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Compound hydro-climatic drivers and atmospheric feedbacks governing flash drought evolution across climatically diverse Maharashtra, India

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A R T I C L E I N F O

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A B S T R A C T

Flash droughts (FDs) are rapidly developing hydro-climatic extremes driven by complex interactions among atmospheric moisture demand, land-surface conditions, and precipitation variability. Due to their rapid onset and severe impacts on agriculture, water resources, ecosystems, understanding the coupled land-atmosphere mechanisms governing FD evolution is essential for drought-prone regions like Maharashtra, India. This study investigates the spatiotemporal characteristics, hydro-climatic triggers and atmospheric feedback mechanisms of flash drought across 36 districts of Maharashtra during 1981-2024 using an Aridity Index (AI) percentile-based approach. High-resolution hydro-meteorological datasets, including precipitation, temperature, soil moisture percentiles and vapor pressure deficit were analyzed at various stages of FD development. The results reveal strong seasonal, and atmospheric controls on FD occurrence. FDs were relatively infrequent during the monsoon season due to sustained rainfall and favorable soil moisture conditions, whereas the non-monsoon and pre-monsoon transition periods exhibited significantly higher frequency (5-25 events), longer durations with mean event durations exceeding 20 days, and faster intensification, particularly across humid and sub-humid regions and semi-arid regions. Spatial analysis identified the semi-arid interior districts of Ahilyanagar, Beed, Dharashiv, Sangli, and Solapur as hotspots of severe and rapidly intensifying FDs, exhibiting intensification rate exceeding 9% per octad. Hydrometeorological analysis demonstrates that rapid soil moisture depletion, precipitation deficits, elevated temperature, and increased VPD collectively accelerate FD intensification. Trigger analysis indicates that precipitation deficit dominates FD initiation, whereas the coupled effects of temperature and precipitation strongly control drought severity and intensification. These findings highlight the importance of integrating atmospheric feedback diagnostics into FD monitoring and early warning systems.

1. Introduction

Drought is one of the most complex and damaging natural hazards affecting agriculture, water resources, and socio-environmental systems worldwide (Jiao et al., 2019; Poonia et al., 2021a; She and Xia, 2018; Soľáková et al., 2014). Conventionally, drought is recognized as a slow evolving hydro-climatic phenomenon (Jiao et al., 2021; Wilhite, 2000; Wilhite et al., 2007; Xue et al., 2024), characterized by prolonged period of below-normal water availability or an inability to meet water demand that may take several months or years to reach its maximum intensity and spatial extent (Sabut and Mishra, 2026). However, in recent studies highlighted the increasing occurrence of rapidly developing drought events that intensify within few weeks and often cause severe impacts. These rapidly evolving events are referred as flash droughts (FD), emerged as one of the most critical hydro-meteorological extremes and often provide limited time for mitigation and response measures. Unlike conventional droughts, rapid-onset drought events develop due to the combined effects of unusually high evaporative demand and insufficient rainfall (Vicente-Serrano et al., 2010; Beguería et al., 2013). The impacts of flash drought events are particularly severe due to their rapid intensification over short period of time (Otkin et al., 2022, 2024; Svoboda et al., 2002). Such rapid intensification of FDs can simultaneously induce heat and water stress, resulting in substantial impacts on agricultural productivity, ecological stability, water resources and regional economies (Otkin et al., 2024). Climate change is expected to intensify hydro-climatic extremes, increasing risk to water resources and disaster

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management (Masalvad et al., 2026; Baheshwar et al., 2026; Mukherjee et al., 2025).

Flash drought development is controlled by a combination of multiple atmospheric and land-surface processes (Zscheischler et al., 2018). The rapid development is primarily driven by the combined effects of different climatic drivers such as precipitation deficits, warmer surface temperature, strong winds, low relative humidity, and higher vapor pressure deficit, which collectively enhance evapotranspiration and accelerate soil moisture depletion (Christian et al., 2019a; Otkin et al., 2013). As soil moisture depletion takes place, atmosphere-land feedback mechanisms may further accelerate drying by increasing sensible heat flux and reduce evaporative cooling. Ford and Labosier (2017) found that variables depicting anomalies in atmospheric evaporative demand or the balance between the supply and demand of surface moisture are closely related to flash drought onset. Similarly, Koster et al. (2019) demonstrated that although precipitation deficit play an important role in flash drought development; however, flash droughts may also develop with near normal precipitation conditions when evaporative demand is exceptionally high (Christian et al., 2021). These findings highlight the complex land-atmosphere interactions governing FD evolution.

Globally flash droughts have been identified as an increasing and spatially widespread climate phenomenon, with hotspot reported across region such as, North America, Africa, Europe and some parts of Asia, including India. Recent studies suggest that climate change, particularly changing precipitation patterns, rising temperature and increasing atmospheric moisture demand, enhancing the frequency, and intensity of FD events worldwide and have raised the concerns regarding food security (Black, 2024; Christian et al., 2024; Das et al., 2020; Hunt et al., 2021; IPCC et al., 2023; Shravan Kumar et al., 2024). Recent global projections further indicate that flash drought occurrence and intensification are expected to increase under future climatic scenarios, particularly over agricultural regions, owing to increasing atmospheric evaporative demand and changing precipitation regimes (Christian et al., 2023). Flash drought can have local as well as regional implications, affecting agricultural crop production and irrigation water requirement at local scale. Sreeparvathy and Srinivas (2022) demonstrated that areas with the highest incidence of meteorological flash droughts are primarily located in arid and semi-arid regions. Numerous previous studies have documented severe crop losses, vegetation stress, and water resources deficits associated with rapidly intensifying drought events in different climatic regions. The 2012 flash drought in the United States had a significant and extensive impact on vegetation, agriculture, and the economy, with more than $30 billion in agricultural losses (Lesinger and Tian, 2022; Liang and Yuan, 2021; Otkin et al., 2016). During the 2013 summer flash drought hit 13 provinces in southern China, destroying almost 2 million hectares of crops in Guizhou and Hunan alone (Yuan et al., 2015). In Russia (2010) flash drought occurred during a sensitive growing stage for winter and spring wheat crops and led to up to 70% lower wheat yields (Hunt et al., 2021). These events demonstrate the severe agricultural, hydrological, and ecological consequences associated with rapidly developing droughts.

