegaon	20° 46′ N	76° 42′ E	280	1944–2013	70
24	Telhara	21° 00′ N	76° 51′ E	286	1944–2013	70
Weather stations						
1	Akola	20° 42′ N	77° 00′ E	282	1969–2010	42
2	Amravati	20° 55′ N	77° 45′ E	366	1969–2012	44
3	Betul*	21° 52′ N	77° 56′ E	653	1969–2012	44
4	Buldana	20° 31′ N	76° 11′ E	565	1969–2011	43
5	Khandwa*	21° 50′ N	76° 22′ E	318	1969–1999#	31

Further data was not available

**Elevations are above mean sea level

*The location of station is outside the basin; however, a considerable portion of these districts falls in the basin the northern part of the basin receives higher rainfall compared to the southern part. The Chikhalda station, located at an elevation of 1084 m, receives the highest average annual rainfall of about 1449.2 mm. The stations located on the windward side of the Gwaligarh mountain ranges, viz., Bhainsdehi, Chikhalda, Dharni, and Burhanpur, receive higher average annual rainfall compared to the stations located on the leeward side of Gwaligarh mountain ranges in the plains of Purna River (see Fig. 1). This spatial variability in rainfall across Upper Tapi Basin is attributed to the predominance of orographic effects. Further, from Fig. 4, it is observed that Amravati generally experiences fairly lower average temperature compared to other districts in the basin. The Amravati, being located in the foot hill of Gwaligarh mountain range (ridge line between Purna and Tapi River catchments) in the north, and the Ajanta and Satmala range (ridge line between Purna and Godavari River catchments) in the east and south, and the large elevation difference of the district (1100 to 250 m), experienced lower average temperature vis-à-vis other plain areas in the Purna subbasin.

2.4 Extreme climatic indices

In present study, to analyze and describe the spatiotemporal variations in extreme rainfall and temperature, a total of 17 indicators have been used. Such indices were established by the Expert Team on Climate Change Detection Monitoring Indices (ETCCDMI) and have been used in several studies for understanding the behavior of climate extremes and their trends (Easterling et al. 2003). A total of 12 rainfall and 5 temperature indices have been used to study the trends in extreme climatic conditions in the basin. The description and definitions of these indices are included in Table 2. From the list of indicators prescribed by ETCCDMI, certain threshold values of indicators were modified in accordance with the Indian Monsoon characteristics. As per IMD, a rainy day is defined as when the rainfall amount recorded in a day equals or exceeds 2.5 mm (Sonar 2014). In present study, the indices R10mm and R20mm prescribed by ETCCDMI have not been considered as heavy and very heavy rainfall days, respectively, as these indices do not represent the nature of ISMR. As per IMD classification, moderate and heavy rainfall days are

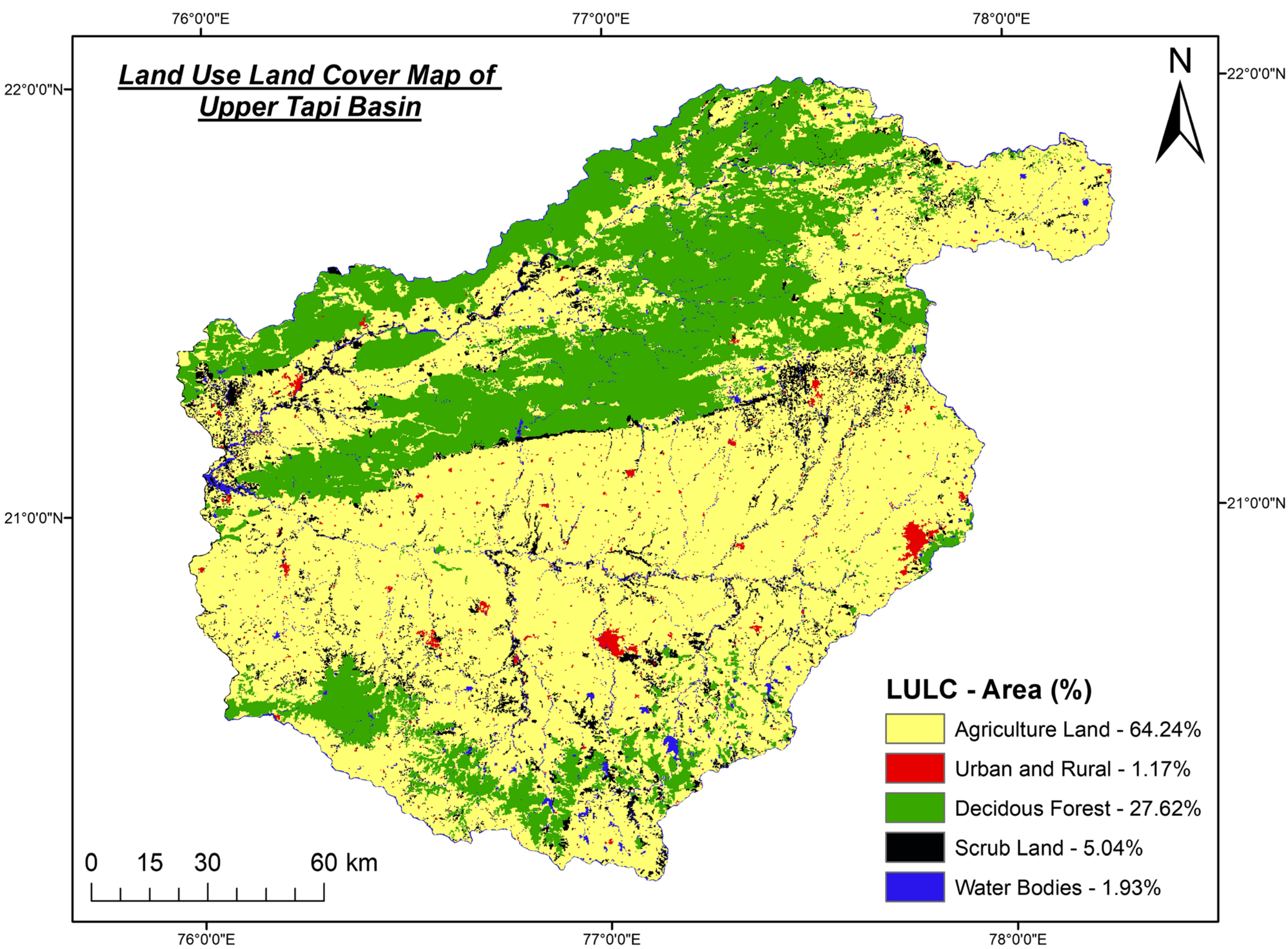

Fig. 2 Land use land cover map of Upper Tapi Basin for the year 2010

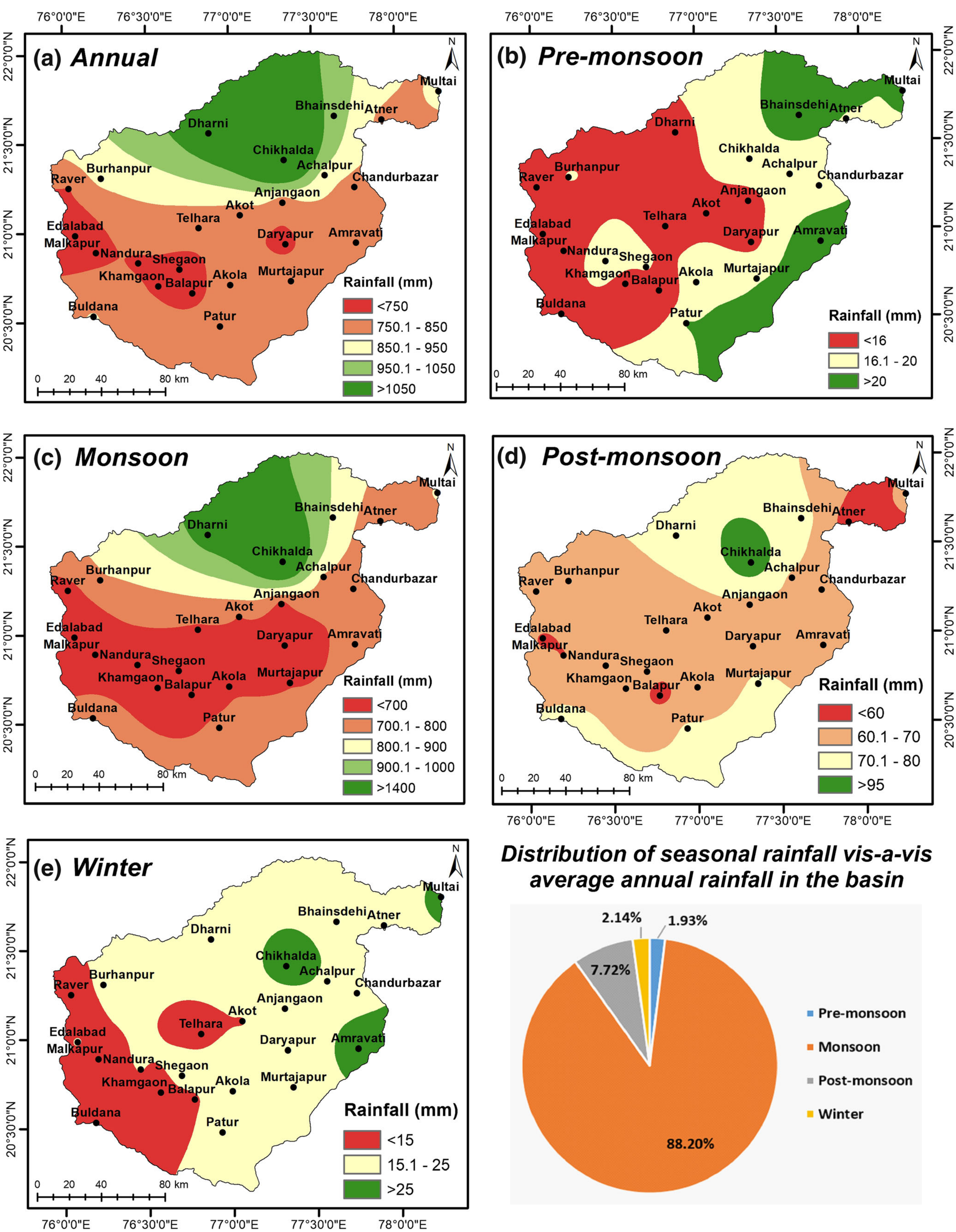

Fig. 3 **a**–**e** Distribution of average rainfall over Upper Tapi Basin (1944–2013)

