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Are Detected Trends in Flood Magnitude and Shifts in the Timing of Floods of A Major River Basin in India, Linked To Anthropogenic Stressors?

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ABSTRACT

Analyzing of trends in flood magnitude and the timing of the dates of flood occurrences of large river basins across globe are essential for understanding changes in water availability (high or low flows) and assessing fidelity of global hydrological models. Our research is motivated by the recent six major consecutive floods in Mahanadi (years: 2001, 2003, 2006, 2008, 2011 and 2013) River Basin (MRB), which is one of the largest peninsular Rivers in India with a catchment area of 14,1589 km^2. We examine the altered risk of flooding focusing on changes in the flood regimes and a shift in the timing of floods over the past four decades (1970-2016) using hydrometric observations across the MRB. A framework for identification of flood regime changes is developed using monsoonal maxima peak discharge (MMPD) and peak over threshold (POT) events at 24 stream gauges over the basin. We find a mix of (insignificant) up/downward trends in flood magnitude at Upper MRB (Region I). On the other hand, the middle reaches of the basin (Region II) showed an upward trend in flood magnitude, with a larger number of sites detect significant trends in flood magnitude for the

POT events. Further, we find the downward trends in MMPD series at Region I is field significant (at 10% significance level) whereas none of the trends in POT series show field significance. Only a few stations detected abrupt changes in the flood time series, and they are spatially clustered at Region I, whereas Region II showed no evidence of change points. A delayed (or earlier) shift in flood timing is apparent for most of the sites, notwithstanding the mean date of flood occurrence is in August irrespective of the type of flood series. The outcomes of the study contribute to ensuring flood resilience at densely populated large river basins.

Keywords: *Mahanadi River Basin, floods, trend analysis, change points, circular statistics.*

1. Introduction

Floods are one of the most commonly occurring natural calamities in India, with an estimated average loss of US $54.3 billion between 1953 and 2016 (Chandra, 2018). Although the Intergovernmental Panel on Climate Change - Special Report on Extremes (Murray and Ebi, 2012) suggests there is a low agreement and hence low confidence regarding changes in the magnitude or frequency of floods at the global scale, using ground-based observational record, a recent study (Halgamuge and Nirmalathas, 2017) have indicated that there have been a moderate increase in flood severity and the number of displaced people (~152k) owing to floods in India during recent decades (1985-2016). With increasing temperature, the frequency and magnitude of fluvial floods are expected to amplify in a warming climate (Hirabayashi et al.; Stocker, 2013).

Analyzing changes in floods is vital in many hydrological applications, such as hydropower production and developing flood risk management portfolios of structural and nonstructural measures (Hall and Solomatine, 2008; Mirza, 2003; Rosner et al., 2014). Further, analyzing temporal changes in flood series could lead to improved flood frequency estimates in a nonstationary climate (Kwon et al., 2008; López and Francés, 2013; Villarini et al., 2009b; Vogel et al., 2011). So far, several studies have analyzed temporal changes in flood magnitude and flood seasonality over continental scales. Examples of recent studies include but are not limited to (Petrow and Merz, 2009) throughout Germany (Cunderlik and Ouarda, 2009), Canada (Burn et al., 2016, 2010, and Burn and Whitfield, 2018), Europe (Blöschl et al., 2017; Hall et al., 2014) and Scandinavia (Matti et al., 2017) and at a watershed scale, Poyang Lake Basin, China (Tian et al., 2011), Mahanadi River basin, India (Jena et al., 2014 and Panda et al., 2013), and Athabasca River Basin, Canada (Bawden et al., 2014). Apart from analyzing monotonic trends, a few studies (Nka et al., 2015; Villarini et al., 2009a) have investigated abrupt change points to detect possible nonstationarities in the flood time series. The details of the key literature, including modeling frameworks highlighting the main findings, are summarized in Table 1.

To the best of our knowledge, so far most of the assessments have focused on analyzing flood seasonality and associated flood regime changes over either North America (Burn et al., 2016; Burn and Whitfield, 2018; Regonda et al., 2005) or Europe (Blöschl et al., 2017) focusing over flood flow across nival and mixed flow regimes in mid-latitudes (35-55° N) and high latitudes (> 60° N). However, most detrimental human impacts owing to floods could be potentially from developing countries because of low flood protection strategies and vulnerability of populations (Tessler et al., 2015).

To fill this research gap, this study contributes to a comprehensive understanding of trends and flood seasonality of Mahanadi River Basin (MRB), one of the largest peninsular Rivers in India covering tropical pluvial discharge regime (domain: 23.5°N – 23.5°S). Mahanadi is one of the major peninsular rivers in India with the catchment area of 14,1589 km^2 (occupying ~ 4.3% of total landmass in the country) and ranked second in the nation concerning water potential and flood-producing capacity (National Institute of Hydrology, 2018). According to the 2011 Census, 23.09 Million people (76% urban and 23% rural) resides (NIH, 2018) at MRB. Between 1985 and 2016 (within a span of 32 years), the MRB has experienced 25-major flood events causing immense losses to life and property; out of which 22 events were due to prolonged monsoon rainfall, extreme precipitation followed by dam releases and only 3 of them were owing to tropical cyclones in the delta region (Brakenridge, 2018). The historical records indicated the MRB had been subjected to severe floods in recent past, i.e., 2001, 2003, 2006, 2008, 2011 and 2013 (Beura, 2015; Jena et al., 2014). The frequency of occurrence of high floods in the MRB is increasing with an increase in extreme rainfalls and loss of forest cover in the middle and lower reaches of the basin (Dadhwal et al., 2010; Jena et al., 2014; Panda et al., 2013). On the other hand, the upper reaches (above the delta region) experience minimum flooding because of control structures, levees, and relatively steep slopes. A detection and attribution study (Mondal and Mujumdar, 2012) over basin-wide monsoon precipitation and streamflow at Hirakud reservoir have shown a marked contribution of human-induced climate change to flow regimes rather than the observed precipitation pattern across the MRB. Thus, understanding the basin-wide flood regime shift at densely populated MRB holds great interest.

Given above challenges in flood flow characterizations and adaptations across MRB, this study aims to examine following primary hypothesis: *Basin-wide floods and their attributes across MRB have not shown any significant changes in severity, frequency, the timing of occurrences and spatial coverage.*

To investigate further whether floods over MRB are becoming more frequent, we have formulated the following set of research questions:

(i) What are the patterns of trends and abrupt changes in extreme flood magnitude across MRB for the period 1970-2016?

(ii) What is the sensitivity of trends and flood seasonality to different flood samplings used to define flood series?

(iii) Are the detected trends in flood magnitude sensitive to catchment morphology (i.e., watershed size and elevation)?

(iv) Is there any shift in timing of flood occurrences in a changing climate?

The paper is organized as follows: the study region, datasets used and the modeling framework including the detailed workflow are described in Section 2. Section 3 discusses the results. Finally, the discussion and the salient conclusions of the study are presented in

Section 4. The analyses are performed on entire MRB consisting of 24 stream gauge records. The outcomes of the research are expected to provide a detailed understanding of the nature of floods in the MRB in a present-day climate. Furthermore, the modeling framework can be easily transferred to understand flood behavior in similar climatic regions and future climate projections.

2. Data and methods

2.1 Study Area and Data

We selected entire MRB (80°30' to 86°50'E longitudes and 19°20' to 23°35'N latitudes) covering the states of Chhattisgarh (52.42%) and Odisha (47.14%) and small portions in Maharashtra (0.23%), Madhya Pradesh (0.11%) and Jharkhand (0.1%). Mahanadi River originates in Dhamtari district of Chhattisgarh and drains into the Bay of Bengal, spanning a total length of 851 km. The MRB is a rain-fed river with maximum precipitation observed between July and the first half of September in general, and there is no significant contribution from groundwater recharge. December and January are the coldest months in the basin with the minimum temperature between 4°C to 12°C, and May is the hottest month with a maximum temperature between 42°C to 45°C (CWC, 2014). Figure 1(a) shows the spatial variability in elevation and stream gauge stations across the basin. Based on basin morphology, the MRB is divided into three distinct regions namely (CWC, 2014):

a. Upper (Region I): Drainage area between the source and Hirakud dam also called upper region. The area of this section is 84,700 km^2 out of which 75,136 km^2 lie in Chhattisgarh state.

b. Middle (Region II): Drainage area between Hirakud dam and head of Delta also called middle region. The area of this region is 50,745 km^2.

c. Lower (Region III): Drainage area between the head of delta and Bay of Bengal also called Delta region (Orissa State Water Plan, 2004).

Approximately, 65% of the basin is upstream from the Hirakud dam (Dadhwal *et al.*, 2010). The Hirakud dam is a multipurpose project intended for flood control, power generation, and irrigation. It was built across the Mahanadi River, about 15 kilometers upstream from Sambalpur town in the state of Odisha during 1957 with a catchment area of 83,400 km^2 (85% of catchment area lying in Chhattisgarh). The dam has a live Storage Capacity of 4823 MCM and Spillway capacity of 42,450 cumecs. Figure 1(b) shows the district wise population density highlighting major cities (Census data 2011) indicating population varies between 1,232 and 40,63,870. The largest population is in Raipur (the state capital of Chhattisgarh) followed by Durg and Bilaspur in Chhattisgarh state; Cuttack, Khordha, and Sundargarh in Odisha state.

2.2 Data Collection and Screening

The daily streamflow discharge data of 43 gauge stations located in the study area between 1971 and 2016 were obtained from the Central Water Commission, Government of India. All these stations have varying length of records; hence we have selected only those stations that have at least 70% data availability during monsoon months (June to September) with a minimum of 10 complete years of record. The pre-processing followed by the data screening procedure led to the exclusion of 19 stations, and the resulting record contains 24 stations.