In India, drought remains one of the most recurrent climate hazards affecting agriculture and water security. Recent evidence suggests that flash drought events are more common and intense during the crop season across Central India (Ullah et al., 2024). Mahto and Mishra (2020) observed that flash drought affected around 10%-15% of rice and maize crop cultivation lands across India during 1951-2018, and about 40% of country faced severe FDs in 1979. Recent studies further suggest that anthropogenic warming and increasing intra-seasonal monsoon variability are likely to amplify flash drought occurrence across India (Mishra et al., 2021), while Archana et al. (2024) reported increasing flash drought occurrence across several Indian cities under changing climatic conditions. Despite these findings, flash drought research in India remains relatively limited compared with conventional drought studies, particularly at regional and sub-regional scales.

Despite the increasing frequency and ecological consequences of flash droughts (FDs), our understanding of their underlying mechanisms and hydro-climatic drivers over western and central peninsular region of India, particularly across Maharashtra remains limited. Previous studies have often characterized FDs using individual metrics such as frequency, duration, or severity, which may underestimate their cumulative impacts and introduce uncertainties in identifying vulnerable regions (Christian et al., 2019b; Mo and Lettenmaier, 2016). Moreover, although land-atmosphere interactions are known to play a critical role in conventional drought evolution (Berg and Sheffield, 2018), recent studies have considerably improved our understanding of coupled soil moisture-atmosphere feedbacks and their role in flash drought evolution (Christian et al., 2024; Harris et al., 2025). However, their influence on the initiation and intensification of FDs over India particularly across climatically diverse regions such as Maharashtra, remains largely unexplored. Several approaches of flash drought identification have been proposed, including soil moisture percentile thresholds, temperature and evapotranspiration based metrics, evaporative stress indicators, and vegetation-based indicators such as Normalized Difference Vegetation Index (NDVI) and Gross Primary Productivity (GPP) (Gong et al., 2022; Hobbins et al., 2016; Poonia et al., 2022; Qing et al., 2022; Zhang et al., 2020, 2024). Soil moisture-based methods directly represent agricultural and vegetation water stress, whereas atmospheric indicators capture variations in evaporative demand and moisture transport processes in the atmosphere. Although these approaches are effective for monitoring specific aspects of FD development, they primarily represent individual component of the land-atmosphere system. In contrast, the Aridity Index (AI), defined as the ratio of precipitation to potential evapotranspiration, integrates both water supply and atmospheric water demand within a single framework. Consequently AI enable the effective identification of rapid transition from humid to dry conditions that characterizes flash drought onset (Qing et al., 2022). More recently, Poonia et al. (2024) demonstrated the applicability of the aridity index for identifying the characteristics, severity, and triggers of FD under diverse climatic conditions in India. In the present study, the aridity index-based approach was adopted because it incorporates both precipitation and potential evaporation into a single indicator. The AI percentiles capture the rapid changes in moisture conditions and making them suitable to identifying FD events and assessing their severity and intensity. However, understanding of flash drought dynamics and the applicability of AI-based assessments across climatically diverse Maharashtra remains limited, highlighting the need for detailed regional investigations.

Maharashtra is an agriculturally important and drought-prone state of India, characterized by strong climatic variability, recurrent dry spells, groundwater stress and a high dependence on rainfed agriculture, making it highly susceptible to flash drought development (Bagwan, 2025; Kalamkar, 2011; Katalakute et al., 2016). Therefore, understanding the spatiotemporal behavior and driving mechanisms of flash drought in this region is crucial for improving drought preparedness and water resource management. The objectives of this study are: (i) to identify flash drought events and assess their historical characteristics like frequency, duration, intensity, and severity; (ii) to analyze their spatial and seasonal variations across 36 districts of Maharashtra; and (iii) to investigate the key hydro-meteorological drivers responsible for their onset, severity, and intensification. This is essential for timely prediction of flash drought by developing an early warning system and for formulation of mitigation strategies and minimizing their impacts. For the present investigation, high-resolution ($0.25^\circ \times 0.25^\circ$) precipitation and potential evaporation datasets corresponding to 44 years (1981–2024) were considered across 36 districts of Maharashtra.

2. Study area and data used

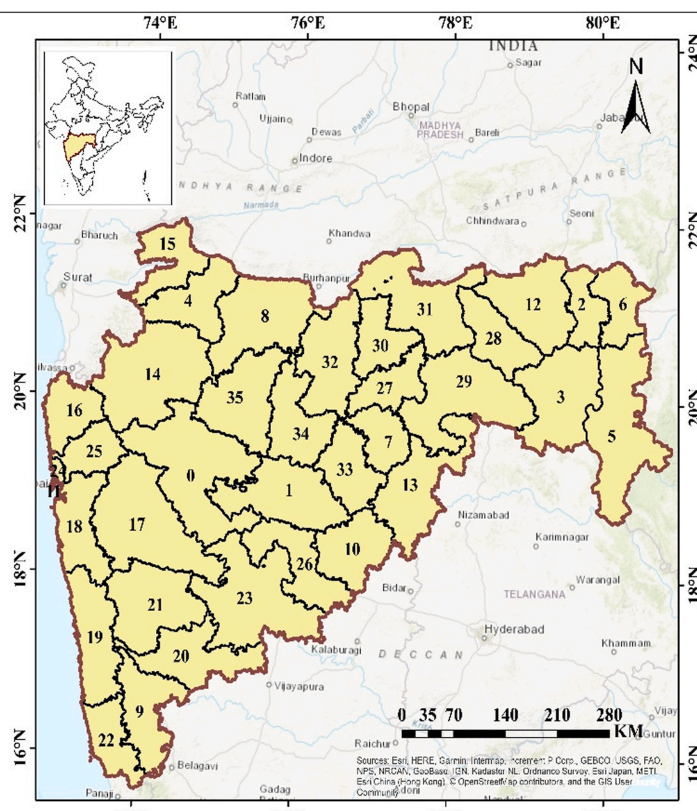
2.1. Study area

The present study was conducted across Maharashtra, a state located in the western India (Fig. 1). Geographically, the state lies between 15°35′N to 22°02′N latitude and 72°36′E to 80°54′E longitude, covering an area of approximately 307,713 km^2 and comprising 36 administrative districts. About 83% of the land area of Maharashtra is characterized by semi-arid climatic conditions (Kalamkar, 2011; World Bank, 2003). The state has a predominantly tropical monsoon climate, with nearly 88.4% of its annual precipitation received during the southwest monsoon season (Jun-September) (IMD Report, 2024). The average maximum temperature ranges from 30 to 40 °C, with peak temperatures generally occurring during March, April, and May (Bagwan, 2025). The state has significant spatial variability in climatic and physiographic conditions, primarily influenced by the Western Ghats, which act as a major orographic barrier to the south west monsoon. As a result, the windward regions including western ghats and coastal region (Konkan) receive high annual rainfall (>2500 mm), whereas the leeward regions, particularly Marathwada and parts of central Maharashtra experience semi-arid to sub-humid climatic conditions with comparatively lower annual rainfall (500-1000 mm) (Gadgil, 2002; Katalakute et al., 2016). These regions are also characterized by high potential evaporation and elevated atmospheric moisture demand, resulting in persistent moisture stress and increased drought risk (Ratna, 2012). This pronounced gradient in precipitation makes Maharashtra highly vulnerable to both meteorological and agricultural drought, around 42.5% area of the state is under drought prone area. According to climate risk mapping the state is exposed to multiple hydro-meteorological hazards, including heat waves, droughts, floods, cyclones, and earthquakes (Development Bank, 2019). Additionally, the state's agriculture is largely rainfed, making it highly sensitive to rapid precipitation deficits and increased evaporative demand. Due to the pronounced spatial heterogeneity in climate, across its districts, make Maharashtra an ideal regional framework for analyzing the occurrence, characteristics and spatiotemporal variability of flash drought events.