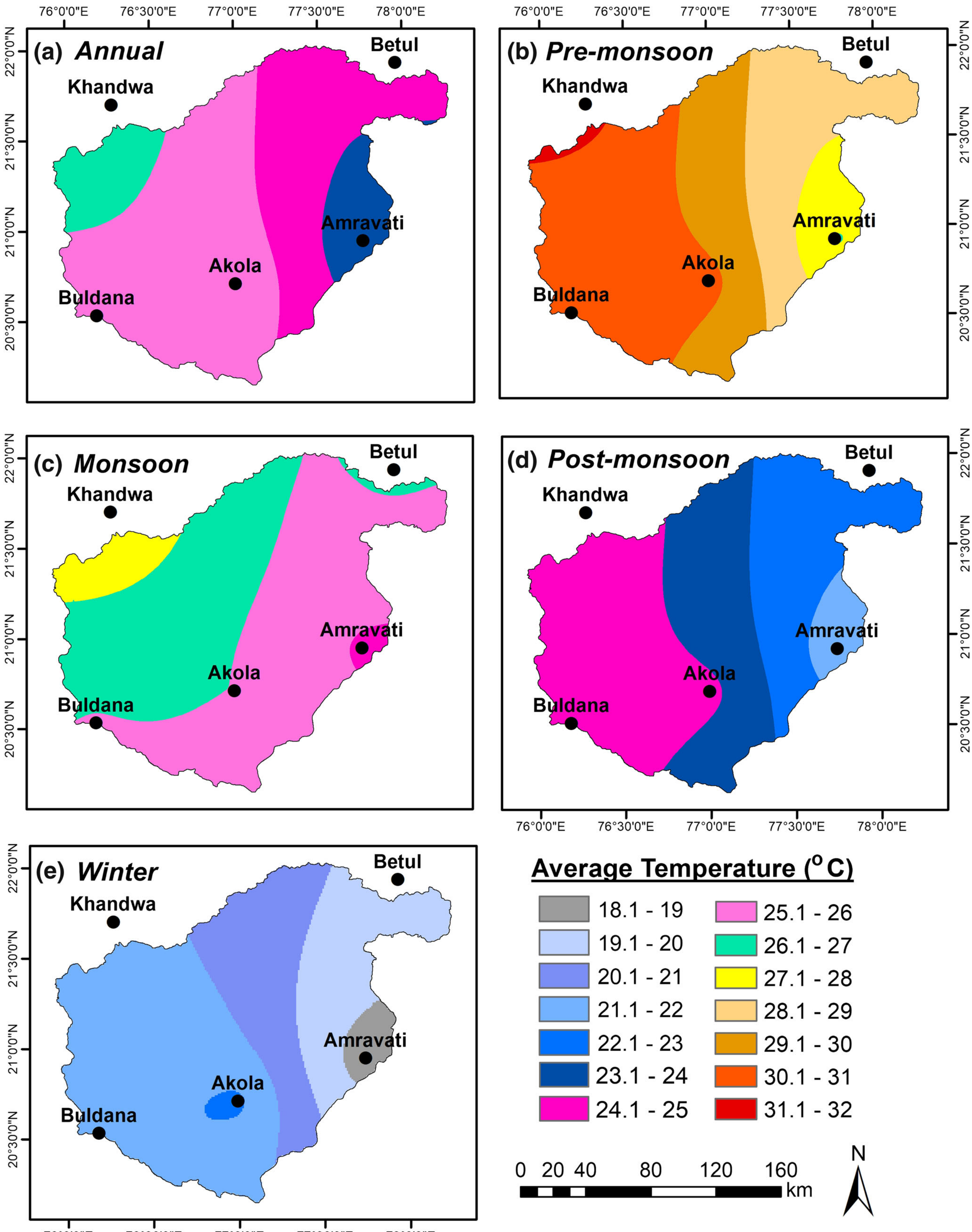

Fig. 4 **a**–**e** Distribution of average temperature over Upper Tapi Basin (1969–2012)

Table 2 Description of extreme climatic indices used in this study

Indicator	Indicator name	Indicator definitions	Units
PRCPTOT	Annual total rainfall	Annual total rainfall from days ≥ 2.5 mm	mm
RD	Rainy days	Number of days when rainfall ≥ 2.5 mm	days
SDII	Simple daily intensity index	The ratio of annual total rainfall to the number of rainy days	mm/day
Rx1day	Maximum 1-day rainfall amount	Annual maximum 1-day rainfall	mm
Rx5day	Maximum 5-day rainfall amount	Annual maximum consecutive 5-day rainfall	mm
R99p	Extremely wet days	Annual total rainfall from days > 99th percentile	mm
R95p	Very wet days	Annual total rainfall from days > 95th percentile	mm
R5TOT	Rainfall extreme proportion	Proportion of annual rainfall from top 5 events in a year	%
Rmod	Number of moderate rainfall days	Number of days when annual rainfall ≥ 7.5 and < 64.5 mm	days
Rheavy	Number of heavy rainfall days	Number of days when annual rainfall ≥ 64.5 and < 124.5 mm	days
CDD	Consecutive dry days	Maximum number of consecutive days when rainfall < 2.5 mm	days
CWD	Consecutive wet days	Maximum number of consecutive days when rainfall ≥ 2.5 mm	days
TXx	Hottest day	Monthly/seasonal/annual maximum value of daily maximum temperature	°C
TXn	Coldest day	Monthly/seasonal/annual minimum value of daily maximum temperature	°C
TNx	Warmest night	Monthly/seasonal/annual maximum value of daily minimum temperature	°C
TNn	Coldest night	Monthly/seasonal/annual minimum value of daily minimum temperature	°C
DTR	Diurnal temperature range	Monthly/seasonal/annual mean difference between daily maximum and minimum temperature	°C

considered as days experiencing rainfall amount between 7.5–64.5 and 64.5–124.5 mm, respectively (Sonar 2014), and used in the present analyses. The extreme rainfall indices considered for the analysis were calculated for each year for each rain gauge station, whereas the variability in temperature indices was investigated at annual, seasonal, and monthly time scales for each weather station.

2.5 Methodology

The stepwise procedure adopted to ascertain the long-term temporal and spatial variability in extreme climatic indices is included in Fig. 5.

3 Results and discussions

3.1 Trends in total rainfall

The statistical analyses of total annual rainfall indicated that annual rainfall varies largely across the basin. The mean and standard deviation of basin-averaged annual rainfall were observed to be 835.1 and 258.8 mm, respectively. Further, the highest and lowest mean annual rainfall recorded in the basin were at Chikhalda (1449.2 mm) and Daryapur (692.3 mm) stations, respectively. The maximum and minimum basin-averaged annual rainfall observed during the study period

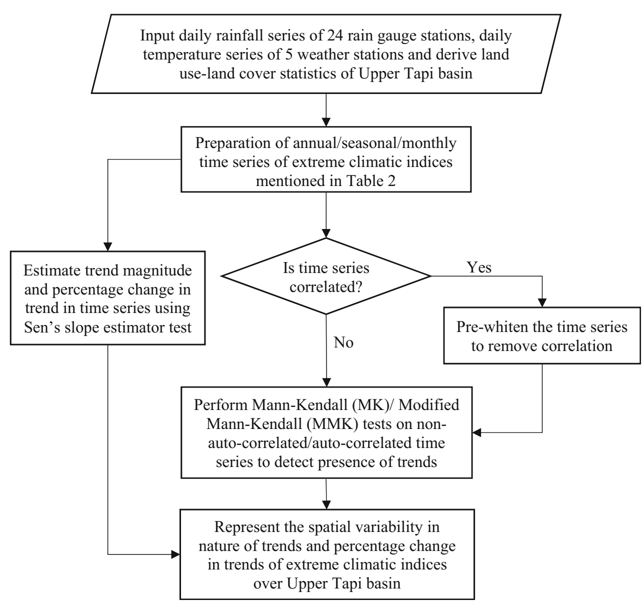

Fig. 5 Methodology for trend assessment of extreme climatic indices adopted in the present study

(1944–2013) were 1230.6 mm in 1988 and 455.8 mm in 1952, respectively. The basin-averaged monthly rainfall recorded during monsoon months, viz., June, July, August, and September, were 134.1, 232.4, 228.4, and 145.2 mm, respectively. The four monsoon months account for 88.4% of total annual rainfall. During the entire year, the basin receives the highest rainfall in July and the lowest rainfall in April month. The nonparametric tests such as MK, MMK, and Sen's slope estimator tests have been applied on total rainfall series of each station at annual, seasonal, and monthly time scales. The time series were checked for presence of serial correlation prior to application of the MK test (Yue et al. 2002). The serially correlated time series were prewhitened to remove the correlation (Burn and Elnur 2002), and then the MK test (Mann 1945; Kendall 1975) was applied. However, the MMK test can be successfully applied even on correlated time series (Hamed and Rao 1998). The results of the tests indicated that the basin largely exhibits a decreasing trend in total annual rainfall (PRCPTOT), wherein 17 out of 24 stations reported decreasing trends in total annual rainfall over the period of 70 years (see Fig. 6a). Significant decreasing trends are reported for Amravati ($Z = -2.57$), Atner ($Z = -3.25$), and Dharni ($Z = -2.23$) stations, while a significant increasing trend is detected for Patur ($Z = 2.18$) station from the MMK test at 5% significance level (Fig. 6a). From the results of Sen's slope estimator test (Hirsch et al. 1982), the median of slope values of PRCPTOT for Atner, Amravati, and Raver stations are indicated as −6.25, −3.32, and −3.17 mm/year, respectively. On other hand, Daryapur exhibited a median slope value of 5.10 mm/year. The percentage change in trends was also evaluated from Sen's slope (β) value (Yue and Hashino 2003) for all the stations, and spatially interpolated maps were prepared for indicating trends in total annual rainfall (Fig. 6a). The percentage change in trend, either positive or negative, within 0–15% is quantified as "nominal," between 15 and 30% as "moderate," between 30 and 45% as "severe," and > 45% as "very severe." The percentage change in total annual rainfall has been found to be largely nominal (negative) across the basin, while severe (negative) percentage change is reported near Multai and Atner stations. Further, the stations in the basin which receive higher rainfall like Multai, Bhainsdehi, Dharni, and Chikhalda show decreasing trends in total annual rainfall, which may have an adverse impact on streamflow in the Tapi River. The reduction in rainfall amount over the time period would significantly affect the agricultural production in the basin. Sharma et al. (2017) reported a decreasing trend in total annual rainfall at 11 out of 17 stations in the Purna River basin during the period 1944–2004, while Kundu et al. (2015) also reported a decreasing total annual rainfall over the period 1901–2011 for Betul and Khandwa (erstwhile East Nemar) districts of Madhya Pradesh State. The decrease in total annual rainfall across the basin, as investigated in the present study, is consistent with the findings of other researchers as well (Kumar and Jain 2011; Jain and Kumar 2012; Duhan and Pandey 2013; Taxak et al. 2014; Mondal et al. 2015; Kundu et al. 2015), related with west central India/Tapi Basin. Singh et al. (2008) reported an increasing trend in monsoon and total annual rainfall for Tapi Basin while considering only one station (Surat in Lower Tapi Basin) in their analyses which is in contradiction with the findings of the present study. Such inconsistency in results reported by Singh et al. (2008) with the present study could be due to the use of rainfall data of a single station of Lower Tapi Basin (Surat City) and drawing the conclusion for the whole Tapi Basin.