Table S1 provides the details of selected discharge gauge stations with a period of data availability. All these gauge stations are located within geographical coordinates of 81°14' to 85°45' E longitudes and 20°05' to 23°12' N latitudes. The MRB was delineated using the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model of 90 m resolution (Jarvis et al., 2008) using Arc GIS10.1 software. The basin has the maximum, and average elevations of 1319 m and 376.2 m above mean sea level (MSL) respectively.

2.3 Modelling Framework

A detailed workflow of the research is shown in Figure 2. The two methods of sampling flood events, namely monsoonal (June-September) maxima peak discharge (MMPD) and Peak over Threshold (POT) events are presented, and the two perspectives of analyses are discussed to characterize floods. Further, the Mann-Kendall trend test and Pettitt change point tests are used to detect monotonic trends and abrupt changes in the time series. Trend analyses were conducted both at '*local* (at-site)' and regional (collection of sites) level. The magnitude of the trend slope was also determined to analyze changes in flood severity. Flood seasonality and the shift in timing of occurrences of floods are explored using circular statistics. In the subsequent section, we have described each of these modeling components:

- *Extraction of Monsoonal Maximum Peak Discharge (MMPD) Events and Peak over Threshold (POT) Events*

The most common indicator of flood trends in rainfed basins in India is the monsoonal maximum discharge events, i.e., the largest daily mean streamflow during monsoon (June to

September) months in each calendar year (1 January –31 December). The independent peak flows during monsoon season (one event per year) were selected from daily mean streamflow records of all the respective gauge stations. Few studies suggest (Burn et al., 2016; Svensson et al., 2005), POT series gives more information about statistical attributes of extremes as compared to the MMPD, revealing a better temporal pattern of flood occurrence. On the other hand, selecting a suitable threshold value for extracting POT data is one of the challenging aspects (Burn et al., 2016). Here, we checked various thresholds, ranging from 98 to 99.9th percentiles at an interval of 0.5, and then finalized a threshold based on 98.5th percentile to select on an average 3- peak discharge events per year. To ensure selected POT events are independent of each other, following the literature (Petrow and Merz, 2009; Svensson et al., 2005), we selected different time spans based on the catchment area of gauge stations, i.e., 5 days for catchment size <45,000 km^2 and 10 days for catchment size between 45,000 km^2 and 100,000 km^2. In our study, about 80% of gauging stations have catchment areas less than 45,000 km^{2,} and the remaining 20% of gauging stations have catchment areas between 45,000 km^2 and 100,000 km^2. If two consecutive POT events occurred within the specified period, the smaller event is dropped, and the higher event is adopted for the analysis.

- *Detection of monotonic trends and change points in peak discharge events*

In this study, the Mann–Kendall (Kendall, 1975; Mann, 1945) and the Pettitt (Pettitt, 1979) tests are used to identify trends and change points in the peak discharge events. For all these tests, the null hypothesis assumes that there is no trend or no change points in the peak discharge events at selected significance levels. The rank-based Mann-Kendall (MK) test is regarded as a robust nonparametric test (Kendall, 1975; Mann, 1945), and widely used for examining trends in many hydroclimatic variables (Burn et al., 2016; Petrow and Merz, 2009), that are not necessarily normally distributed (Kunkel et al., 1999). However, the presence of autocorrelations in a time series set can increase the expected number of false positive outcomes for the Mann–Kendall test statistics (Storch et al., 1999). Therefore, trends in MMPD and POT time series were evaluated using the modified Mann–Kendall trend test with corrections for ties and auto-correlation (Hamed and Ramachandra Rao, 1998; Reddy and Ganguli, 2013) at a 10% significance level. The magnitude of slope (change per unit time) is estimated using the Theil-Sen Slope (Sen, 1968; Theil, 1950).

While the power of trend estimates at a gauge (or '*local*') level is assessed using standard statistical significance tests available in the literature, the nature of trend at a regional level is analyzed using field significance test. The field significance is evaluated using False Discovery Rate (FDR) based approach (Benjamini and Hochberg, 1995; Benjamini and Yekutieli, 2001), which has been compared to other methods and shown to be relatively insensitive to spatial dependence among sites (Khaliq et al., 2009). The power of the field significance test is evaluated at the same significance level as their locally identified trend.

The time series of flood series are tested for abrupt changes in means (i.e., average peak discharge) by applying the Pettitt test for single change-point detection (Villarini et al., 2012). When dealing with long historical data sets, the change-point analysis is preferred as it provides point (or time) of change that has occurred in the time series with a statistical significance level of the changes detected (Perreault et al., 2000; Rodionov, 2005; Villarini et al., 2009a). We calculate the power of the statistical test at three significance levels of α = 5%, 10%, and 15%. At α = 10% significance level, only 3 and 2 out of 24 stations had a change point for MMPD and POT events, respectively. Hence, we relaxed the significance level up to α = 15%, to increase the power of the test. All three statistical tests described here are nonparametric, which are robust to the presence of outlier and the length of the time series.

- *Detection of Seasonality trends in peak discharge events*

The shift in seasonality of the flood series is detected using the directional or circular statistics (Mardia, 1972; Pewsey et al., 2013), which is widely used method to define the timing (date of occurrence) and the persistence of flood events (Burn et al., 2016; Cunderlik, 2004; Dhakal et al., 2015; Tian et al., 2011). Laaha and Blöschl (2006) summarized the seasonality indices and how they can be estimated based on the discharge time series. In this method, the date of occurrence of a peak flow, as a directional statistic of time, is translated into location on the circumference of a circle, with the mathematical convention that the start of the flood season is shown at its most easterly point and time proceeds in a counter-clockwise direction (Fisher 1993; Mardia, 1972). Once individual dates of flood occurrences are expressed as a directional variable, then directional mean and variance can be calculated.

The date of flood occurrence *(Julian Date)*$_i$ can be converted to an angular value *(*θ_i*)*, in radians for an event "*i*" using:

$$\theta_i = (Julian\,Date)_i \frac{2\pi}{len\,yr} \tag{1}$$

Where, *Julian Date* = 1 for 1 January and *Julian Date* = 365 for 31 December (or 366 for leap year); *len yr* is the number of days in a year, i.e., 365 for a normal year and 366 for a leap year.

For a sample of *n* events, the X - and Y -coordinates of the mean date can be determined as (Burn and Whitfield, 2018)

$$\bar{X} = \frac{\sum_{i=1}^{n} q_i \cos\theta_i}{\sum_{i=1}^{n} q_i};\bar{Y} = \frac{\sum_{i=1}^{n} q_i \sin\theta_i}{\sum_{i=1}^{n} q_i} \tag{2}$$

Here, the equation (2) is derived using the weighted average of extreme events by weighing the peak discharge. Here, $\bar{X}$ and $\bar{Y}$ represent the x- and y-coordinates of the mean event date. Based on the time of occurrence of a flood event in a year, the mean event angle is obtained by

$$Mean\ Angle = \begin{cases} \tan^{-1}\left(\dfrac{\overline{Y}}{\overline{X}}\right), & if\ \overline{X} > 0\ and\ \overline{Y} > 0 \\ 180 - \tan^{-1}\left(\dfrac{\overline{Y}}{\overline{X}}\right), & if\ \overline{X} < 0\ and\ \overline{Y} > 0 \\ 180 + \tan^{-1}\left(\dfrac{\overline{Y}}{\overline{X}}\right), & if\ \overline{X} < 0\ and\ \overline{Y} < 0 \\ 360 - \tan^{-1}\left(\dfrac{\overline{Y}}{\overline{X}}\right), & if\ \overline{X} > 0\ and\ \overline{Y} < 0 \end{cases} \tag{3}$$

The mean event date can then be determined as:

$$Mean\ Date = Mean\ Angle \times \left(\frac{len\ yr}{2\pi}\right) \tag{4}$$

Where *Mean Date* is the average date of occurrence of the extreme events. The persistence ($\overline{r}$) of extreme events can be determined from:

$$\overline{r} = \sqrt{\overline{X}^2 + \overline{Y}^2}\ , \qquad 0 \leq \overline{r} \leq 1 \tag{5}$$

The dimensionless '*r*' indicates the variability in the timing of flood events with $\overline{r}$ = 0, indicates no persistence, i.e., flood events are uniformly distributed throughout the year, whereas, $\overline{r}$ = 1 indicates high persistence, i.e., all floods at a station occur on the same day of the year (Laaha and Blöschl, 2006). Mean date of flood occurrence may occur at a period of the year when no events are observed (Burn and Whitfield, 2018). Circular variance provides the variability of peak discharge events about the mean date for individual stations (Dhakal et al., 2015). The long-term evolution of the circular variance σ^2 is computed using the circular variance.

$$\sigma^2 = -2\ln(\bar{r}) \tag{6}$$

The trend in the timing of floods was estimated by the nonparametric adjusted Theil-Sen slope estimator. The trend estimator β_{circular} is the median of the difference of dates over all possible pairs of years (*i* and *j*) within the time series,

$$\beta_{circular} = median\left(\frac{Julian\,Date_j - Julian\,date_i + k}{j - i}\right) \tag{7}$$

With

$$k = \begin{cases} -\bar{m} & if \quad (Julian\,Date_j - Julian\,date_i) > \bar{m}/2 \\ \bar{m} & if \quad (Julian\,Date_j - Julian\,date_i) < -\bar{m}/2 \\ 0, & otherwise \end{cases} \tag{8}$$

Where,

$$\bar{m} = \frac{1}{n}\sum_{i=1}^{n}(len\,yr)_i \tag{9}$$

Where k adjusts to the circular nature of the dates and β has units of days per year.