2.2. Hydro-meteorological data

Multiple hydro-meteorological datasets were utilized to characterize atmospheric moisture demand, land-atmosphere interactions and water availability for flash drought identification. Daily potential evaporation (Ep) data were obtained from the Global Land Evaporation Amsterdam Model (GLEAM v4.2a) (https://www.gleam.eu/) for the period 1981-2024, available at a spatial resolution of 0.25° × 0.25°. The GLEAM evaporation model integrates satellite-based observations which are primarily derived from multiple sensors like microwave sensors, vegetation optical depth and radiation data to constrain the potential evaporation rates (Martens et al., 2017). The daily gridded precipitation and temperature datasets for the period 1981-2024 were obtained from the India Meteorological Department (IMD) at a spatial resolution of 0.25° × 0.25° and 1° × 1° respectively. This precipitation data set was developed using Shepard's interpolation technique after rigorous quality control procedures to ensure data homogeneity and consistency (Srivastava et al., 2009). Also, daily relative humidity data were collected from the NCAR/NCEP reanalysis dataset. Daily temperature and relative humidity were subsequently used to calculate the vapor pressure deficit (VPD), defined as the difference between saturated water vapor pressure, determined by near-surface temperature, and actual water vapor pressure, determined by dew-point temperature (Qing et al., 2022; Seager et al., 2015).

Daily soil moisture (SM) data covering the period from 1981 to 2024 were obtained from the ERA5 reanalysis dataset developed by European Centre for Medium-Range Weather Forecasts (ECMWF) (https://cds.climate.copernicus.eu/datasets) at a spatial high resolution



Id	District Name	Id	District Name
0	Ahilyanagar	18	Raigad
1	Beed	19	Ratnagiri
2	Bhandara	20	Sangli
3	Chandrapur	21	Satara
4	Dhule	22	Sindhudurg
5	Gadchiroli	23	Solapur
6	Gondia	24	Mumbai Suburban
7	Hingoli	25	Thane
8	Jalgaon	26	Dharashiv
9	Kolhapur	27	Washim
10	Latur	28	Wardha
11	Mumbai	29	Yavatmal
12	Nagpur	30	Akola
13	Nanded	31	Amravati
14	Nashik	32	Buldhana
15	Nandurbar	33	Parbhani
16	Palghar	34	Jalna
17	Pune	35	Chhatrapati Sambhaji Nagar

Fig. 1. Location map of the study area (36 administrative districts of Maharashtra).

0.25° × 0.25° at daily scale. Previous studies have demonstrated that ERA-5 and GLDAS-NOAH soil moisture datasets exhibit superior performance compared with other available products, including ESA-CCI soil moisture, IMDAA soil moisture, and MERRA-2 soil moisture datasets (Cheng et al., 2015; Zawadzki and Kędzior, 2014). To ensure spatial compatibility among the different datasets, all variables were regridded to a common spatial resolution of 0.25° × 0.25° using the bilinear interpolation method, and subsequently aggregated to an octad (8-day) temporal resolution for the period 1981-2024. This harmonization allowed consistent integration of precipitation, potential evaporation, soil moisture and atmospheric variables for subsequent flash drought analysis across the 36 districts of Maharashtra.

3. Methodology

3.1. Flash drought identification using aridity index (AI)

Flash droughts are primarily driven by rapid moisture imbalance caused by precipitation deficits and elevated atmospheric evaporative demand, which accelerate soil moisture depletion and vegetation stress (Ford et al., 2015; Hunt et al., 2014; Otkin et al., 2018; Qing et al., 2022; Wilhite, 2000). Previous studies have shown that atmospheric aridity provides perfect condition for the occurrence of flash droughts (Qing et al., 2022). Therefore, in the present analysis, the Aridity Index (AI) was used as the primary indicator to quantify moisture availability in the land-atmosphere system. The long-term mean annual aridity index map over Maharashtra region presented in Fig. 2 extracted from the data for the period of 1981 to 2024 and classified into categories as suggested by Middleton et al. (1992). The results indicate that Maharashtra is largely covered by semi-arid climatic conditions, with most central and interior regions experiencing moderate water stress and rainfall variability.

Aridity Index (AI) represents the balance between water supply and atmospheric demand and was computed as the ratio of precipitation (P) to potential evaporation (E_P) (Qing et al., 2022). For this, initially aggregated daily precipitation and potential evaporation data 1981-2024 into 8 days average or octad-mean data to reduce the high frequency variability inherent in daily data resulting in 46-time steps per year. Each year is further divided into two seasons: monsoon (19th - 34th octads) and non-monsoon season (residual octads 1st - 18th and 35th - 46th octads). The aridity index was calculated using Eq. (1) for 1981-2024 for each grid cell and octad period using the ratio of precipitation to potential evaporation as expressed in the World Atlas of Desertification (Cherlet et al., 2018; Crapart et al., 2026).

$$\mathrm{AI} = \frac{\sum_{i=1}^{8} \text{Daily Precipitation } (\mathrm{P})}{\sum_{i=1}^{8} \text{Daily Potential Evaporation } (\mathrm{E_P})} \tag{1}$$

The lower values of the aridity index indicate increasing atmospheric moisture demand relative to water supply, reflecting enhanced surface drying conditions. Similar aridity-based indicators have been widely applied for monitoring rapid drought development and hydro-climatic stress (Christian et al., 2019a; Poonia et al., 2024). The detailed methodological framework adopted in the study for flash drought identification and analysis is presented in Fig. 3.