The principal rainfall season for the basin is southwest (SW) monsoon which starts during mid-June and ends in late September. The retreating monsoon also causes some rainfall (≈ 7.7% of total annual rainfall) during the October–November months. From the trend analyses of seasonal total rainfall, a decreasing trend in monsoon rainfall (Fig. 6c) is observed at 14 stations across the basin, with Amravati, Atner, and Raver stations experiencing a significant decrease as MMK Z-statistic for these stations are found to be −2.01, −2.57, and −2.27, respectively. On the other hand, the remaining 10 stations report increasing trends in monsoon rainfall. The postmonsoon period (Fig. 6d) shows an increasing trend at 13 stations and a decreasing trend at 10 stations and no trend was observed at one station (Anjangaon). The winter and premonsoon rainfall exhibit a decreasing trend at all the 24 stations, wherein Amravati, Atner, Chikhalda, and Khamgaon show significant decreasing trends in winter and Achalpur, Atner, Bhainsdehi, Buldana, Dharni, Multai, Murtajapur, and Patur show significant decreasing trends in premonsoon period. Such significant decreasing trends, particularly in the winter season, would adversely affect the Rabi crops of the command areas in the Upper Tapi Basin. The percentage change in trend has been found to be very severe (negative) across the entire basin during premonsoon (Fig. 6b) and winter (Fig. 6e) seasons, while nominal and moderate (positive) percentage change is reported for the monsoon and postmonsoon period at most places. The maximum and minimum values of Sen's slope for monsoon rainfall are found to be 4.01 and −4.05 mm/year at Daryapur and Atner stations, respectively. Jain and Kumar (2012) reported a decreasing trend in premonsoon and monsoon rainfall, an increasing trend in postmonsoon rainfall, and no trend in winter rainfall across the Tapi Basin. Kundu et al. (2015, 2016) reported decreasing trends in total rainfall in all seasons across Madhya Pradesh State for the period 1901–2011. Thus, results reported herein at the subbasin scale (finer scale) are different compared to the previous studies (coarse scale) in the context of trends in winter rainfall (Jain and Kumar 2012) and postmonsoon rainfall (Kundu et al. 2015, 2016). The decrease in monsoon rainfall would affect the water requirements for Kharif crops such as cotton, sorghum, pigeon pea, green grams, etc. that are being cultivated in the region.

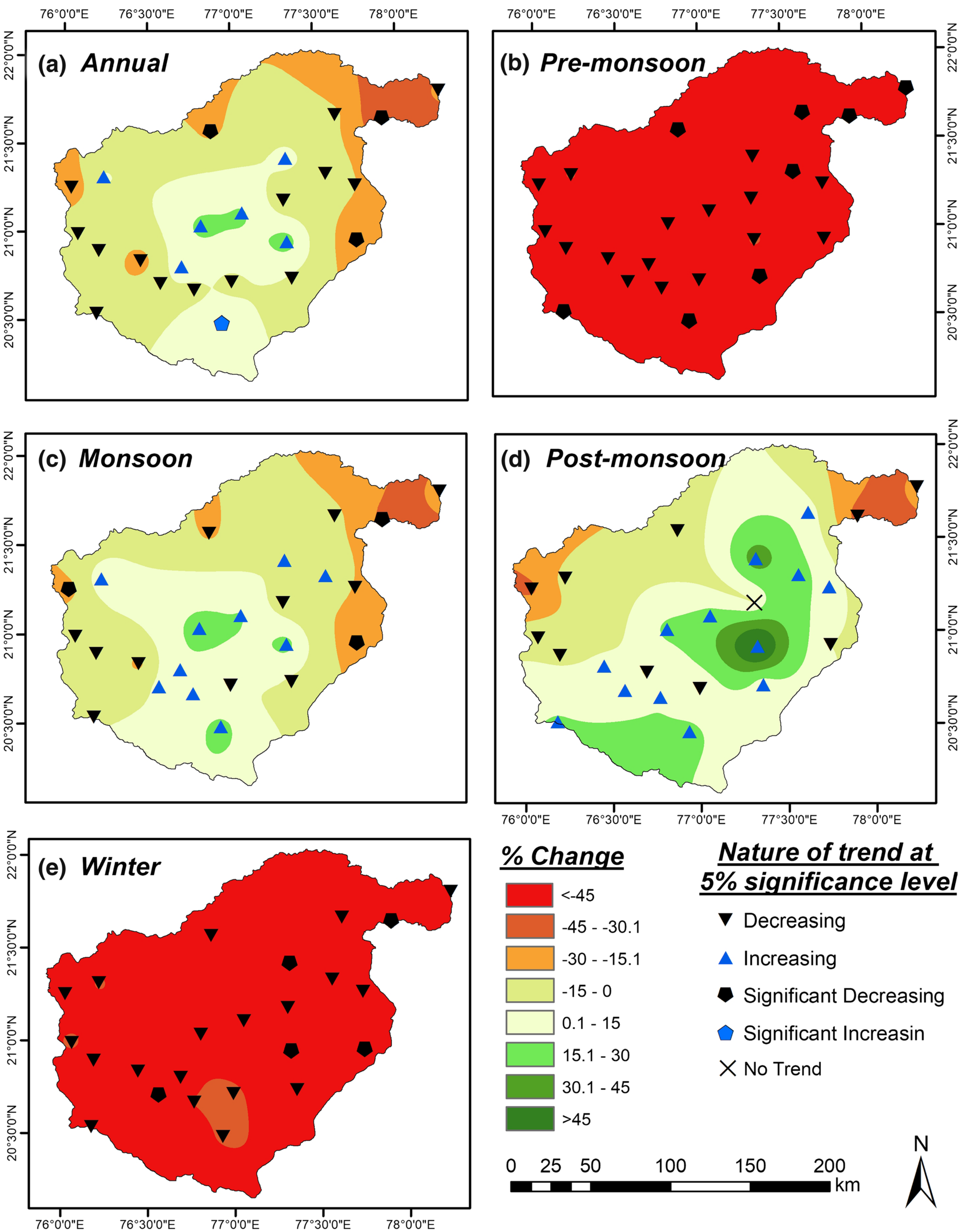

Fig. 6 **a**–**e** Spatial distribution of trends in seasonal and annual total rainfall over Upper Tapi Basin

The trends in total monthly rainfall for all the stations are also examined, and decreasing trends have been reported for most of the months. The results of statistical tests revealed that total rainfall exhibits a largely decreasing trend across the basin (see Supplementary Fig. S1) during January–May, July, September, November, and December months. The monsoon months were observed to display dichotomic trends, wherein total rainfall showed an increasing trend during June and August months and a decreasing trend during July and September months across the basin. For the month of September, more than 75% stations exhibited a decreasing trend in total rainfall across the basin, while an increasing trend is observed in October month. The percentage change in decreasing trend has been found to be very severe at most of the stations for January–May and November–December months. Also, severe (decreasing) percentage change is observed in September month compared to other monsoon months which could be indicative of early withdrawal of SW monsoon from the basin. Previous researchers (Panda and Kumar 2014; Panda et al. 2016) also pointed out such dichotomy within monsoon months, with wetting tendency during June and August months and drying tendency during July and September months, for the entire India.

3.2 Trends in rainy days and rainfall intensity

The trends in rainy days (RD) and simple daily intensity index (SDII) were also worked out for different stations from available daily rainfall data for the Upper Tapi Basin. From the preliminary statistical analyses, the occurrence of RD has been found to vary from 37 days (Edalabad) to 67 days (Chikhalda), while SDII was found to vary between 16.9 mm/day (Daryapur) and 22.7 mm/day (Dharni), during the study period. From Fig. 7b, a decreasing trend in RD is observed across 20 stations, with 11 stations (Achalpur, Amravati, Atner, Bhainsdehi, Buldana, Dharni, Khamgaon, Multai, Murtajapur, Nandura, and Raver) exhibiting a significant decreasing trend at 5% significance level from the MMK test. However, only Daryapur station reported a significant increase ($Z = 3.34$) in RD and had a median slope of 0.24 days/year. The median slopes of RD for Atner, Nandura, Bhainsdehi, Amravati, Achalpur, and Raver are found to be −0.40, −0.25, −0.23, −0.22, −0.21, and −0.20 days/year, respectively. Further, severe and very severe (negative) percentage change in trend in RD is reported at nine stations, namely, Achalpur, Amravati, Atner, Bhainsdehi, Buldana, Khamgaon, Multai, Murtajapur, Nandura, and Raver (see Fig. 7b). The results of the present study were in agreement with Kumar and Jain (2011), where decreases in rainy days were reported over the entire Tapi Basin. The SDII has been found to increase at 18 stations across the basin, while a decreasing trend was observed at the remaining 6 stations (see Fig. 7c). The major urban centers such as Amravati, Akola, Buldana, and Burhanpur have reported an increasing trend in SDII having MMK Z values as 2.98, 0.23, 1.65, and 0.61, respectively. Further, the stations located at high altitudes such as Bhainsdehi, Chikhalda, and Multai also experience an increasing trend in SDII, wherein the median slopes for these stations are found to be 0.03, 0.04, and 0.02 (mm/day)/year, respectively. This reported increase in storm intensity would escalate the risk of flash floods which can further exacerbate due to incapability of existing urban drainage systems in rapidly urbanizing cities. The overall increase in SDII may also cause damage to the standing crops and might have high socioeconomic impact in the region. Also, high intensity rainfall may potentially lead to soil erosion in the basin, which could aggravate sedimentation issues in Hathnur reservoir.