3. Results

3.1 Presence of Spatially Coherent Monotonic trends and Abrupt Change Points

Presence of monotonic trends in flood time series at individual stream gauges is evaluated using the Mann-Kendall trend test with correction for ties and autocorrelation. Figure 3 shows the spatial trends in Monsoon peak discharge (June to September) and POT discharge events for all the 24 gauge stations in MRB. While none of the monsoonal maxima discharge events showed a local significant increasing trend (at 10% significance level) using MMPD time series (Fig. 3(a)), the POT discharge events showed significant increasing trends at Kurubhata, Hirakud Dam and Kantamal gauging stations (Fig. 3(b)). In both MMPD and POT flood trends, Region **I** exhibited a mixture of increasing and decreasing trends with the latter dominating the former. This might be the consequence of changing rainfall patterns over the basin and a significant decreasing rainfall trends over the basin, especially during August (Panda et al., 2013). Further, since there is no major control structure upstream of the Hirakud reservoir, the stream flow at most of the gauging sites upstream to Hirakud reservoir can be considered unregulated (Panda et al., 2013).

Most of the stations in Region **II** except Tikarapara showed increasing trends (either significant or insignificant). For example, despite the presence of dense deciduous vegetative cover, an increasing trend in flood magnitude at Kantamal sub-basin could be attributed to deforestation at the upstream sub-basins as reported in an earlier study (Mishra et al., 2008). Also, the review of the literature (Jena et al., 2014) suggests, the recent (post-1957, the year of Hirakud dam construction) incidence of high floods in this region is due to an increase in extreme rainfall in the middle reaches of the basin. An insignificant decreasing trend at Tikarapara gauge station is due to the dense vegetative cover, and the medium textured soil type over the watershed area, which amplifies the infiltration processes and hence reducing runoff over the basin (CWC, 2014). An insignificant increasing trend at Naraj gauge station could be attributed to proximity to the coast of the Bay of Bengal and high-tide induced flooding across the delta (distance between Naraj gauging station and the coastline of the Bay of Bengal is only 120 km) region that could extend inwards due to small width of the delta

(Choudhury et al., 2012). As extreme sea level resulting from severe storm surges across the Bay of Bengal (Flierl and Robinson, 1972; Milliman et al., 1989) pushes ocean tides upstream, the tidal signal propagates from river estuaries to inland, which in turn can amplify the risk of flooding in delta region (Ensign and Noe, 2018; Lyddon et al., 2018). The floods in the low-lying delta region can stem from the superposition of storm surges and river floods, which is frequently associated with common meteorological drivers, such as low-pressure synoptic systems and extreme precipitation. The moisture-laden air-mass from coast move inland over the catchment leading to heavy and persistent rainfall, causing inland flooding. Our findings corroborate well with Panda et al. (2013), in which the authors identified significant upward trends in rainfall across the southwestern and coastal parts of the basin. The synoptic disturbances over the Bay of Bengal, leading to flash flood generating extreme rainfalls (Panda et al., 2013) could be the potential causes of increasing flood trends in this region. Then we apply a field significance test to understand regional behavior of trend across MRB, which indicated a downward trend (significant) over Region **I** for MMPD events at 10% significance level. On the other hand, the middle region does not show any field significant upward or downward trend. Further, we could not find the presence of any significant trend for the POT time series across the regions. Table S2 presents the results of field significance test in all regions across MRB.

Next, we detect abrupt changes in the flood time series using the Pettitt test. Change points in a long historical data arises due to multiple consequences such as a shift in gauge location, changes in land use and land cover, reservoir regulations, as well as climatic variations

(Villarini et al., 2009a). Fig. 4 shows the identification of change points (in location or mean of the distribution) of MMPD and POT events.

In MMPD events (Fig. 4(a)), only 3 (16.67% of all the stations over MRB) out of 24 stations in the basin show statistically significant change points at 10% significance level. The stream gauge location, Andhiyarkore shows a presence of significant change point at 15% significance level. For POT events (Fig. 4(b)), two stations (Bamnidhi and Manendragarh) exhibits abrupt changes at 10% significance level while Kurubhata gauge station shows significant change point at 15% significance level. None of the stations had a change point at 5% significance level.

A closer look reveals, all these stations are spatially distributed over the northern part of the basin at Region **I**. It was observed that all these stations (i.e., Andhiyarkore, Bamnidhi, Ghatora, Kurubhata, and Manendragarh) had a change point during the end of the 20th and beginning of the 21st centuries. However, it should be noted that no discernible spatial patterns could be identified based on the detected change points with respect to the mean. Further, the detected change points at Bamnidhi (1987 and 1978 for MMPD and POT events, respectively) and Manendragarh (2003 and 2004 for MMPD and POT events, respectively) are close to the year of construction of 'mega-dams' (1985, 1976 and 2004) with a height > 15 m (Best, 2019) up-streams to the respective gauge stations (WRIS, 2015). Details of these dams, their capacity, and the corresponding gauge locations are presented in Table S3. For remaining stream gauges, we could not identify any specific reasons for the abrupt changes.

To summarize, our findings suggest following in relation to flood trends across MRB: (i) for MMPD events, ~ 67% (12 out of 18 stations) gauge stations showed (either significant or insignificant) decreasing trend in flood magnitude at Region I, whereas 67% (4 out of 6 stations) gauge stations showed (insignificant) increasing trend across Region II. (ii) For POT events, at region I, ~ 56% (10 out of 18 stations) gauge stations showed spatially coherent (either significant or insignificant) decreasing trends, whereas, at Region II, 80% (4 out of 5 stations) gauge stations showed (either significant or insignificant) increasing trends in flood magnitude. (iii) Overall, a larger number of stations show upward trends in flood magnitude for POT events (52% stations) than that of the MMPD event (42% stations) (iv) On the other hand, ~ 17% and 13% of the stations show change points for MMPD and POT events, respectively.

3.2 Little Evidence of Scale-Dependency in the Nature of Flood Samplings

Next, we analyze the influence of scale-dependency in the results of trend estimates. The objective of the scale-dependency test is to investigate if the nature of changes in streamflow patterns is related to the catchment size and elevation of the basins. For this, the relative changes in each of the flood indicators are plotted against the basin area and mean basin elevation. Fig. 5 presents three-dimensional plots to analyze the role of catchment size and mean basin elevation on flood trends. The significant changes are marked (Fig. 5) in solid. We observe no clear pattern of scale-dependency across MRB. There are no spatial scales and elevations, where significant changes are concentrated. However, for MMPD events, decreasing trends are more concentrated between 1000 and 3000 km^2 catchment area and the mean elevation between 490 and 700 m MSL (Fig. S1). However, none of these downward trends are statistically significant. On the other hand, a few evidence of significant increasing trends (at three of the gauging stations, Kurubhata, Kantamal, and Hirakud dam) are observed for larger catchments (catchment area more than 1000 km^2) with higher basin elevation (ranges between 250 and 500 m MSL) for the POT flood events (Fig. S1). Despite locating at a higher elevation, the downward trend in Manendragarh station for both flood series is attributed to the construction of mega-dams upstream in 2004 (Table S3).

3.3 No Notable Changes in Flood Seasonality

The seasonality in flood responses is determined using directional statistics. The changes in the timing (mean date), flood variability (σ) and persistence $(\bar{r})$ are evaluated for individual stream gauge locations. Seasonality measures of MMPD and POT peak discharge events are plotted in a polar plot as shown in Fig. 6. The mean occurrence date of flood for each of the station is represented as an angle measured counterclockwise relative to 1st January, and the persistence of the flood events are shown as the distance from the center of the polar plot. The circular variance (σ^2) for individual gauge stations are represented by the size of respective circles, with small circle size indicating less variance and large circle size indicating more variance. Fig. 7 gives information on the mean date of flood events in details. The x-axis represents the mean date of MMPD and POT peak discharge events in the August month.

For both MMPD and POT peak discharge events, the seasonality analysis indicates the persistence of floods across all gauges with mean flood dates occurring in August. For majority of the gauging station, the mean flood dates are concentrated around the second week of August for both MMPD and POT events with the exception for Andhiarkore gauge station, situated at the Upper MRB (Region I), which showed the mean flood date close to September (28 August) for the MMPD events (Fig. 6 (a)). However, considering both methods for flood samplings, the POT events show relatively less regular mean flood dates with higher circular variance than that of the MMPD events. Taken together, we infer that the peak discharge events are highly regular in MRB. Our results are in agreement with Burn and Whitfield (2018), in which authors found that stream gauges in the pluvial flood regime, in general, show a very few (significant) changes in flood seasonality than that of the other flood regimes.

3.4 Shifts in the timing of flood peaks

The shifts in the timing of flood peaks are analyzed using an adjusted Theil - Sen slope estimator with the correction for the circular nature of mean dates. Fig. 8 summarizes the results of changes in timings of MMPD and POT discharge events in MRB. While the location of the stream gauges is represented using a square box, the hues in red and green of the boxes indicate the gauges with earlier and late occurrences of peak discharge events. The stream gauge with color in white represents the flood events that have concurred with the mean flood date at respective stream gauge location, whereas darker shades show a substantial deviation from the mean flood date. For POT series, we exclude Naraj station from the analysis (Fig. 8(b)) since the number of discharge events was found to be less than ten for this site.