The calculated AI values were fitted into five probability distributions (normal, lognormal, Weibull, Gamma, and Exponential), and the best-fit distribution was obtained using Kolmogorov–Smirnov (K–S) test. To account for spatial and seasonal climatic variability, AI values were transformed into percentile-based anomalies using long-term climatological distribution for each grid cell and corresponding octad. This percentile-based approach enables consistent identification of extreme drying events across heterogeneous climate zones. Flash drought was identified based on the rapid decline in AI percentiles, as shown in Fig. 4. An FD events was defined when the octad AI dropped from at or above

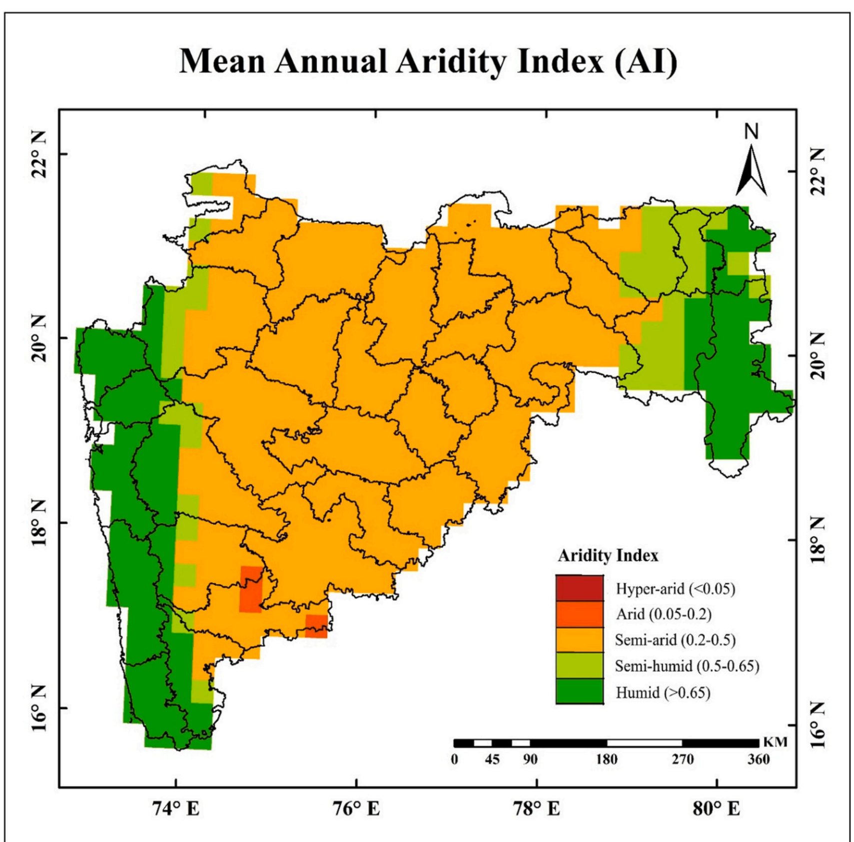


Fig. 2. Spatial distribution of the long-term mean annual Aridity Index (AI) across Maharashtra during 1981–2024.

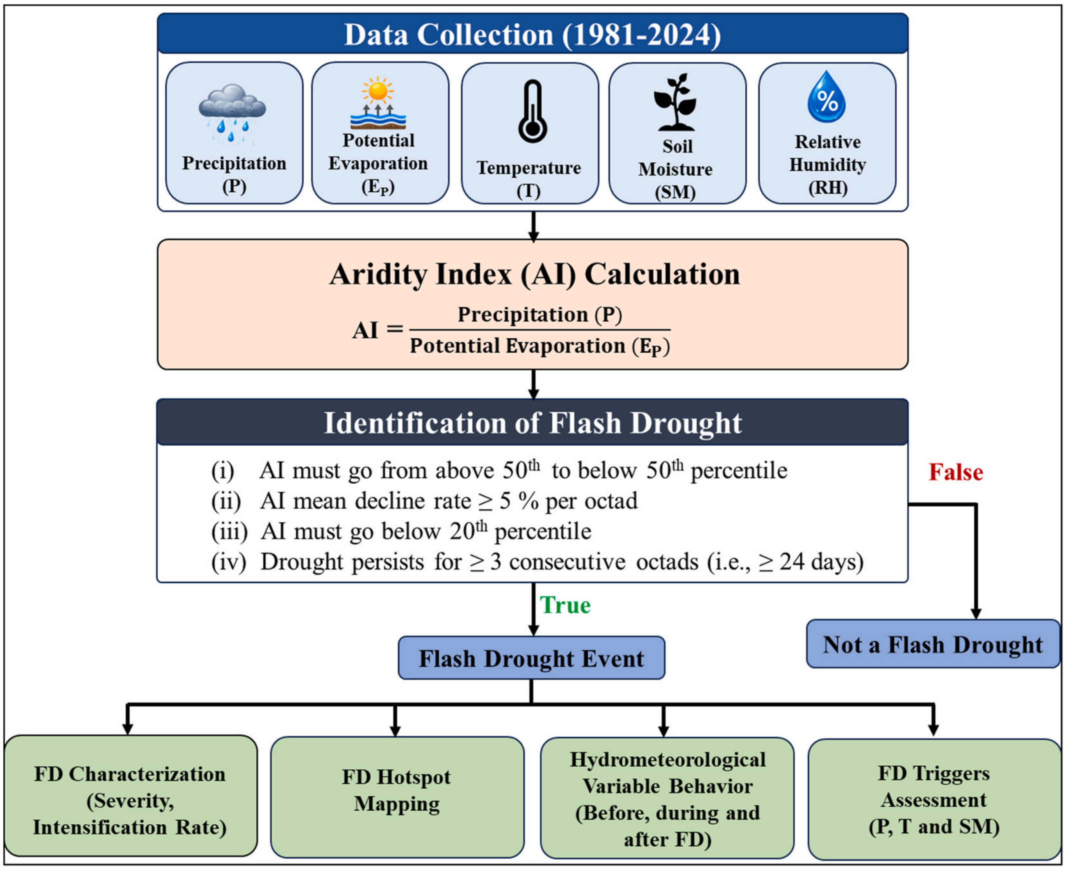


Fig. 3. Methodological framework for flash drought identification and analysis.