3.3 Trends in frequency and magnitude of extreme rainfall

The trends in extreme rainfall indices (see Table 2) were analyzed using MK, MMK, and Sen's slope estimator tests. These indices were categorized into various classes, viz., absolute indices such as maximum 1-day rainfall (Rx1day) and maximum 5-day rainfall (Rx5day); threshold indices such as moderate rainfall days (Rmod) and heavy rainfall days (Rheavy); percentile-based indices such as very wet days (R95p) and extremely wet days (R99p); and a relative index called rainfall extreme proportion (R5TOT). The aforesaid indices provide a fair comparison between occurrences of extreme rainfall events for different climatic regions. From the data analysis, maximum 1-day rainfall (Rx1day) of 411.2 mm was observed at Dharni in the year 1965, followed by 405.2 mm at Multai in the year 1991. The maximum 5-day rainfall (Rx5day) recorded at Telhara was 616.5 mm in the year 1959. The trend analyses of extreme rainfall indicated heterogeneous trends in Rx1day and Rx5day across the basin, wherein half of the stations exhibit an increasing trend, while the remaining half exhibit a decreasing trend (see Fig. 7d, e). It can be seen that Patur station shows a significant increasing trend in Rx1day ($Z = 2.13$) and Rx5day ($Z = 2.07$), whereas a significant decreasing trend is observed in Rx1day ($Z = -2.43$) at Raver station. From Fig. 7d, e, it can be seen that major stations exhibit nominal to moderate percentage change in trends in Rx1day and Rx5day. Severe percentage change in trend in Rx1day and Rx5day was observed at Raver (−32.0%) and Patur (36.4%) stations, respectively. From the above discussion, heterogeneous trends are observed in extreme rainfall magnitude over the basin, which could be attributed to asymmetric air temperature due to global warming as well as localized changes brought in by possible human interventions in the basin.

The percentile-based indices such as extremely wet days (R99p) and very wet days (R95p), wherein the total rainfall

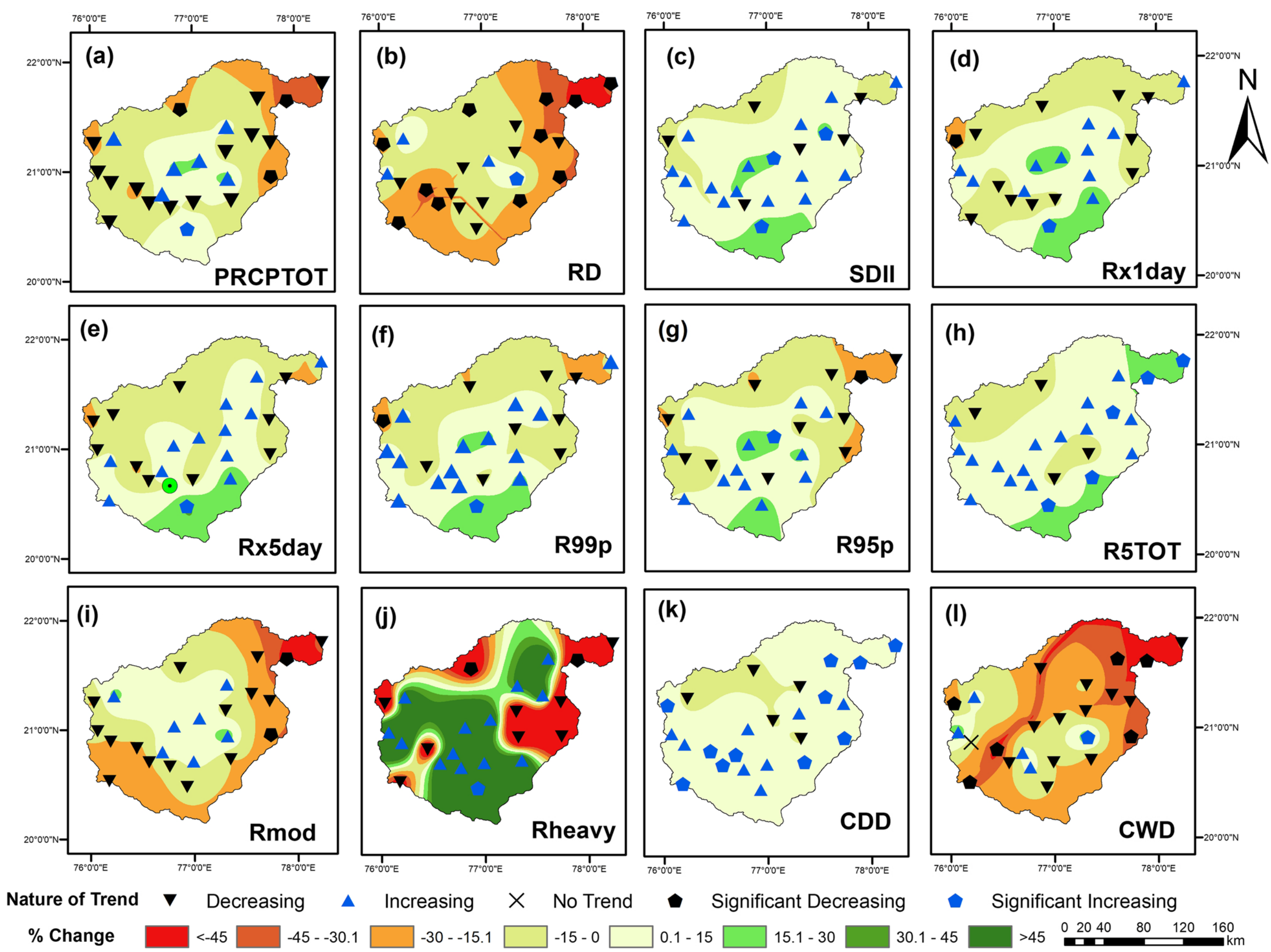

Fig. 7 **a–l** Spatial distribution of trends in extreme rainfall indices over Upper Tapi Basin

amount from the days exceeds a certain percentile value, were computed from the daily rainfall series at a station using Weibull's plotting position formula. The percentile based indices provide a fair comparison between the variability in extreme rainfall magnitudes for different climatic regions. From the results of trend analyses, it has been found that both R99p and R95p show an increasing trend across the basin. The MMK test statistics revealed that R99p and R95p showed an increasing trend at 15 and 13 stations, respectively. From Fig. 7 f, g, nominal to moderate percentage changes in trend in R99p and R95p are observed for all the stations, except Raver and Patur for R99p and Atner for R95p. Further, a significant increasing trend in R95p with median slopes of 3.41, 2.37, and 2.06 mm/year is observed for Daryapur, Patur, and Telhara stations, respectively, while Atner reported a significant decreasing trend with a slope of − 3.04 mm/year. Further, R5TOT, a relative index indicating the contribution of the top 5 rainfall events in the total annual rainfall, has been computed to quantify the severity in occurrence of extreme rainfall, and gauge the nonuniformity in distribution of total rainfall during the year. The results of the trend analyses show that R5TOT is increasing at 20 stations, out of which 5 stations, namely, Achalpur, Atner, Multai, Murtajapur, and Patur, show a significant increasing trend (see Fig. 7h). The median of Sen's slope values of R5TOT for these stations was found to be 0.08, 0.16, 0.11, 0.12, and 0.09% per year, respectively. The percentage change in trend in R5TOT was found to be nominal to moderate (positive) at most places in the basin (see Fig. 7h). Thus, the present study indicates that extreme rainfall events have shown increasing trends across the basin, which are in agreement with previous studies related with trends in extreme precipitation across India/central India (Sen Roy and Balling 2004; Goswami et al. 2006; Deshpande et al. 2016; Bisht et al. 2017).

The threshold-based indices such as moderate (Rmod) and heavy (Rheavy) rainy days are computed to study the possible effects of changes in frequency of the occurrence of extreme rainfall over the basin. The climate of the basin ranges from subhumid to semiarid; hence, the occurrence of exceptionally heavy rainfall events (i.e., days when rainfall amount > 124.5 mm) was observed to occur rarely and hence not included in the analyses. However, trends in percentile-based indices were analyzed to consider the changes in extreme heavy rainfall events across the basin. From the results of trend analyses, it has been found that Rmod exhibits largely decreasing trends across the basin (see Fig. 7i). The Rmod was found to decrease at 17 stations, with 2 stations (Amravati and Atner) showing a significant decrease. From Fig. 7i, the percentage change in trend in Rmod was found to be very severe for Atner station, while for the other stations, nominal to moderate percentage change is reported. The median slope of Rmod at Amravati and Atner was reported to be − 0.25 and − 0.12 days/year, respectively, from Sen's slope test. Further, Rheavy exhibited an increasing trend at 14 stations, while a decreasing trend is observed at the remaining 10 stations (see Fig. 7j). The increase in Rheavy was reported at Achalpur, Akola, Akot, Balapur, Bhainsdehi, Burhanpur, Chikhalda, Edalabad, Khamgaon, Malkapur, Murtajapur, Patur, Shegaon, and Telhara, with Patur experiencing a significant increase. From Fig. 7j, a significant positive increase in Rheavy is reported for the rain gauge stations in a hilly area, while a significant decrease is observed for the stations located in a plain area of the basin. Further, most of the stations are experiencing severe to very severe percentage change in trend in Rheavy, with as much as 14 stations exhibiting positive and the remaining 10 stations exhibiting negative effects. The increase in Rheavy necessitates strengthening of existing storm water networks in the urban area to efficiently dispose rain water and avert flood-like situations in these regions. The decrease in Rmod throws concern to the water managers concerning the water availability in the basin to meet the demands of the inhabitants.