For the MMPD events (Fig. 8(a)), most of the stations in Region II showed an earlier occurrence of peak discharge events. At Delta region, Naraj located at relatively low elevation (Table S1) shows a delay in flood occurrence up to 18 days (per decade). While the stream gauge at Manendragarh, situated at a relatively higher elevation (Table S1), experiences an earlier appearance of flood date. In contrast to MMPD events, for POT events (Fig. 8(b)), we find no shifts in flood timings across most of the gauges at region II, rather surprisingly a delayed occurrence of peak event at Kesinga. A few gauging stations show disparate trends in flood timing for MMPD and POT events, with an earlier occurrence of flood for MMPD events while delayed for the POT event and vice versa.

For both methods of flood samplings, the Hirakud dam showed a delayed date of flood occurrence, whereas, Tikarpara near the delta showed an earlier appearance of floods. The delay in flood dates in Hirakud could be attributed to a shift towards greater water inflow during September in Hirakud reservoir in recent decades as shown in a latest report (Choudhury et al., 2012) based on analysis of trends of mean inflow (1958-2008) records. The delayed flood timing in Hirakud has critical implications for flood control operation of the dam since, by the monsoon end (i.e., during September), dam management authorities are in a dilemma whether to open the reservoir gate. For instance, severe floods in downstream of Hirakud during the year 2001, 2008 and 2011 (Brakenridge, 2018; Jena *et al.*,

2014) were triggered by the delay in releasing water from several full dams coupled with abnormally heavy monsoonal precipitation. On the other hand, an earlier flood occurrence at Tikarpara could be attributed to the loss of forest cover area across the middle reaches of the basin (Dadhwal et al., 2010). Based on modeling of streamflow across the Mahanadi basin (with an outlet at Munduli, which is located at 4.5 km upstream to Naraj), Dadhwal *et al.* (2010) concluded that the decrease in forest cover by about 5.7% have resulted in an increase in fluvial discharge by approximately 4.5% at Munduli in the delta. Furthermore, the heavy rainfall induces a massive inflow in the Hirakud reservoir leading to the dam authorities to open gates of the dam, causing flash floods in the delta region (Panda et al., 2013).

For region I, ~56% (10 out of 18) and 61% (11 out of 18) of the stations show delay in flood occurrences for both MMPD events and POT events respectively, while at region II, ~ 67% (4 out of 6) exhibits earlier dates of floods for MMPD events, whereas, no shifts in flood timing is observed for POT events at 60% (3 out of 5) stations. Overall, our results suggest more number of stream gauges show delayed flood occurrence for both methods of flood samples.

It is interesting to note that for both methods of flood samplings, we find sites with upward (downward) trends in flood magnitude, however, with delayed (earlier) dates of flood occurrences. Considering basin as a whole, ~33% and ~17% of the stations unveiled a downward trend in flood magnitude with an earlier date of flood occurrence for MMPD and POT events respectively. On the other hand, ~29% - 35% of the stations show upward trends in flood magnitude with a delayed shift in flood timings for both methods of flood samplings. Table S4 presents the list of these stations name.

4. Discussion and conclusions

This paper contributes to the comprehensive assessment of flood trends in densely populated Mahanadi river basin. Unlike previous assessments (Jena et al., 2014; Panda et al., 2013), here we investigate three novel aspects: *first*, a comparative analysis of spatial patterns in (either significant or insignificant) upward/downward trends in two different flood series derived from the monsoonal maximum (MMPD) and peak over threshold (POT) events. While monotonic trends in flood series are evaluated using nonparametric Mann Kendall trend statistics, the abrupt shifts in flood time series are detected using Pettitt test for single change-point analysis. Besides, assessing the results of local significance at individual stream gauge locations, we evaluated the regional trend using field significance test. Second, we assess the sensitivity of flood magnitudes trends concerning catchment size and mean basin elevation. Finally, we assess the persistence of the flood events and shifts in the timing of flood flow using directional statistics. While most of the earlier assessments are limited to the river basins across mid- and high latitude nations, to the best of our knowledge, this study is the first to assess the seasonality and shift in the date of flood occurrences in a large tropical river basin, MRB (MRB as a whole consist of a drainage area of 1,41,589 km^2, the mean annual discharge is 1,895 m^3/s with a maximum of 6,352 m^3/s during monsoon months [Dadhwal et al., 2010]). By leveraging in-situ observations, our analyses detect flood rich and flood poor region across MRB, which can serve as a basis for attributing hydrologic response to climate change under the effect of multiple drivers (Vano et al., 2015; Vano and Lettenmaier, 2014).

Although detected trends in flood magnitude (Fig. 1) and shifts (delayed or earlier) in timing of floods (Fig. 8; Table S4) over MRB could be linked to human intervention (Best, 2019; Choudhury et al., 2012; Dadhwal et al., 2010; Mishra et al., 2008) rainfall-induced runoff during monsoon season (June – September) is one of the major flood generating drivers in the basin (Jena et al., 2014; Panda et al., 2013). Further, upward trends in floods in the delta region could be attributed to superposition of extreme sea level, such as severe storm surges (Flierl and Robinson, 1972; Milliman et al., 1989) and river floods in the delta region, which is frequently associated with a severe storm resulting from synoptic low-pressure systems and extreme precipitation. One of the plausible physical mechanisms is to link extreme precipitation event to an increase in the magnitude of river floods in a warming climate. Despite most of the gauges in the middle reaches show an upward trend in flood magnitude, our analyses based on the seasonality index indicate a relatively regular peak discharge (persistence index ranges between 0.88 and 0.95 for MMPD events and 0.87 and 0.92 for POT events) with mean date of flood occurrences during the mid of August for most of the gauges. These results indicate that flood events are mostly modulated by changes in flood generating processes (available antecedent moisture content in the catchment and shift in atmospheric circulation pattern that results into change in dominant storm mechanism) rather than the increase in precipitation extremes in response to increase in surface warming (Sharma et al., 2018; Wasko and Sharma, 2017). The review of the literature suggests

(Pattanayak et al., 2017) a linkage between large-scale atmospheric circulation pattern (such as sea surface temperature, SST) and basin hydroclimatology (such as precipitation, temperature minima, and temperature maxima) over MRB. A strong linkage was identified especially during the 1980s, which was attributed to changes in Pacific Decadal SST patterns and anthropogenic effects (Pattanayak et al., 2017).

The key insights from the study are summarized as follows:

- A spatially coherent pattern of the flood is observed in MRB using both methods of flood samplings - Region I shows a mixture of (insignificant) increasing and decreasing trend, in which the number of gauges with downward trends is more than that of the number gauges with upward trends. While the majority of gauges show evidence of insignificant up/downward trends in flood magnitude (at 10% significance level), only Bamnidhi and Manendragarh show (significant) downward trends, whereas Kurubhata shows a (significant) upward trend in flood magnitude. On the other hand, at Region II, the middle reach of MRB, we find most of the stations show (either significant/insignificant) upward trends. Further, the downward trends in Region I are field significant. Also, while we find a few evidences of (significant) change points at Region I, no such change points are detected across the Region II.

- Except for construction of a few major dams upstream that have affected the nature of flood trends, overall, we observe no clear linkage between flood severity and catchment morphology (i.e., mean basin elevation and watershed area). For MMPD events (insignificant) downward trends in flood magnitude for stream gauges (out of which two of them is statistically significant) are clustered between 1000 and 3000 km^2 area with elevation ranges from 490 – 700 m MSL. On the other hand, for POT event, we find a few evidence of a significant upward trend for larger catchment (of an area more than 1000 km^2) with high basin elevation (between 250 and 500 m MSL). The stream gauge at Manendragarh, located at upstream gauges of MRB showed a downward trend in flood magnitude for both MMPD as well POT events despite being located at higher elevation (668m above mean sea level) and smaller catchment area (~ 1000 km^2), which is attributed to construction of a dam near this site.

- The seasonality of flood responses in both methods of flood samplings suggests the mean date of flood occurrences are concentrated around the mid of August for most of the stream gauges with the exception for the Andhiarkore at Region I, for which the mean flood date is closed to September (28th August) for MMPD events. Although we note the nature of mean date of flood occurrences are more or less uniform across both methods of flood samplings, the POT events show relatively less regular mean flood dates with higher circular variance than that of the MMPD events.

- Around half of the stream gauges across MRB exhibit delay in the date of flood occurrences, which is in agreement with both methods of flood samplings. About ~29% (~33%) and ~35% (~17%) of the stations indicate an upward (downward) trend but with delay (early) occurrence of floods for MMPD and POT events, respectively.

Although we find a spatially coherent flood pattern in MRB using both methods of flood samplings, the nature of trends differs case by case basis. This is because, while in monsoonal maxima event, we select the maximum peak flow of each year during monsoon month (June to September), POT sample are extracted from all peak values from the total time series that lie above a certain truncation level, while ensuring each of the selected samples are independent of one another. Thus, a very low discharge value, especially during a dry period, can also be a part of MMPD event, whereas, some peaks that are not MMPD but are still very high could be a part of POT event (Bezak et al., 2014).

A few caveats could be considered. We considered trends in flood magnitudes and seasonality in flood occurrences across MRB using ground-based observation. The specific insights are conditioned on the quality of site-specific information used in the analyses. Based on the availability of good quality in-situ observations, the analysis is limited to the recent four decades. Although many studies so far analyzed the influence of hydro-meteorological drivers, precipitation and air temperature in generating peak discharge across MRB, no studies, to date analyzed the role of catchment wetness in simulating the nature of floods. However, extreme precipitation does not necessarily lead to fluvial floods (Sharma et al., 2018; Wasko and Sharma, 2017), antecedent catchment wetness often strongly controls the nature of flood peaks across the river basin (Merz et al., 2018; Schröter et al., 2015). Hence, future research will be directed towards understanding the role of catchment processes, such as antecedent moisture content, in modulating the nature of flood flows in a large river basin system, such as in MRB.