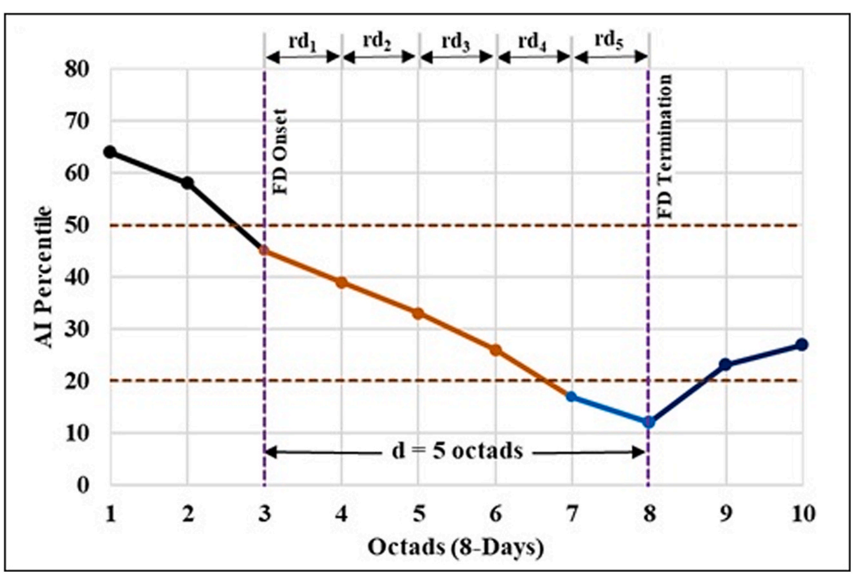


Fig. 4. Schematic representation of flash drought (FD) identification based on the Aridity Index (AI).

the 50th percentile to below the 50th percentile. The event intensifies as AI further declines below the 20th percentile, representing severe moisture deficit condition. The average decline rate was required to be at least 5 percent or more for each octad. The condition indicates a transition from near-normal moisture conditions to severe dryness. These thresholds (50th and 20th) are consistent with the physical interpretation of Aridity Index and its conventional climatic classification, i.e. hyper-arid lands (AI <0.05), arid lands (0.05≤ AI <0.2), semi-arid lands (0.2≤ AI <0.5) and dry sub-humid lands (0.5≤ AI <0.65) (Thornthwaite, 1948). The 50th percentile denotes near-normal moisture availability, whereas 20th percentile represents substantially dry conditions. Consequently, a rapid decline in AI from above the 50th percentile to below the 20th percentile within a short period captures the abrupt moisture depletion that characterize flash drought development. To distinguish flash droughts from short-term fluctuations, a minimum duration of flash drought event was defined as three consecutive octads i.e. 24 days. The 50th and 20th percentiles were determined throughout the same octad for each year over the period of 1981-2024, allowing interannual comparison under similar seasonal conditions. The onset development began at the onset point, defined as the first point where AI percentile values were above 50th percentile threshold and subsequently begin to decline at a rate greater than 5th percentile point per octad. The onset development phase continued until the end point, as the point at which AI percentile dropped below the 20th percentile threshold, indicating the transition into drought condition. The duration between onset starts and end point represents the onset time of flash drought event and characterizes the rapid intensification of drying conditions. After the onset development phase, the drought condition persisted while AI remained below 20th percentile. The FD termination phase was initiated when the rate of AI decline fell below 5 percentile points per octad or when AI exhibited signs of recovery. The FD event was considered ended once AI values exceeded the 20th percentile. This percentile-based rapid intensification approach effectively captures the abrupt onset, persistence and recovery phases of flash drought, thereby distinguishing it from conventional slowly evolving drought events.

3.2. Flash drought characteristics

Flash drought characteristics were quantified in terms of severity, intensification rate, duration, and intensity to assess their spatiotemporal behavior across Maharashtra. Previous studies have primarily relied on soil moisture percentile decline and standardized drought indices to characterize flash drought. However, in the monsoon dependent regions like Maharashtra, where had high rainfall variability and diverse climatic conditions, aridity index (AI) percentile-based approach is adopted as it effectively captures integrated effects of precipitation and atmospheric evaporative demand, which are the key climatic driver for FD development. FD intensification is the rate of decline in hydroclimatic variable and severity is measured by magnitude of deficit during the event period. (Ford and Labosier, 2017; Otkin et al., 2018; Yuan et al., 2019).

In the present study flash drought severity (S) is estimated as difference between Aridity Index (AI) percentile values at the onset and termination of the event (Otkin et al., 2018). The flash drought duration (d) was defined as the total number of consecutive octads during which the event persisted. The FD intensification rate (RD) is the average rate of decline in AI percentile between successive octads from the initiation to the termination of FD event, expressed as:

$$\mathrm{RD} = \frac{\sum_{i=1}^{d} rd_i}{d}$$

Where, $\mathrm{rd_i}$ represents the change in AI percentile values between two consecutive octads and d is the event duration (in octads). The average flash drought intensity (I) was subsequently computed as the ratio of total drought severity to the duration of the event, expressed as:

$$\mathrm{I} = \frac{S}{d}$$

This integrated framework enables a comprehensive characterization of flash drought evolution, including its onset, rapid intensification, persistence, and recovery across climatically heterogeneous regions.

3.3. Trend analysis using Mann-Kandell test

To analyze the long-term changes in flash drought characteristics, the non-parametric Mann-Kendall (MK) test was used. The MK trend test has been widely applied in previous studies to detect monotonic trends in several hydro-climatic extremes including flash drought characteristics (Christian et al., 2021; Sreeparvathy and Srinivas, 2022). In this test, the null hypothesis (H_o) assumes that there is no significant trend in the dataset, while alternative hypothesis (H_1) represents the presence of a statistically significant trend. The statistical significance of the detected trends was assessed using the standardized test statistic (Z), with a confidence level of 95% ($p < 0.05$).

3.4. Flash drought triggers

Previous studies have demonstrated that flash drought development is strongly associated with abnormally high temperatures, prolonged precipitation deficits, soil moisture deficits, or a combination of them (Otkin et al., 2018; Pendergrass et al., 2020). Prolonged precipitation deficits reduce surface water availability, while elevated temperature enhances atmospheric evaporative demand, accelerating evapotranspiration and soil moisture depletion. Therefore, these three climatic variables precipitation (P), air temperature (T), and soil moisture (SM)) and their compound combination were selected as key climatic drivers to explore the underlying mechanisms of flash droughts in Maharashtra region and for detecting trigger for flash drought identification. For this study, we have considered seven driver scenarios, including three single-driver and four compound-driver conditions. In first three scenario only single driver consider:

(i) Precipitation as trigger when Precipitation (P) < 40th percentile with soil moisture (SM) < 40th percentile;
(ii) Temperature as trigger when temperature anomaly ($T_{anomaly}$) exceeding standard deviation (σ) with SM < 40th percentile; and
(iii) Soil moisture as trigger when soil moisture (SM) declines below 40th to below 20th percentile

The compound-driver scenarios were defined as the simultaneous occurrence of their corresponding single-driver conditions:

(iv) Precipitation-temperature (P-T);
(v) Precipitation-soil moisture (P–S);
(vi) Temperature-soil moisture (T-S); and
(vii) Precipitation-temperature-soil moisture (P-T-S).