3.4 Trends in dry and wet spells

The duration-based indices such as consecutive dry days (CDD) and consecutive wet days (CWD) in the study area are computed to analyze the frequency of dry and wet spells in a year. The statistical analysis reveals that CDD varies from 307 days (Edalabad) to 275 days (Chikhalda) having basin average of 296 days, while CWD varies from 44 days (Chikhalda) to 18 days (Edalabad) having basin average value of 24 days. Further, the results of trend analyses showed increasing trends in CDD at 19 stations, while decreasing trends in CWD at 18 stations across the basin (see Fig. 7k). The dry spells are found to increase significantly at 11 stations, namely, Achalpur, Amravati, Atner, Bhainsdehi, Buldana, Khamgaon, Multai, Murtajapur, Nandura, Raver, and Shegaon. From Fig. 7k, the percentage change in trend in CDD has been reported to be nominal (positive) for most stations across the basin. From Fig. 7a, k, it can be seen that an increase in CDD exhibits a direct correlation with a decrease in PRCPTOT. The increase in dry spells and reduction in total rainfall may intensify water crisis in the basin. The CWD, on the other hand, reported significant decreasing trends at 6 stations, namely, Amravati, Atner, Bhainsdehi, Buldana, Nandura, and Raver stations (see Fig. 7l). However, very severe (negative) percentage change in the trend in CWD is reported at Atner (− 61.7%) and Nandura (− 55.7%) stations. From Fig. 7j, l, it is revealed that a decrease in CWD is directly correlated with an increase in Rheavy in the study area. From the above discussion, it is clear that persistent increase in CDD and concurrent decrease in CWD have resulted in a decrease of PRCPTOT across the basin, which would have a severe negative impact on the water resources of the basin. Moreover, the decrease in CWD (Fig. 7l) implies reduction in the number of wet spells, and the concurrent increase in SDII (Fig. 7c) shall lead to localized flood-like situations in the basin.

3.5 Trends in extreme temperature indices

The trends in extreme temperature indices, namely, hottest day (TXx), coldest day (TXn), warmest night (TNx), coldest night (TNn), and diurnal temperature range (DTR), derived from observed time series of twice-daily maximum and minimum temperature at five weather stations in the basin are investigated. The spatial variation of annual and seasonal trend in hottest day (TXx) is shown in Fig. 8. The geographical locations of Betul and Khandwa weather stations are outside the basin boundary; however, in the subsequent maps, they are marked within the respective district area falling under the Upper Tapi Basin. From Fig. 8, an increasing trend in TXx is observed at all the stations for annual, premonsoon, and monsoon periods, whereas a decreasing trend in TXx is observed at Khandwa and Akola during postmonsoon and at Khandwa during winter. The percentage change in trend for extreme temperature indices has been classified differently than that for rainfall indices, given the fact that variability in temperature is very less compared to rainfall. Therefore, the percentage change in trend for temperature indices, either positive or negative, within 0–5% is quantified as "nominal," between 5 and 10% as "moderate," between 10 and 15% as "severe," and > 15% as "very severe." The percentage change in trend for all the seasons was mostly found to be nominal (positive), except during postmonsoon for Khandwa and Akola stations. Further, it can be seen that a significant increasing trend in annual TXx can be observed for Betul ($Z = 3.04$) and Buldana ($Z = 2.72$) stations. The median slope of annual TXx was reported to be 0.042 and 0.046 °C/year for Betul and Buldana stations. The nature and percentage change in trend of monthly TXx for different stations are also represented (see Supplementary Fig. S2). It can be seen that TXx is exhibiting an increasing trend in all months for Betul and Buldana stations, whereas a decreasing trend during March, August, and September months for the rest of the stations. From the results of the trend analyses, significant increasing trends in TXx were reported for Buldana and Betul at 5%

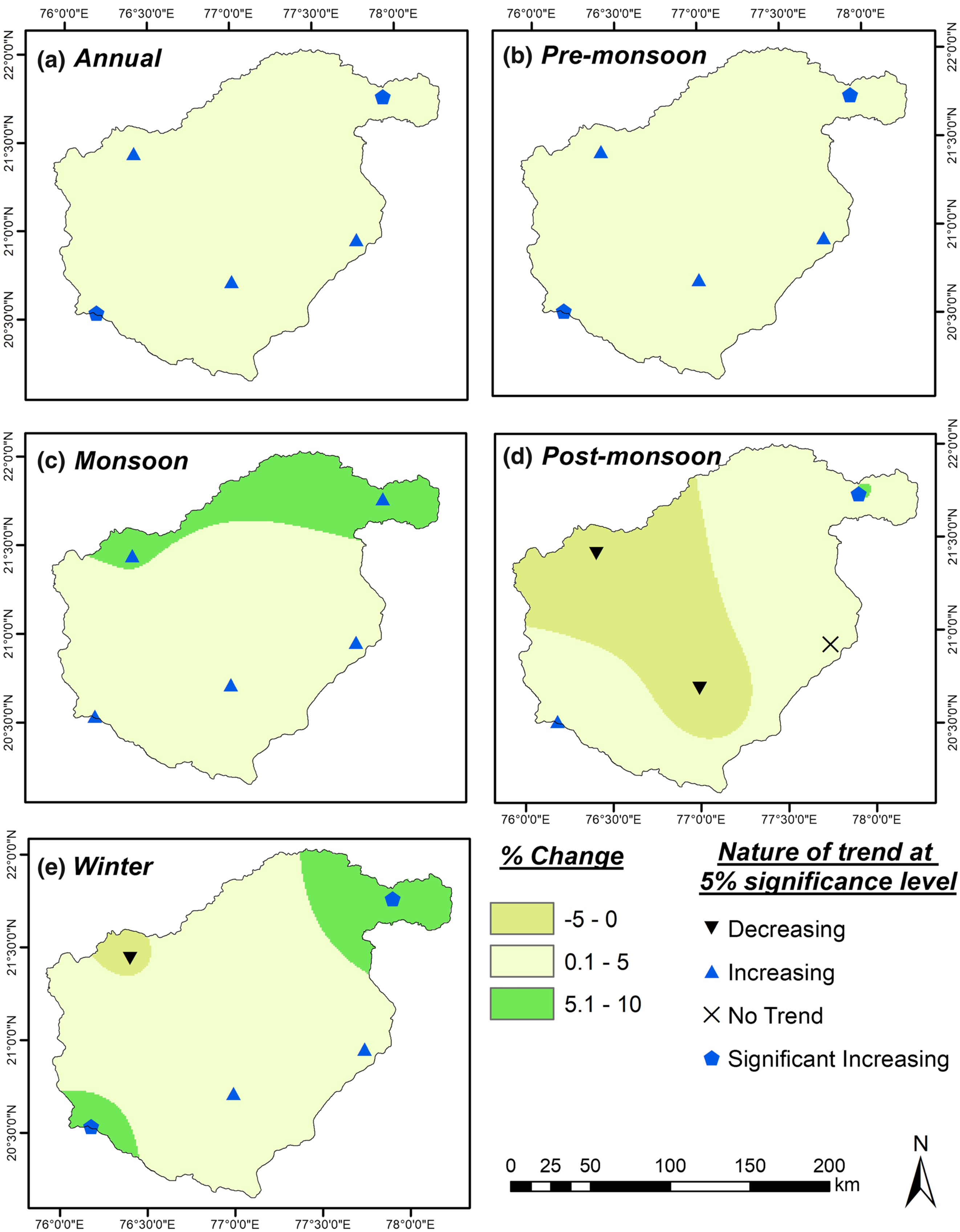

Fig. 8 **a**–**e** Spatial distribution of trends in seasonal and annual hottest day (TXx) over Upper Tapi Basin

significance level during January to May, August (only Betul), November, and December months. The maximum basin average value of median slope of TXx is found to be 0.048 °C/year in December, followed by 0.041 °C/year in January, wherein all the stations reported a increasing trend in TXx. From Fig. S2, it can be seen that the basin largely experiences nominal to moderate (positive and negative) percentage change in trend of TXx for all the months except December wherein a severe increasing trend in hottest day (TXx) temperature is reported.

The spatial distribution of annual coldest day (TXn) indicates a decreasing trend at all the stations except Betul, wherein a significant decrease is reported for Amravati ($Z = -2.19$) and Khandwa ($Z = -6.01$) stations (see Fig. 9). Further, a significant increasing trend in TXn for premonsoon ($Z = 2.14$) and monsoon ($Z = 2.90$) seasons is observed in Betul. The trend in monthly TXn highlights the presence of a nonmonotonic nature of trend for most of the months, except July and August, wherein largely decreasing and increasing trends are observed in July and August months, respectively (see Supplementary Fig. S3). The maximum and minimum basin average values of median of slopes of TXn are found to be 0.047 and −0.034 °C/year for November and January months, respectively. The severe and very severe (negative) percentage change in trend is reported during January and July months, whereas for the other months, nominal and moderate percentage change in trend in TXn is observed. The Upper Tapi Basin, located away from the oceans in the central heartland of India, experiences significant heating during the summer months (i.e., premonsoon season). Further, the overall increase in hottest and coldest day temperature implies an increase in the temperature across the basins which may be responsible for the increase in water vapor and its circulation pattern in the atmosphere and, subsequently, occurrence of extreme events in the basin (Goswami et al. 2006; Liu et al. 2015; Kendon et al. 2014; Min et al. 2011. From Figs. 8c, d and 9c, d, it is seen that hottest and coldest day temperatures are increasing during the monsoon and postmonsoon months. In other words, the region is showing warming trends during the monsoon and postmonsoon periods. The availability of large surface water and vegetation, and the subsequent increase in temperature during the aforesaid season, would cause major loss of water in evapotranspiration. This may lead to shortage of water availability in the study region. Jhajharia et al. (2014) reported an increasing trend in monthly $T_{\max}$ for Akola, Betul, and Buldana and a decreasing trend for Amravati. The findings of the present study are in agreement with the results of Duhan et al. (2013), Jhajharia et al. (2014), and Kundu et al. (2016) derived for Madhya Pradesh State and Godavari Basin, wherein an increasing trend of annual and seasonal $T_{\max}$ for Betul, Buldana, and Khandwa and a decreasing trend for Amravati were reported.