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Author contribution

The first author carried out the analyses under the guidance of the second and the third author and prepared the first draft. The second author conceived the idea and helped in writing the manuscript. All three authors interpreted the results, contributed in writing and reviewed the manuscript.

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Fig. 1. Mahanadi river basin (a) Elevation map (b) District wise population density with highlighting major cities (Census data 2011).

Fig.2. Flowchart summarizing the workflow.

Fig. 3. Spatial trends at the 10% significance level (a) MMPD events and (b) POT events. The size of a triangle is proportional to the magnitude of trends calculated by the Theil Sen slope estimator.

Fig. 4. Change point analysis (Pettitt test) of (a) MMPD events and (b) POT events for gauge stations at a significance level of 5, 10 and 15%, respectively. While the single change point analysis is performed by the Pettitt test, differences in mean stream flow after and before the detected change points are shown using the triangle. The downward orientation of the triangle indicates a decrease in mean stream flow after change point years at respective gauge location.

Fig. 5. Scale dependency relative to flood trends of MMPD events (*upper panel*) and POT events (*lower panel*)**.** Mann-Kendall trend statistics are plotted as a function of the Catchment size (in km^2) and Catchment elevation (in m). Shaded triangles indicate significant changes at the 10% significance level.

Fig. 6. The circular plots of mean date and persistence of floods using (*left panel*) MMPD and (*right panel*) POT events. The size of the circle indicates the value of circular variance with larger (smaller) size indicates a larger (smaller) variance.

Fig. 7. Mean occurrence dates of Monsoonal Peak Discharge (MMPD) and Peak over Threshold (POT) flood events.

Fig. 8. Trends in flood timing of (a) MMPD events and (b) POT events at individual gauge stations. The shift in the date of flood occurrences is calculated in days per decade.

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Table 1. Summary of some past relevant studies and their key insights

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Table 1. Summary of some past relevant studies and their key insights

	Study	Region	Approach & Dataset Information	Key findings
Trend analysis	*Petrow and Merz (2009)*	Throughout Germany	(i) Sites: 145 discharge gauges across Germany (ii) Period of analyses: 52 years (1951–2002) (iii) Data: Annual maximum series and peak over threshold discharge series (iv) Approach: Non-parametric Mann–Kendall test for trends in flood magnitude and frequency	(1) Most of the stations showed significant increasing flood trend (at 10% significance level). (2) Very few stations exhibited decreasing trends and were not field-significant. (3) Stations with significant trends were spatially clustered over the region.
	Tian et al. (2011)	Poyang Lake Basin, China	(i) Sites: 10 hydrological stations were considered across Poyang Lake Basin (ii) Period of analyses: nearly 50 years of observed records (1957–2003) (iii)Data: Annual maximum and minimum flow, annual peak-over-threshold flows (iv) Approach: Non-parametric Mann-Kendall (MK) test and the linear regression method	(1) Both methods showed good agreement with each other in detecting flood trends. (2) Most annual maximum flows occurred between April to July, owing to southeast monsoon. (3) No significant upward/downward trends in flood magnitude are noted. (4) In contrast, a significant increasing trend was observed for low flow events.
	Panda et al. (2013)	Mahanadi River Basin, India	(i) Sites: 19 gauging stations spread across the basin (ii) Period of analyses: 1972–2007 (iii)Data: Seasonal and sub-seasonal streamflow and rainfall variables were analyzed (iv)Approach: The Mann–Kendall nonparametric test after removing the serial correlation	(1) The streamflow was primarily controlled by the rainfall over the basin. (2) Increasing trends in flood magnitude in June while decreasing trends in August (3) Increased trends in both pre- and post-monsoon season streamflow and rainfall time series.

	Bawden et al. (2014)	Athabasca River Basin, Canada	(i) Sites: 19 gauge stations of Athabasca River Basin (ii) Period of analyses: Varying record length between 1952 and 2010 (iii) Data: Twenty flood indicators like annual and monthly mean flows, mean flow for the warm season, annual maximum and minimum daily flow were used (iv) Approach: Trend detection using the Mann–Kendall (MK) non-parametric test	(1) Strong decreasing trends in the annual warm season (March – October) and summer stream flows (2) Trends in streamflow were more strongly linked to precipitation than to air temperature
	Jena et al. (2014)	Mahanadi River Basin, India	(i) Sites: Two gauge stations at upper and middle reaches of the basin (ii) Period of analyses: 1957-2011 for streamflow record and 1957-2007 for rainfall data (iii) Data: Annual peak streamflow releases and $1^{o}\times1^{o}$ Gridded daily rainfall data. (iv) Approach: A non-parametric Mann–Kendall test	(1) The upper region of the basin showed no (significant) trend in rainfall while the middle region showed an increasing trend in rainfall. (2) The middle reach showed a significant increasing trend due to an upward trend in extreme rainfall in the middle reaches of the basin.
Seasonality analysis	*Bloschl et al. (2017)*	Entire Europe	(i) Sites: 4262 hydrometric stations from 38 European countries (ii) Period of analyses: 1960-2010 (iii) Data: Dates of occurrence of annual flood peaks (iv) Approach: Circular statistics, Theil-Sen slope estimator and a centered 10-year moving average method	(1) Earlier spring snowmelt floods throughout northeastern Europe (2) Late winter floods around the North Sea and some sectors of the Mediterranean coast (3) Earlier winter floods in Western Europe.

	Cunderlik and Ouarda (2009)	Canada	(i) Sites: 162 streamflow records from relatively pristine and stable land-use conditioned watersheds (i) Period of analyses: 1974 to 2003 (ii) Data: Dominant Seasonal floods were analyzed (iii) Approach: The Mann–Kendall test in conjunction with the method of pre-whitening was used in the trend analysis and Directional statistics was used for seasonality analysis	(1) The snowmelt floods shifted toward the earlier times of the year. (2) No significant trends were found in the timing of the rainfall dominated flood events. (3) The magnitude of the floods has been decreasing over the last three decades.
Both trend and seasonality analysis	*Burn et al. (2010)*	Canada	(i) Sites: 68 streamflow gauging stations in Canada (ii) Period of analyses: A record length of at least 50 years (1957–2006) (iii) Data: Extreme hydrological events (both high and low flows) drawn from annual and spring events (iv) Approach: Trends were analyzed using the Mann–Kendall test. A bootstrap resamplings-based field significance test was used to determine the *regional* trend. Seasonality measures that characterize the timing and persistence of extreme hydrologic events were examined using directional statistics	(1) High flow events showed decreasing trends whereas low flow events showed both decreasing and increasing trends in flow magnitude. (2) Nival sites showed an earlier high flow occurrence and an earlier low flow occurrence. (3) Pluvial sites tend to experience a later annual maximum flow in the more recent part of the record.
	Burn et al. (2016)	Canada	(i) Sites: 132 gauging stations spread over Canada (ii) Period of analyses: Four periods ranging from 50 to 80 years (iii) Data: Peak over threshold (POT) dataset	(1) There was an increased number of over threshold events. (2) There was increased importance of both rains on snow events and rainfall events

		(iv) Approach: Trend and Seasonality analysis were examined using the Mann–Kendall non-parametric test and directional statistics respectively.	and decreased importance of snowmelt events. (3) A transition of mixed flood regime to a more pluvial regime whereas nival catchments transition towards a more mixed response was observed.
Matti et al. (2017)	Scandinavia	(i) Sites: 59 catchments across Scandinavia (ii) Period of analyses: A record length of 54-122 years (1892–2014) (iii) Data: Seasonal maximum daily flows in a hydrological year (iv) Approach: Circular or directional statistics were used to assess flood seasonality and modified Mann–Kendall trend test was used for trend analysis	(1) Summer maximum daily flows showed a decreasing trend while winter and spring maximum daily flows showed an increasing trend (2) Snowmelt-dominated regime is shifting towards rainfall-dominated with consistent changes towards earlier flood peaks
Burn and Whitfield (2018)	Canada and the northern United States	(i) Sites: Hydrometric reference streamflow gauging stations at 27 natural watersheds (ii) Period of analyses: Past 100 years record span from 1916 to 2015 (iii) Data: Only POT time series (iv) Approach: Circular statistics were used to explore changes in the nature of the flood regime, Mann-Kendall non-parametric test was used for trend detection, and block bootstrap resamplings was used to correct for serial correlation in the data	(1) All flood regime show an increased number of threshold exceeding events. (2) A shift in the nival flood regime to a mixed regime and mixed flood regime to a pluvial regime is noted.