4. Results and discussion

4.1. Flash drought characteristics

4.1.1. Spatial and seasonal characteristics

The spatial variability of flash drought (FD) characteristics, such as event frequency, mean duration and maximum duration during monsoon (M: 19th–34th octads), non-monsoon (NM: 1st to 18th and 35th to 46th), and their transition periods (from monsoon to non-monsoon and non-monsoon to monsoon season) were determined for the period 1981–2024 and the results are presented in Figs. 5–7.

The analysis indicates a considerable seasonal and spatial variability in FD occurrence across the state. The spatial pattern of FD frequency shows strong seasonal variation across the state (Fig. 5). Frequency is defined as the total number of FD events during the study period (Poonia et al., 2021b; Zhang et al., 2020). The average frequency of flash droughts in Maharashtra generally varied between 1 and 23 events. During the monsoon season (Fig. 5a), FD frequency remained relatively low (<2 events) across most districts, reflecting regular seasonal rainfall and sustained monsoon activity which ensures higher soil moisture and prevents the rapid surface drying. Similar seasonal behavior was also reported in previous studies (Archana et al., 2024; Poonia et al., 2022). However, relatively higher frequencies (5-15 events) were observed in central (Ahilyanagar, Pune) and southern (Sangli, Solapur) part of Maharashtra, indicating the influence of intermittent monsoon breaks. In contrast, the non-monsoon season (Fig. 5b), exhibits a substantial increase in flash drought events (with an average 20.2 events) across the state. Most districts experienced 5-25 events, while southern and coastal

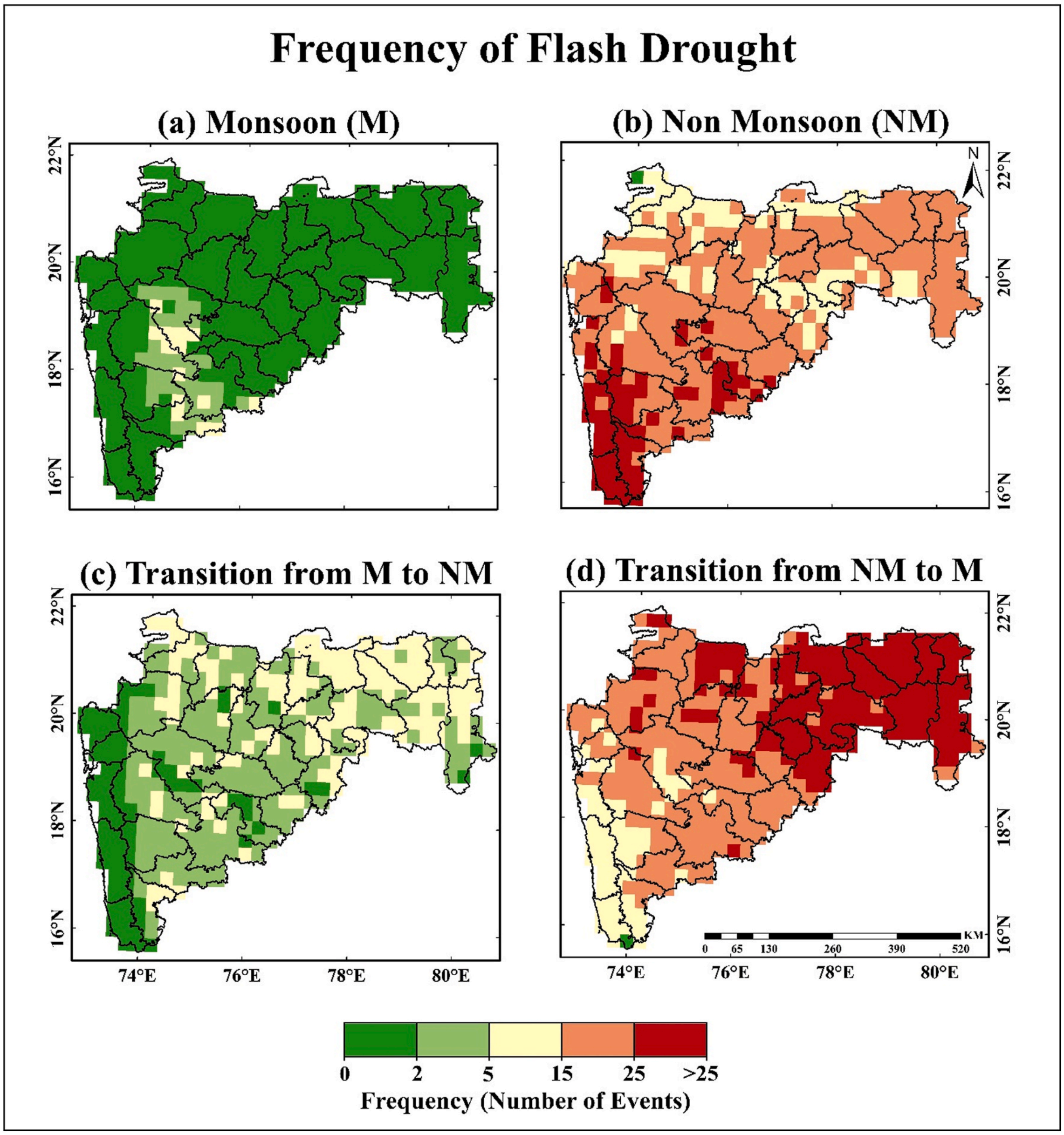


Fig. 5. Mean flash drought frequency across Maharashtra during 1981–2024 for (a) monsoon (M), (b) non-monsoon (NM), (c) monsoon-to-non-monsoon transition, and (d) non-monsoon-to-monsoon transition periods.

regions such as Solapur, Dharashiv, Ratnagiri and Sindhudurg recorded frequencies exceeding 25 events. Christian et al. (2019a) also found that higher flash drought frequency occurs during the pre-monsoon period. During the transition periods, FD frequency was markedly higher during the non-monsoon to monsoon (Fig. 5d) compared with the transition from monsoon to non-monsoon (Fig. 5c), particularly evident in eastern and central districts. This is primarily caused by pre-monsoon heat stress and delayed rainfall accelerate soil moisture depletion which create a favorable condition for flash drought events development.

The spatial and seasonal variability of mean and maximum duration of flash drought event across the Maharashtra also exhibited strong seasonal contrasts (Figs. 6 and 7). In present study mean flash drought duration was calculated as the ratio of the cumulative duration of all the FD events to the total number of events while maximum drought duration represents the longest-lasting individual FD event observed during the study period.