The minimum temperature series was analyzed to work out the warmest (TNx) and coldest nights (TNn) on different temporal scales. From Fig. 10, it can be seen that annual TNx exhibits an increasing trend at three stations (Akola, Betul, and Buldana) and a decreasing trend at two stations (Amravati and Khandwa). From Fig. 10, it can be seen that TNx shows an increasing trend during the premonsoon and monsoon seasons at all stations except Amravati, whereas a significant decreasing trend in annual TNx is seen for Amravati. The monsoon TNx exhibited a significant increasing trend for Buldana ($Z = 2.51$) and Khandwa ($Z = 2.63$) and a significant decreasing trend for Amravati ($Z = -3.72$). From Supplementary Fig. S4, it is seen that TNx has shown overall increasing trends for May to October months and a decreasing trend for November to April months (except for January where mixed trends are observed). The maximum and minimum basin average values of median slope of TNx are found to be 0.023 and −0.041 °C/year in September and March months, respectively. The percentage change in trends of TNx is found to be nominal to moderate (positive and negative) for most of the months except February, March, and November. Further, Amravati experiences a decreasing trend in TNx for all the months, with as many as 8 months exhibiting a significant decrease, whereas Khandwa experiences an increasing trend in TNx for all the months except April and December.

The spatial distribution of nature and percentage change in trend in coldest night temperature (TNn) is shown in Fig. 11 for annual and seasonal scales. The basin largely experiences a decreasing trend in TNn during premonsoon, postmonsoon, and winter seasons and annually also and an increasing trend during the monsoon period (see Fig. 11). The percentage change in trend in TNn is found to be severe and very severe (negative) in the southern part of the basin except during the monsoon season. It is found that Amravati and Betul (except monsoon) experience a decreasing trend in TNn at annual and seasonal scales. From Supplementary Fig. S5, TNn exhibits a decreasing trend for all months for Amravati and an increasing trend for Khandwa (except April and May). On the other hand, Akola and Buldana stations exhibit a decreasing trend during January–April and October–December and an increasing trend from May to October. The maximum and minimum basin average values of median slope of TNn are found to be 0.020 and −0.036 °C/year for September and April months, respectively. From Figs. 10 and 11, it is apparent that temperature of the warmest night is also increasing, while the cold night is decreasing (except monsoon) in the study region. Thus, overall, the minimum temperature is found to decrease at a slower rate in most parts of the basin. The results of the present study confirm the findings of Jhajharia et al. (2014) derived for Godavari Basin, wherein they reported a decreasing trend in $T_{\min}$ for Amravati for all the months and an increasing trend for Betul (except March and December). Duhan

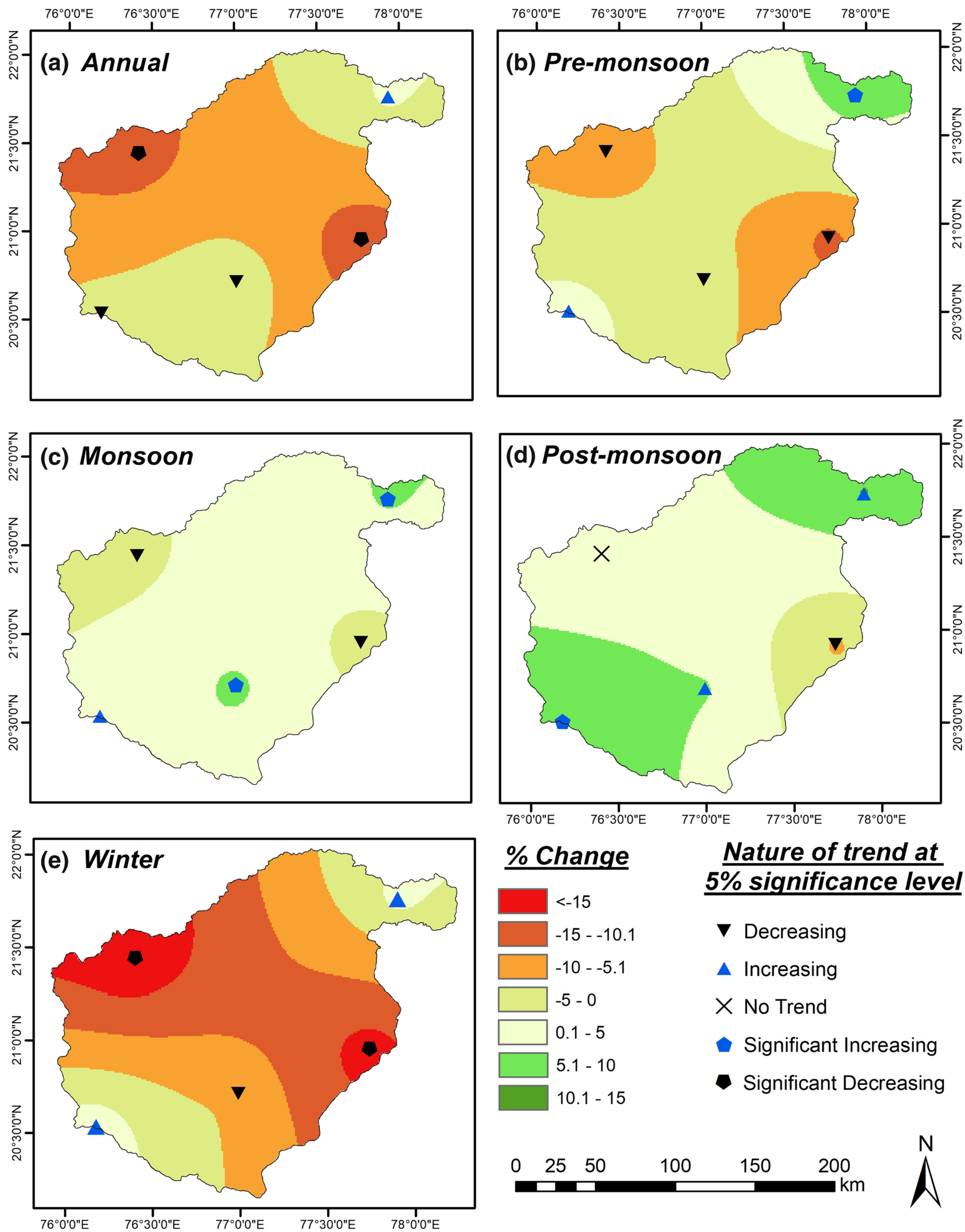

Fig. 9 **a–e** Spatial distribution of trends in seasonal and annual coldest day (TXn) over Upper Tapi Basin

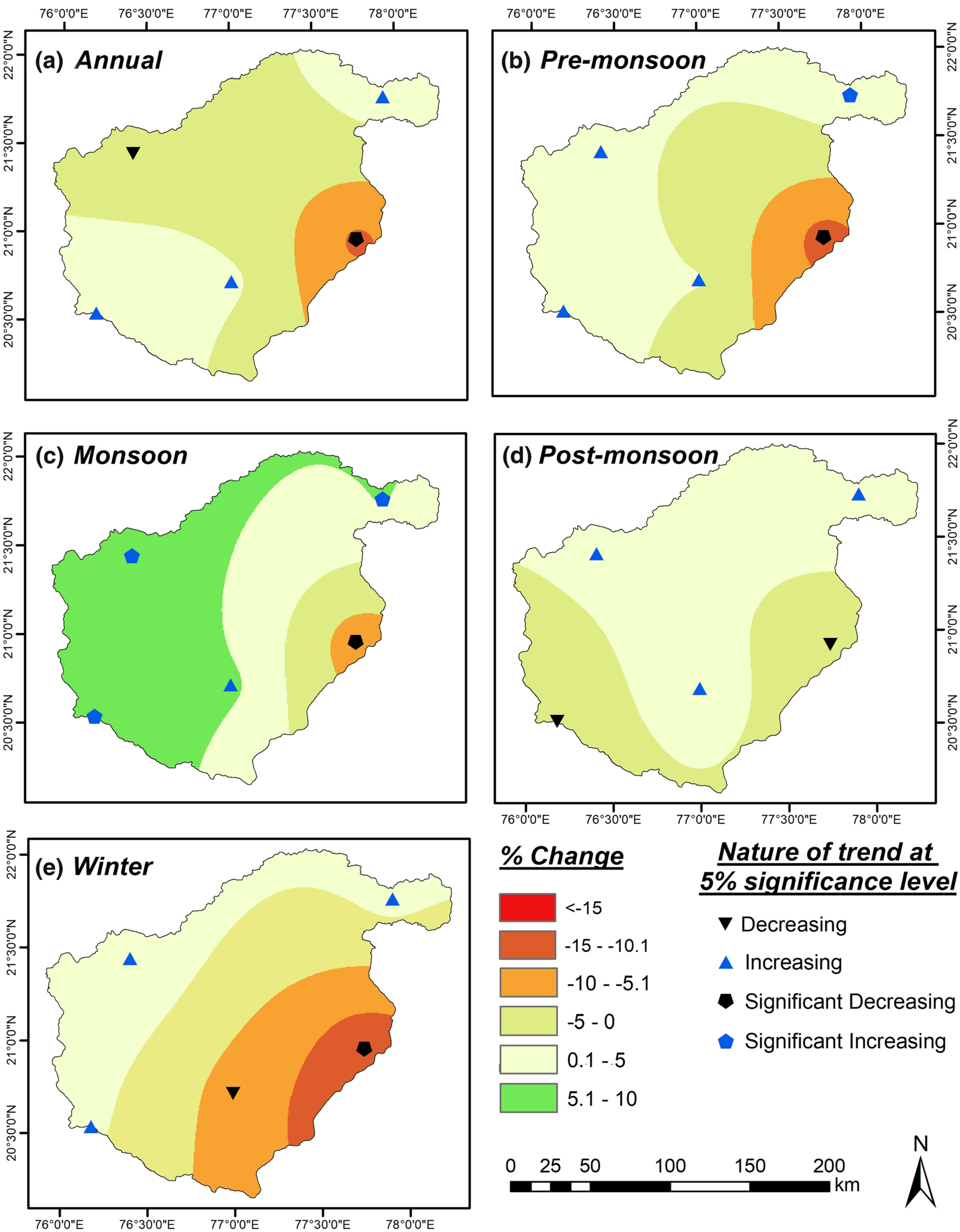

Fig. 10 **a–e** Spatial distribution of trends in seasonal and annual warmest night (TNx) over Upper Tapi Basin