Change Point Analysis	*Villarini et al. (2009)*	The continental United States	(i) Sites: 50 stream gauging stations (ii) Period of analyses: Varying length for different stations with at least 100 years record starting from 1838 (iii) Data: Annual maximum peak discharge. (iv) Approach: A nonparametric Pettitt test was performed to detect abrupt changes in mean and variance of peak flows	(1) 18 and 6 out of 50 stations exhibited a significant abrupt change in the mean and variance respectively. (2) Land use and land cover changes and gauge height variations have led to change points.
	Nka et al. (2015)	West Africa	(i) Sites: 11 catchments across West Africa (ii) Period of analyses: 1950-2010 (iii) Data: Annual maximum and POT series (iv) Approach: The Pettitt test was used to identify change points in the data	(1) Most of the change points lie between 1950 and 2000 (2) Land use changes are the primary contributing factor for the change in flood magnitude.
In our study*	*This study*	Mahanadi River Basin, India	(i) Number of sites: 24 gauge stations (ii) Analyses period: varies between 1971 and 2016 (iii) Flood Event Samplings: Both Monsoon maximum series (MMPD) and peak over threshold (POT) series (iv) Approach: (a) Trend Detection: Mann-Kendall trend statistics to analyze monotonic trends and Pettitt change point statistics to identify abrupt shifts in the peak discharge time series. Field significance test was conducted to investigate the nature of the regional trend.	(1) POT events showed increasing trend while MMPD events showed a mixture of increasing and decreasing trends in the middle reach (2) Mean date of peak discharge for all the sites was found during August (3) Delayed floods at lower reaches of Mahanadi River Basin

	(b) Seasonality analyses: using directional statistics. (c) Change in timing of flood: Adjusted Theil-Sen slope estimator as employed in Bloschl et al. (2017)	

*Contributions of current paper is added for the completeness

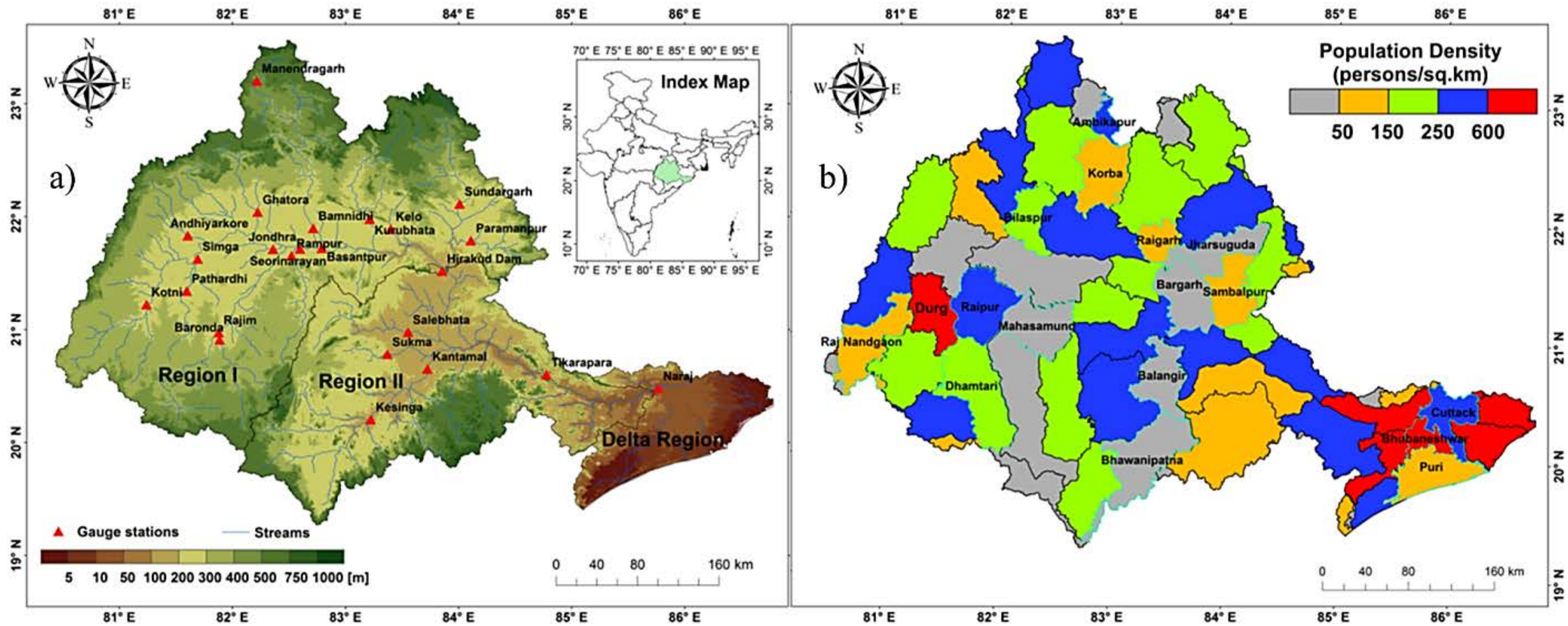

Fig. 1. Mahanadi river basin (a) Elevation map (b) District wise population density with highlighting major cities (Census data 2011).

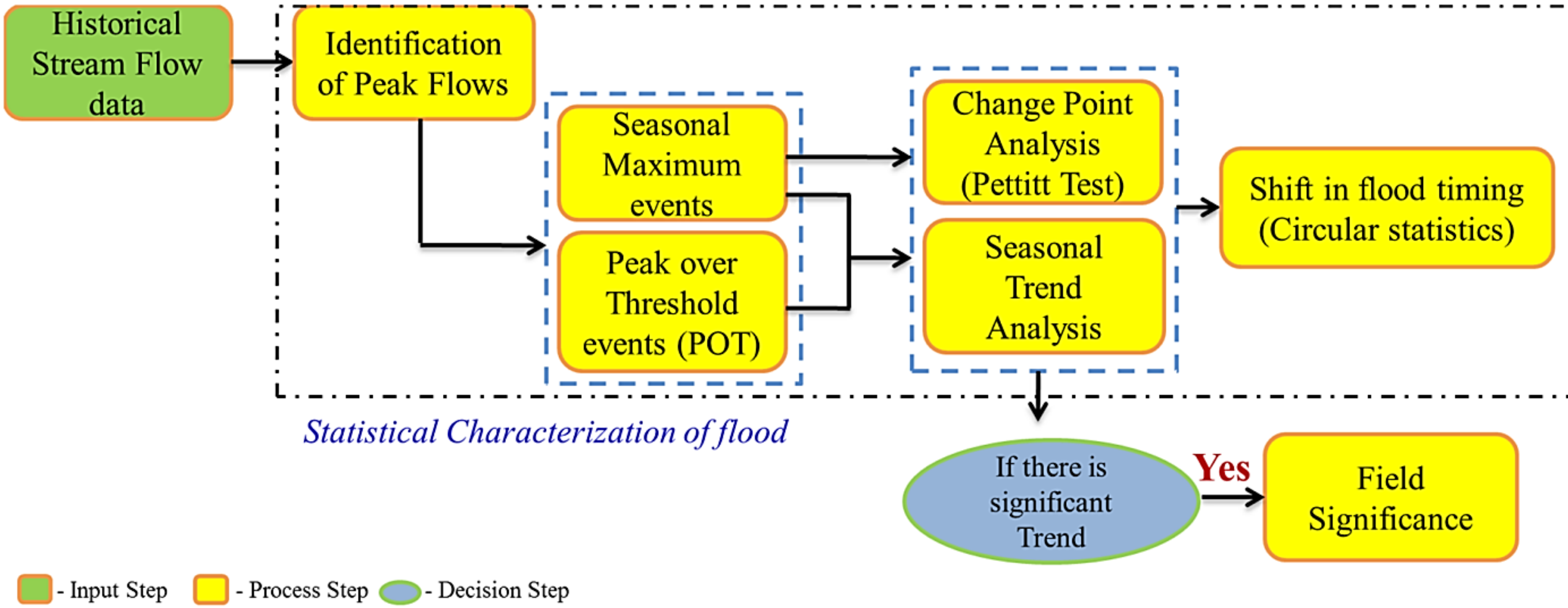

Fig.2. Flowchart summarizing the workflow.

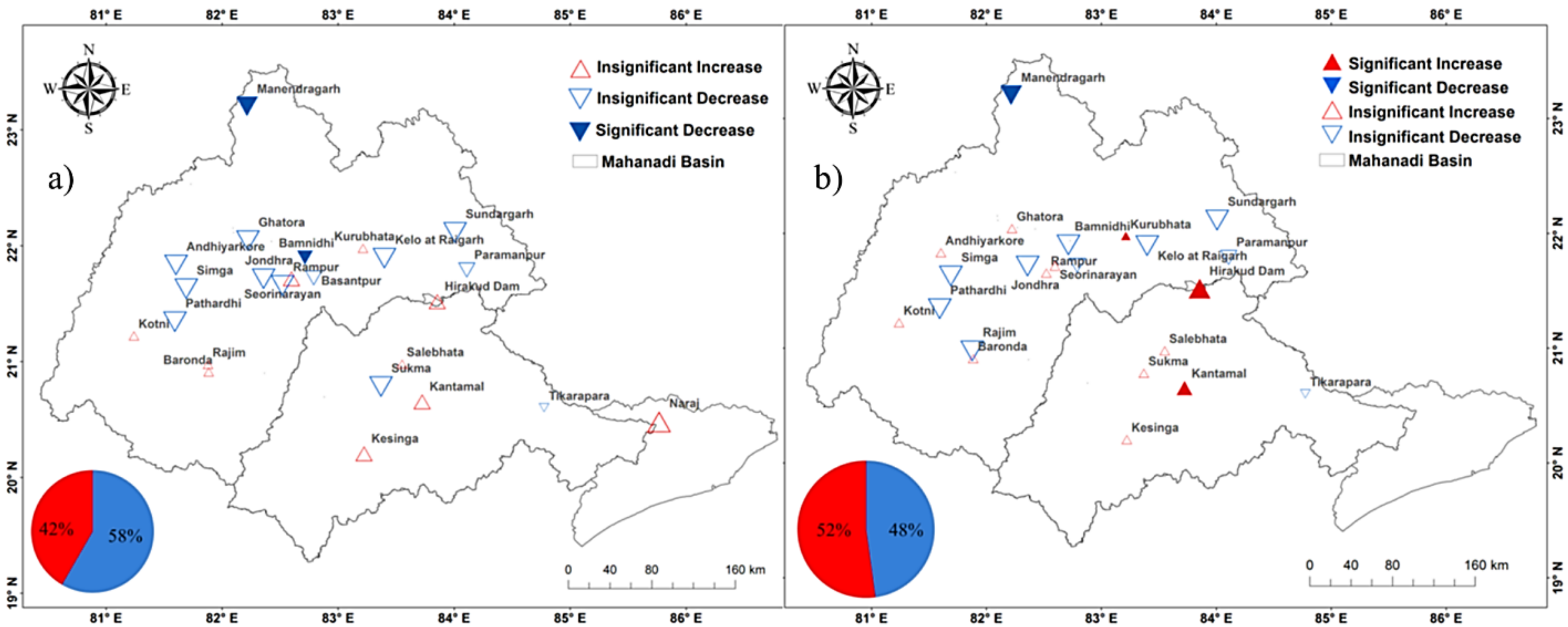

Fig. 3. Spatial trends at the 10% significance level (a) MMPD events and (b) POT events. The size of a triangle is proportional to the magnitude of trends calculated by the Theil Sen slope estimator.