During monsoon season, both mean and maximum duration remained relatively low (average 9.7 and 11 days, respectively) across most districts (Fig. 6a and 7a), especially in western and eastern parts, where frequent rainfall interrupts drought development. However, districts experiencing recurrent monsoon breaks showed relatively longer mean (>25 days) and maximum duration (30-40 days). In the non-monsoon season (Fig. 6b), FD exhibits a substantial increase in mean duration (20-25 days) across most districts especially Thane, Nashik, Palghar and Pune. The relatively low spatial variability during this season suggests that atmospheric evaporative demand, rather than rainfall variability govern FD persistence, consistent with established FD mechanisms (Ford and Labosier, 2017; Otkin et al., 2018). During transition period from monsoon to non-monsoon (Fig. 6c and 7c), FD events are generally short lived (<15 days) with maximum duration varies between 10 and 30 days, across large parts of the state, indicating the role of residual soil moisture from the preceding monsoon. In contrast during the transition from non-monsoon to monsoon (Fig. 6d and 7d), FD events exhibited moderate to longer mean duration i.e. 20-25 days (Fig. 6d), particularly in central and western Parts of the state such as Pune, Satara, Sangli, Kolhapur, Palghar and Nashik. The

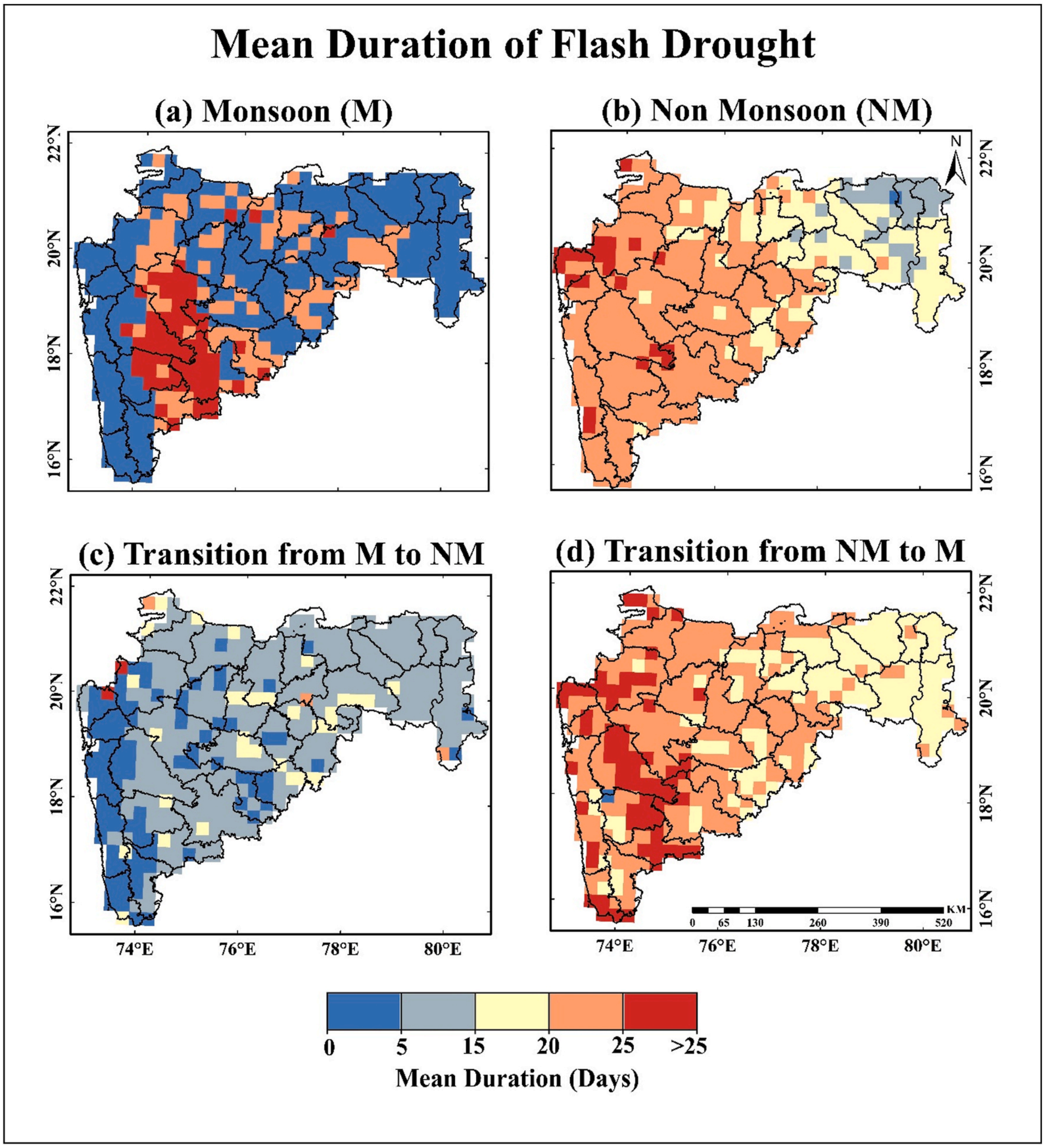


Fig. 6. Mean flash drought duration across Maharashtra during 1981–2024 for (a) monsoon (M), (b) non-monsoon (NM), (c) monsoon-to-non-monsoon transition, and (d) non-monsoon-to-monsoon transition periods.

maximum duration of FD events during this phase ranges from 30 to 40 days in the large part of the state. These findings are consistent with the previous finding (Li et al., 2024). This reflects prolonged pre-monsoon dry conditions, where high temperature and vapor pressure deficit (VPD) accelerate soil moisture depletion prior to the onset of rainfall, thereby sustaining FD events for extended periods (Mo and Lettenmaier, 2016).

Overall, the most critical FD condition occurred during the transition phase from non-monsoon to monsoon, where large area of the state experienced both the highest frequency and longest duration of FD events (more than 30-40 days), followed by non-monsoon season. Result indicates that flash drought events occurrence is strongly governed by seasonal rainfall variability and atmospheric evaporative demand. High frequency during non-monsoon and pre-monsoon periods indicates that these seasons are particularly prone to rapid moisture stress, especially in semi-arid regions, emphasizes the need for drought preparedness, improved drought monitoring and sustainable water management practices.