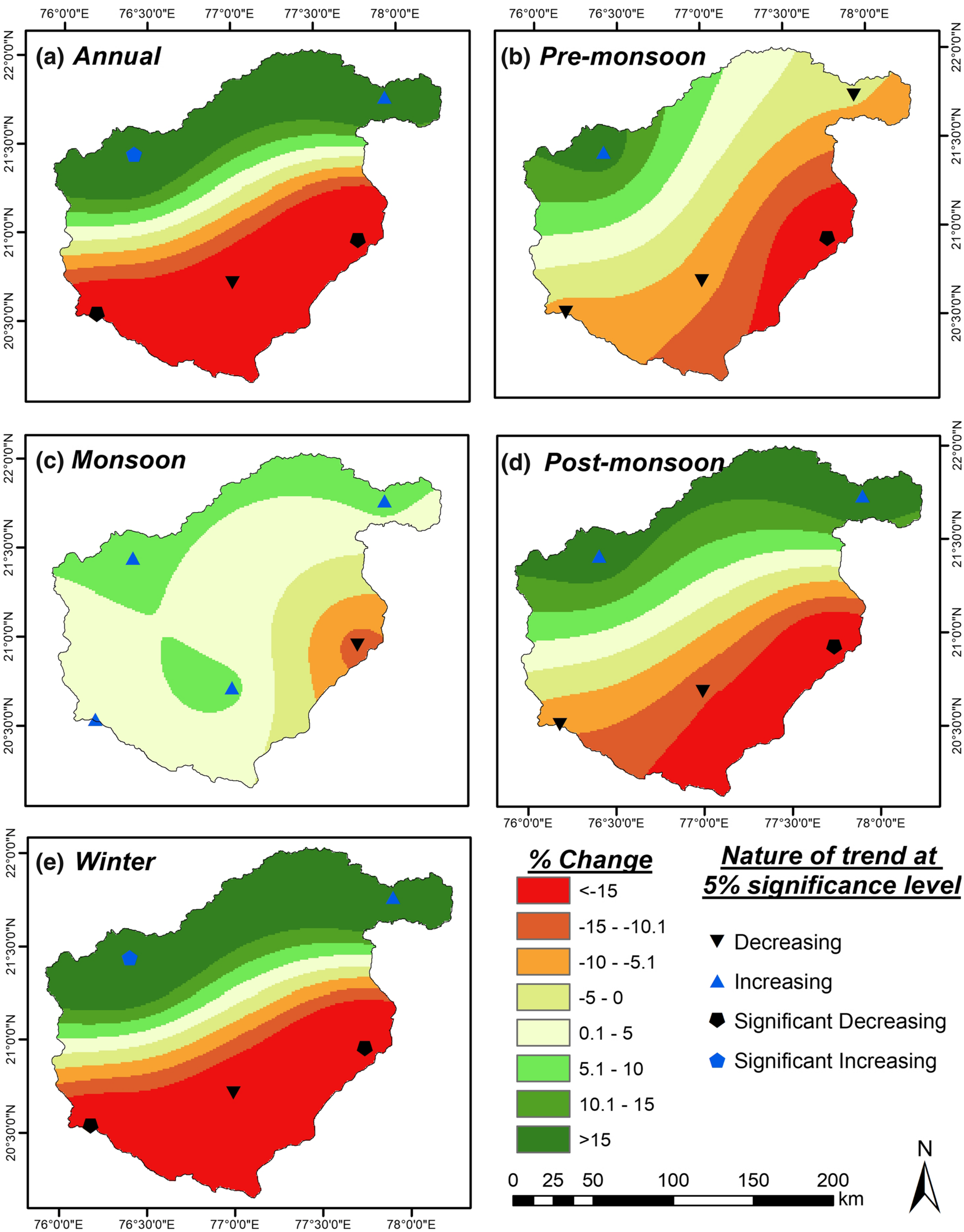

Fig. 11 **a**–**e** Spatial distribution of trends in seasonal and annual coldest night (TNn) over Upper Tapi Basin

et al. (2013) and Kundu et al. (2016) reported an increasing trend in T_{min} for Betul and Khandwa during annual, winter, summer, and monsoon seasons (period 1961–2001), which is in line with the results of the present study, except that for the premonsoon period at Betul which exhibits a decreasing trend. Subash and Sikka (2014) analyzed temperature trends across different homogeneous temperature regions of India and reported an increasing trend in minimum temperature for the Interior Peninsula region on annual, seasonal, and monthly bases, which do not confirm with the results of the present study as the temperature fluctuations on finer scales have not been captured by the former.

The DTR has been worked out from the daily data as the difference between maximum and minimum temperatures. The spatial distribution of percentage change in trend in DTR for annual/seasonal and monthly scales is shown in Fig. 12 and Supplementary Fig. S6, respectively. The annual trend in DTR is significantly decreased for Khandwa ($Z = -3.43$), while an increasing trend is observed for Akola, Amravati, and Betul with a significant increase for Buldana ($Z = 2.89$). The basin largely experiences a decreasing trend only in monsoon and an increasing trend for the rest of the seasons. From Fig. S6, it is evident that DTR is decreasing for Khandwa for all the months, whereas for Amravati, DTR is found to increase for all the months except September. For Betul, DTR is increasing for all the months except July–September, whereas Amravati experiences an increasing trend during January–April and October–December, no trend in May and August, and a decreasing trend during the rest of the months. From Fig. S6, it is highlighted that Khandwa experiences severe to very severe percentage change in trend in DTR for most of the months (except April–June and December). Similar results are obtained for annual and seasonal DTR trends except for monsoon. The increase in T_{max} and a decrease in T_{min} would widen the diurnal temperature range and result in rainfall fluctuations in the basin (Kang et al. 2009). The increase in DTR could be due to increase in cloud cover, atmospheric aerosols, and other local factors such as urbanization, deforestation, and irrigation (Karl et al. 1993; Dai et al. 1997). No specific studies have reported trend and variability in DTR for central India region/Tapi Basin; however, Rai et al. (2012) reported variations in DTR over India for two nonglobal (1901–1909 and 1946–1975) and global (1910–1945 and 1976–2003) warming periods as defined by IPCC. They reported an increase in annual and seasonal DTR, with the largest increase in winter and the smallest in postmonsoon, which adheres with the findings of the present study for Upper Tapi Basin. From the foregoing discussion, it is apparent that, invariably, DTR increases for all the seasons in the study region except during monsoon months. The increase in DTR would have an adverse impact on human health, particularly aggravating cardiovascular and respiratory diseases in the study region (Cheng et al. 2014).

3.6 Anthropogenic influences on climatic variables

The decade wise land use-land cover statistics (1980–2010), for the present study, were extracted from Pal (2016) and used in further analyses to explore their linkages with trends in extreme rainfall and temperature indices. The land use-land cover was classified into five major classes, and their decadal variability, in terms of percentage of total area, is shown in Fig. 13. The land use changes affect atmospheric processes, like precipitation, convection, temperature, and cloud properties (Kharol et al. 2013). From Fig. 13, it is seen that forest cover and scrubland have considerably transformed into agricultural and urban lands across the basin. The conversion of deciduous forests to grasslands and pastures is primarily driven by the grazing operations and associated agricultural activities in the basin. Such conversion has varied hydrological impacts, including reduction in cloud condensation, reduced moisture availability and moisture interception due to reduction in leaf area index, increase in soil evaporation and runoff, and decrease in transpiration over the basin (Pielke et al. 2007). The aforesaid hydrological impacts result in higher fluxes of soil moisture and surface runoff over the landscape, causing soil erosion and poor soil productivity in the basin. The conversion of forest cover into agricultural land and urban areas (see Fig. 13a–c) has been associated with increase in temperature throughout the year which exerts variable influences on regional moisture fluxes due to changing cropping pattern, irrigation requirements, and transpiration rates in the basin. Niyogi et al. (2010) reported that reduction in monsoon rainfall in India is due to intensification of agricultural land as a result of improved irrigation and developed canal systems. From Fig. 13b, it can be seen that urban area is also expanding in the basin. The urbanization has been found to have a direct influence on T_{min} due to storing of significant amount of waste heat in the building walls and streets which is released during the night time and thereby leading to warmer night conditions (Gadgil and Dhorde 2005).