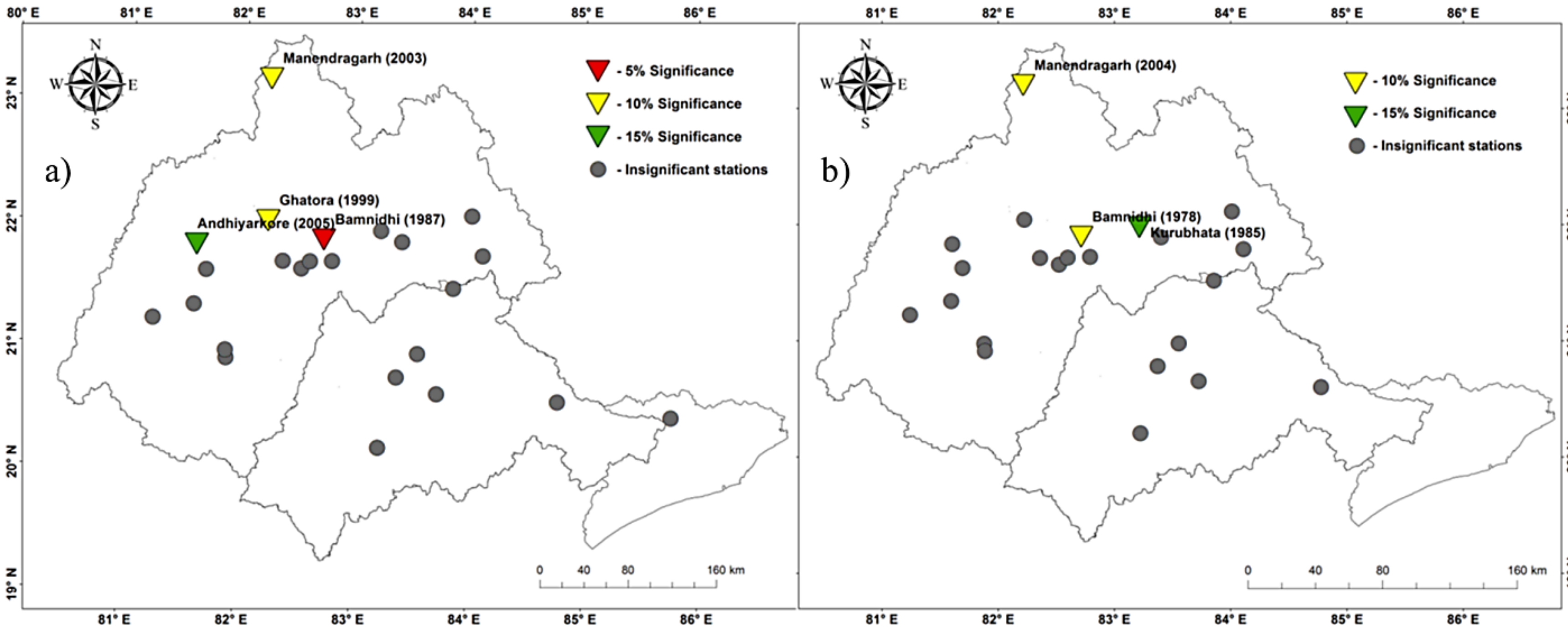

Fig. 4. Change point analysis (Pettitt test) of (a) MMPD events and (b) POT events for gauge stations at a significance level of 5, 10 and 15%, respectively. While the single change point analysis is performed by the Pettitt test, differences in mean stream flow after and before the detected change points are shown using the triangle. The downward orientation of the triangle indicates a decrease in mean stream flow after change point years at respective gauge location.

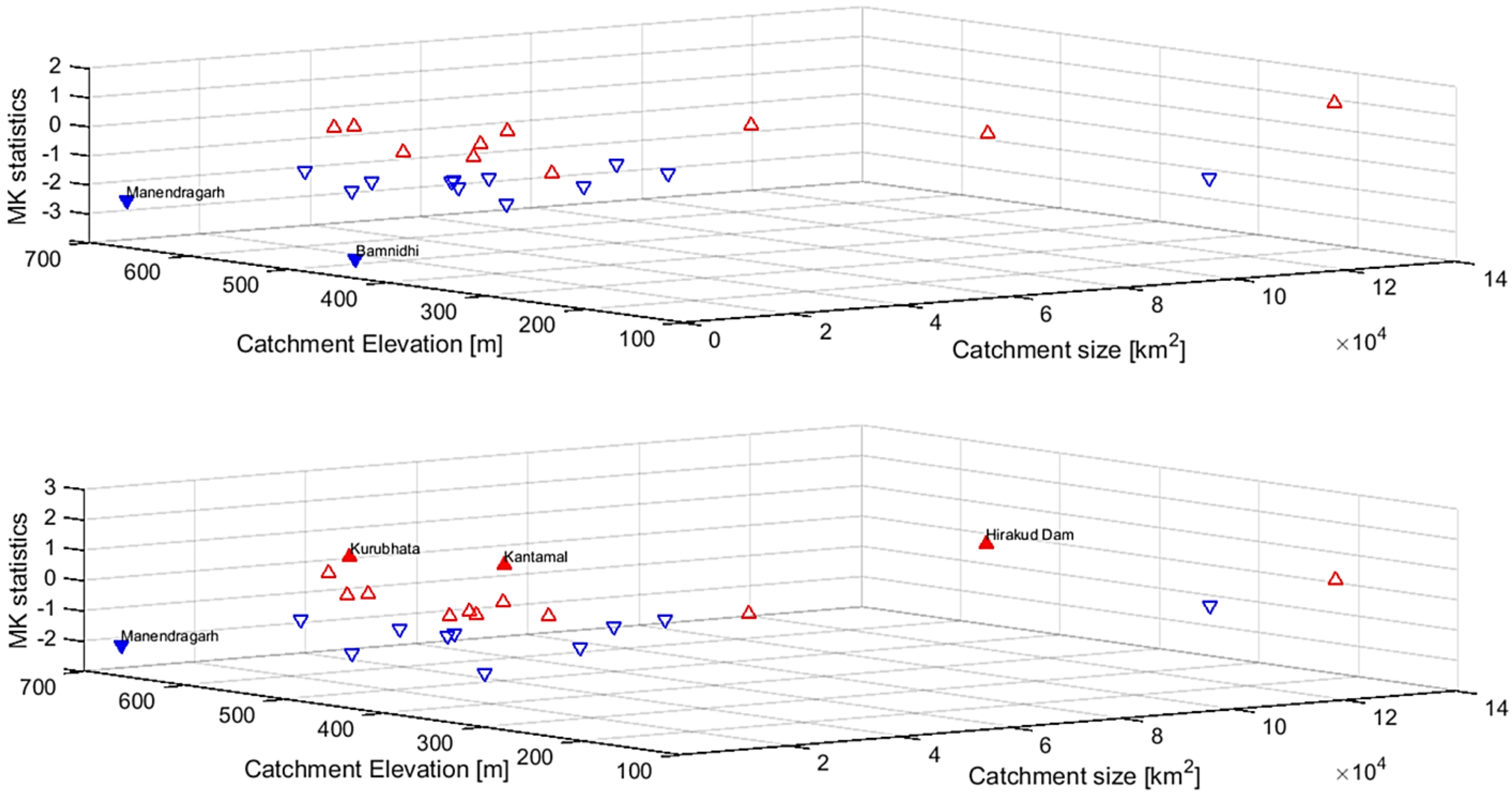

Fig. 5. Scale dependency relative to flood trends of MMPD events (*upper panel*) and POT events (*lower panel*)**.** Mann-Kendall trend statistics are plotted as a function of the Catchment size (in km^2) and Catchment elevation (in m). Shaded triangles indicate significant changes at the 10% significance level.

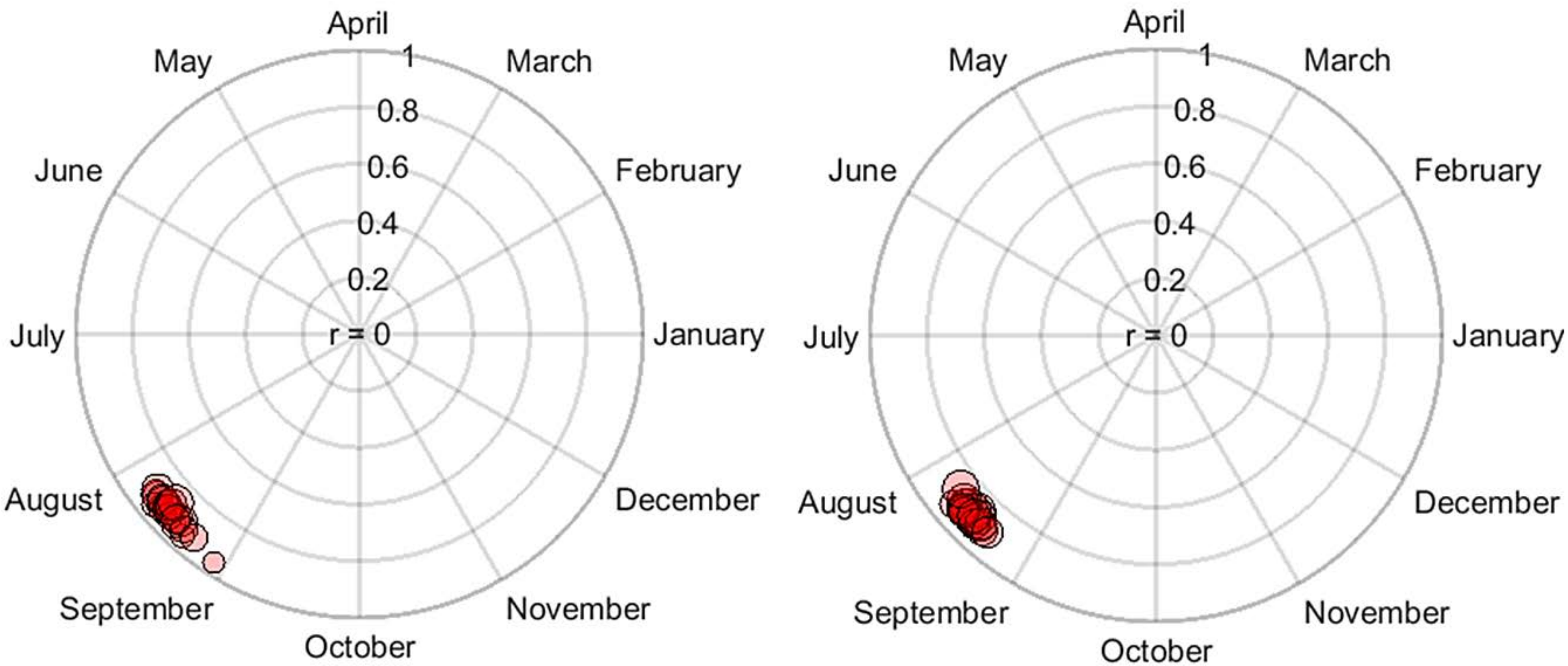

Fig. 6. The circular plots of mean date and persistence of floods using (*left panel*) MMPD and (*right panel*) POT events. The size of the circle indicates the value of circular variance with larger (smaller) size indicates a larger (smaller) variance.

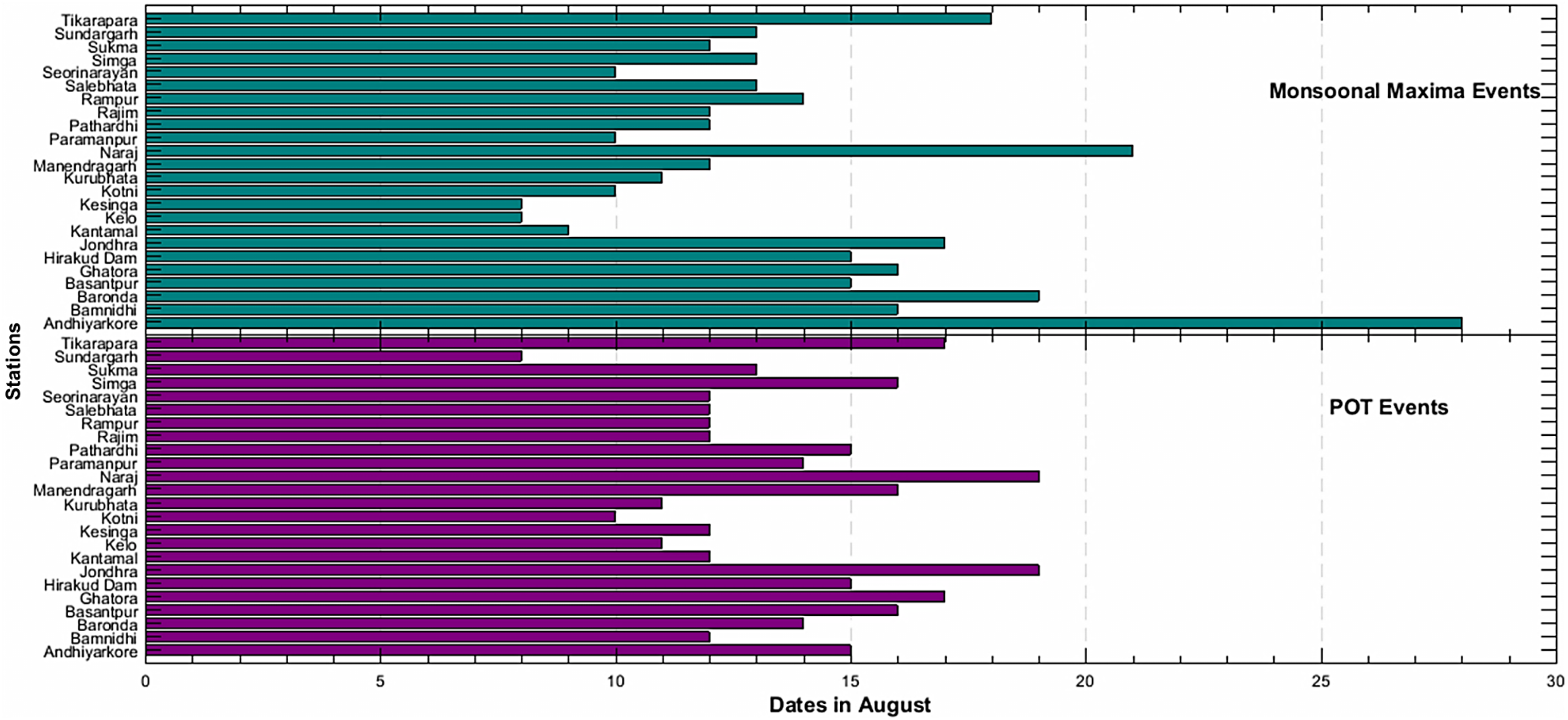

Fig. 7. Mean occurrence dates of Monsoonal Peak Discharge (MMPD) and Peak over Threshold (POT) flood events.

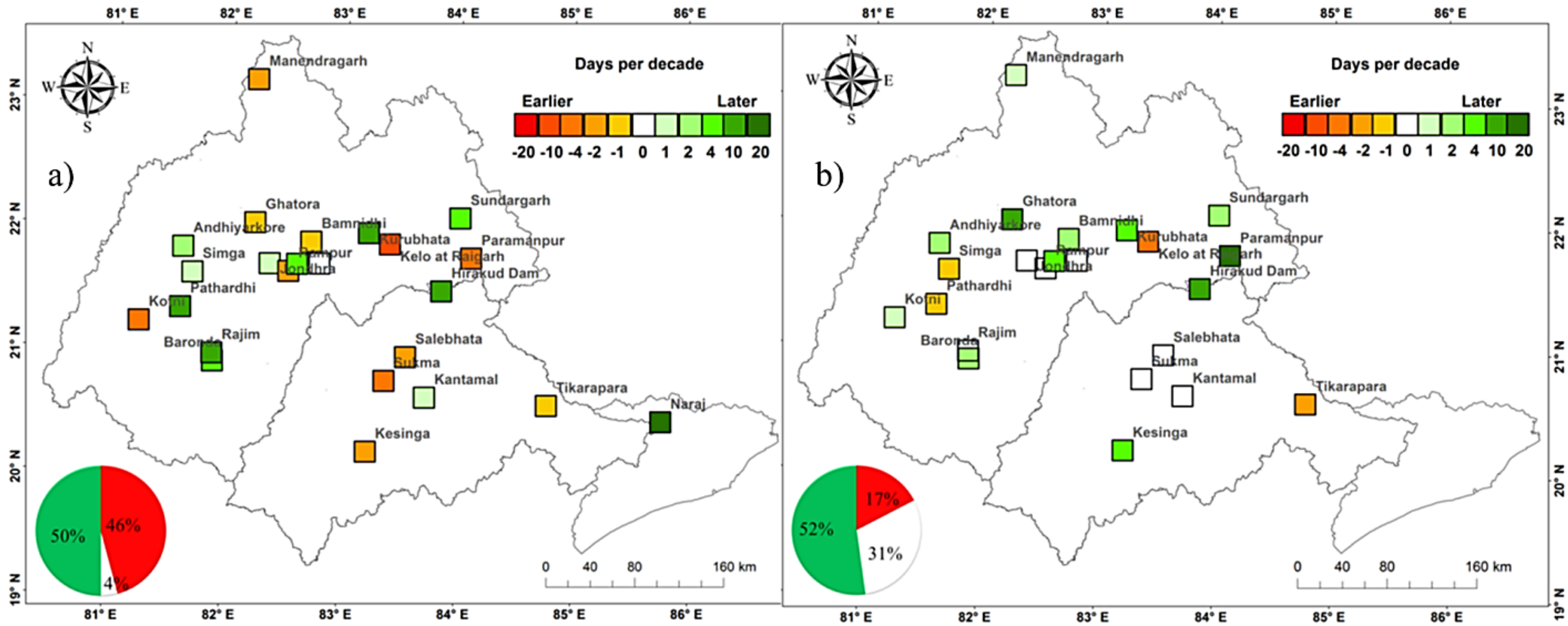

Fig. 8. Trends in flood timing of (a) MMPD events and (b) POT events at individual gauge stations. The shift in the date of flood occurrences is calculated in days per decade.