The human activities contribute to climate change by causing changes in the Earth's atmosphere in terms of greenhouse gases, aerosols, and cloudiness (IPCC 2007). The increase in population in the basin has intensified the human influences in the environment such as rapid pace of urbanization, deforestation on a large scale for resource exploration, and increase in consumption of vehicular fuel, thereby an increase in aerosol content. The population statistics of the districts falling in the study area are shown in Table 3. The population of the last three census, viz., 1991, 2001, and 2011, was analyzed, and it was found that all the districts reported a significant increase in the population. Total increase in the basin population has been worked out to be around 20%. The population growth is principally detected in urban areas due to migration of rural population. Around urban areas, natural landscapes have been modified to paved surfaces, which are more capable of storing

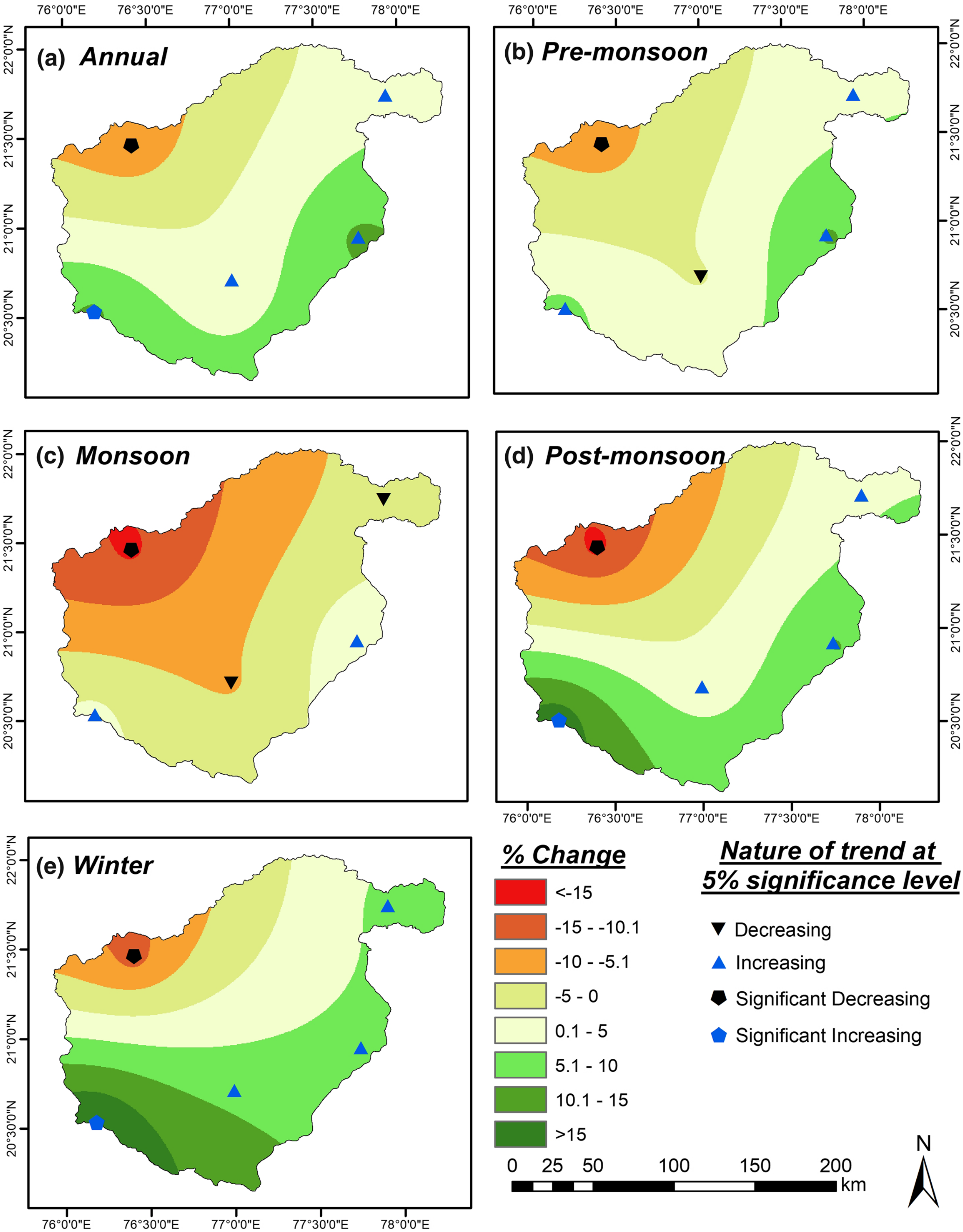

Fig. 12 **a**–**e** Spatial distribution of trends in seasonal and annual diurnal temperature range (DTR) over Upper Tapi Basin

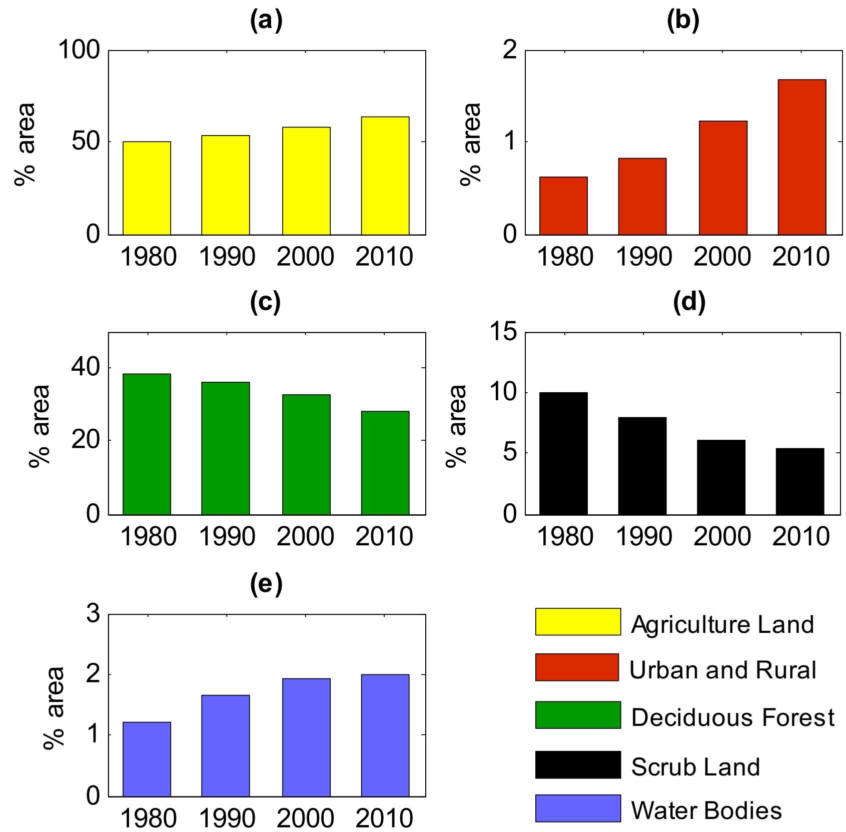

Fig. 13 **a**–**e** Decadal changes in land use-land cover in Upper Tapi Basin

solar energy and converting it to sensible heat, resulting in increase to temperature compared to surrounding environments. Kaufmann et al. (2007) observed a strong impact of urbanization on reduction in rainfall causing dry winters over the Pearl River Basin, China. Ramanathan et al. (2001) observed that aerosols mitigate significantly surface heating and evaporation, slow the hydrological cycle, and ultimately, show impacts on rainfall extremes and minimum-maximum temperature in the catchment. The decline in rainfall trends has been noticed in the past two decades in the basin, wherein the population escalation has been significant. With increasing population trend, the water demand in the basin would also increase in the near future. With decreasing water availability and increasing water demand in the basin, there exists a need to formulate policies for water conservation and take action to ensure sustainable drinking and irrigation water availability in the basin.

4 Conclusions

The long-term spatiotemporal trends and variability in extreme rainfall and temperature indices, recommended by ETCCDMI, have been analyzed at finer spatial scales for the Upper Tapi Basin, India. The trends in the time series at different temporal scales have been investigated using nonparametric Mann-Kendall, Modified Mann-Kendall, and Sen's slope estimator tests. The key findings from the foregoing study are summarized below:

1. The total annual rainfall has been found to decrease at 17 out of 24 rain gauge stations across the basin. Overall, seasonal rainfall has been found to have a decreasing trend for all seasons except postmonsoon. Further, rainfall in monsoon months displayed dichotomic trends, wherein increasing and decreasing trends in total rainfall are observed in June and August and in July and September months, respectively. The assessment of seasonal variations in rainfall would be useful in the precise estimation of additional requirements of water for fulfilling the agricultural and municipal needs in the basin.
2. The number of rainy days has been reported to decrease significantly at almost 50% stations in the basin, whereas the rainfall intensity has been found to increase at almost 75% stations in the basin. The heavy rainy days and extreme rainfall events (R99p and R95p) exhibited increasing trends across the basin. The changes in the frequency and magnitude of extreme events would have adverse effects on human lives, infrastructure, natural resources, and ecosystem in the basin.
3. The CDD exhibited inverse correlation with annual total rainfall (PRCPTOT), wherein the increase in dry spells

Table 3 Population statistics of districts in Upper Tapi Basin for census of 1991, 2001, and 2011

District (state*)	Total district area (km^2)	% of district area in the basin	Population 01/03/1991 census	Population 01/03/2001 census	Population 01/03/2011 census	% increase in population in two decades
Betul (MP)	10,043	39.71	1,181,501	1,395,175	1,575,362	33.34
East Nimar (MP)	7352	9.77	898,596	1,078,251	1,310,061	45.79
Burhanpur (MP)	3427	88.05	533,066	634,883	757,847	42.17
Amravati (MH)	12,210	65.82	2,200,057	2,607,160	2,888,445	31.29
Akola (MH)	5676	100.0	1,352,271	1,629,633	1,813,906	34.14
Buldana (MH)	9661	59.66	1,886,299	2,232,480	2,586,258	37.11
Washim (MH)	4898	21.05	862,000	1,020,822	1,197,160	38.88

Source: The Office of Registrar General and Census Commissioner of India and CWC (2014) (http://www.geohive.com /cntry/india.aspx visited on April 10, 2016)

**MP* Madhya Pradesh, *MH* Maharashtra

would result in decrease in total rainfall, which is likely to intensify the water crisis in the future. On other hand, the decrease in CWD implies a reduction in the number of wet spells, which would critically affect the water availability during the growing season of rain-fed crops and may result into reduced crop yields. Such spatiotemporal information would be useful for the planners and policy makers for implementation of location-specific adaptation and mitigation measures against drought vulnerability in the basin.

4. The temperature indices such as hottest day, coldest day, and warmest night have been found to increase in most of the months, while a decreasing trend is observed in coldest night for most of the months (except monsoon months) across the basin. The overall increase in maximum temperature, particularly, during monsoon and postmonsoon months, would increase evapotranspiration and evaporation losses and, subsequently, result in reduced water availability in the basin.
5. The diurnal temperature range has been found to have an increasing trend at different temporal scales except for monsoon months. The increase in diurnal temperature would have a adverse impact on human health, particularly, aggravating the cardiovascular and respiratory diseases.
6. The agricultural land and urban areas are increasing while the forest cover is decreasing since last 30 years in the basin. Such trends in the land use-land cover are due to fast increase in population and industrialization, which lead to direct rise in local temperature due to development of urban heat islands in the region. The adverse impact of anthropogenic activities on local climate can be minimized by enforcing suitable regulation measures like afforestation, development of wet lands, increasing green cover in urban areas, and promoting green building concept.

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