4.1.2. Hydro-climatic evolution of flash drought

To better understand the physical mechanism of flash drought, the spatio-temporal evolution of hydroclimatic variables during distinct phases of flash drought was analyzed (Fig. 8). The analysis highlights a clear transition from near-normal moisture conditions to rapid drying and subsequent recovery, governed by both meteorological and land-atmosphere interactions. Prior to FD onset (Fig. 8a), near normal precipitation anomalies observed across most districts, accompanied soil moisture availability around 50th percentile (Fig. 8i) and deeply negative vapor pressure deficit (VPD) anomalies (Fig. 8m). In contrast temperature anomalies (Fig. 8e) during this phase were positive, particularly over central and southern regions, suggesting the early development of thermal stress. This indicates that FD events may develop from preconditioned moisture deficiency and thermal stress rather than purity sudden rainfall failure. During the initiation of FD

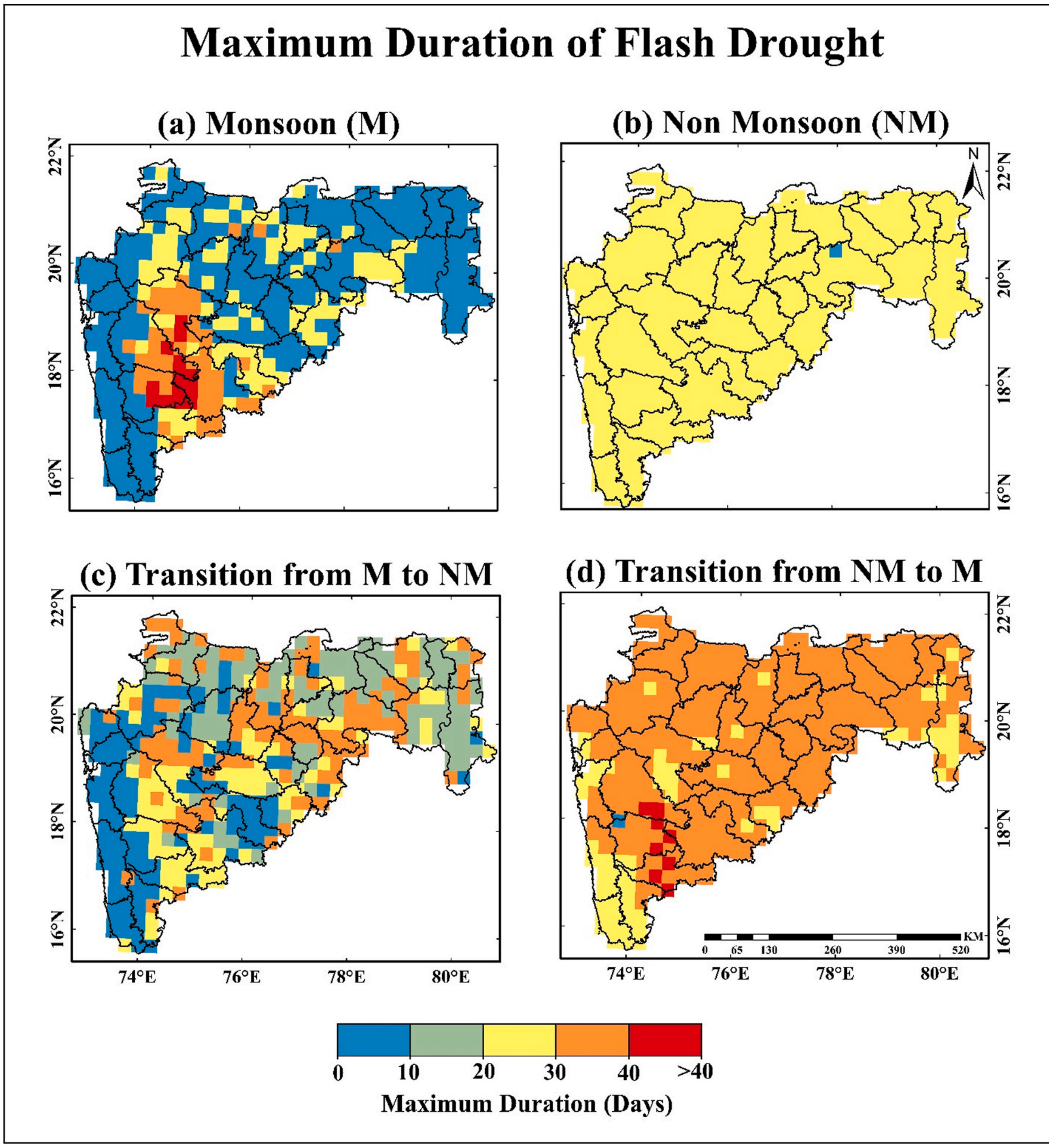


Fig. 7. Maximum duration of flash drought across Maharashtra during 1981–2024 for (a) monsoon (M), (b) non-monsoon (NM), (c) monsoon-to-non-monsoon transition, and (d) non-monsoon-to-monsoon transition periods.

rapid decline in soil moisture percentile, dropping from above 45th percentile to nearly 30th percentile (Fig. 8j). Concurrently widespread negative precipitation and positive VPD anomalies, highlighting the abrupt transition towards moisture stress. SM anomalies play a critical role in constraining evapotranspiration by regulating the flash drought rapid intensification condition (Lu et al., 2026). During the intensification phase, precipitation anomalies became strongly negative all over the region while SM percentile declines approximately 17th percentile, especially in southern and eastern districts (Fig. 8c–k). Simultaneously, persistent positive temperature anomalies remained and elevated over central Maharashtra with localized hotspots in the northeastern region, sustaining high VPD all over the region. These condition collectively enhanced evapotranspiration, leading to rapid soil moisture depletion and increased aridity. Similar mechanisms have been reported in previous studies (Lu et al., 2026; Poonia et al., 2024). However, during the termination phase, all the hydroclimatic conditions showed stabilization. Precipitation anomalies gradually returned to near-normal conditions, while temperature and VPD anomalies weakened across most of the districts. This reduction in atmospheric demand plays a crucial role in limiting further moisture loss. Consequently, soil moisture percentile showed the noticeable recovery toward pre-onset conditions, although residual moisture deficits remained in southern districts (Kolhapur, Sangli, Satara and Sindhudurg) as well as eastern (Gadchiroli) districts.

These results confirm that flash drought evolution in Maharashtra is primarily governed by the coupled effects of precipitation deficits, elevated temperature, increasing atmospheric moisture demand, and rapid soil moisture depletion.

4.2. *Trend analysis of flash drought characteristics*

The long-term changes in the flash drought characteristics including frequency, mean duration and rate of intensification assessed across Maharashtra for the period of 1981-2024 using the non-parametric Mann-Kendall (MK) test at 95% confidence level (Fig. S1). The trend analysis indicates that most regions do not show statistically significant trends, suggesting that FD characteristics largely influenced by

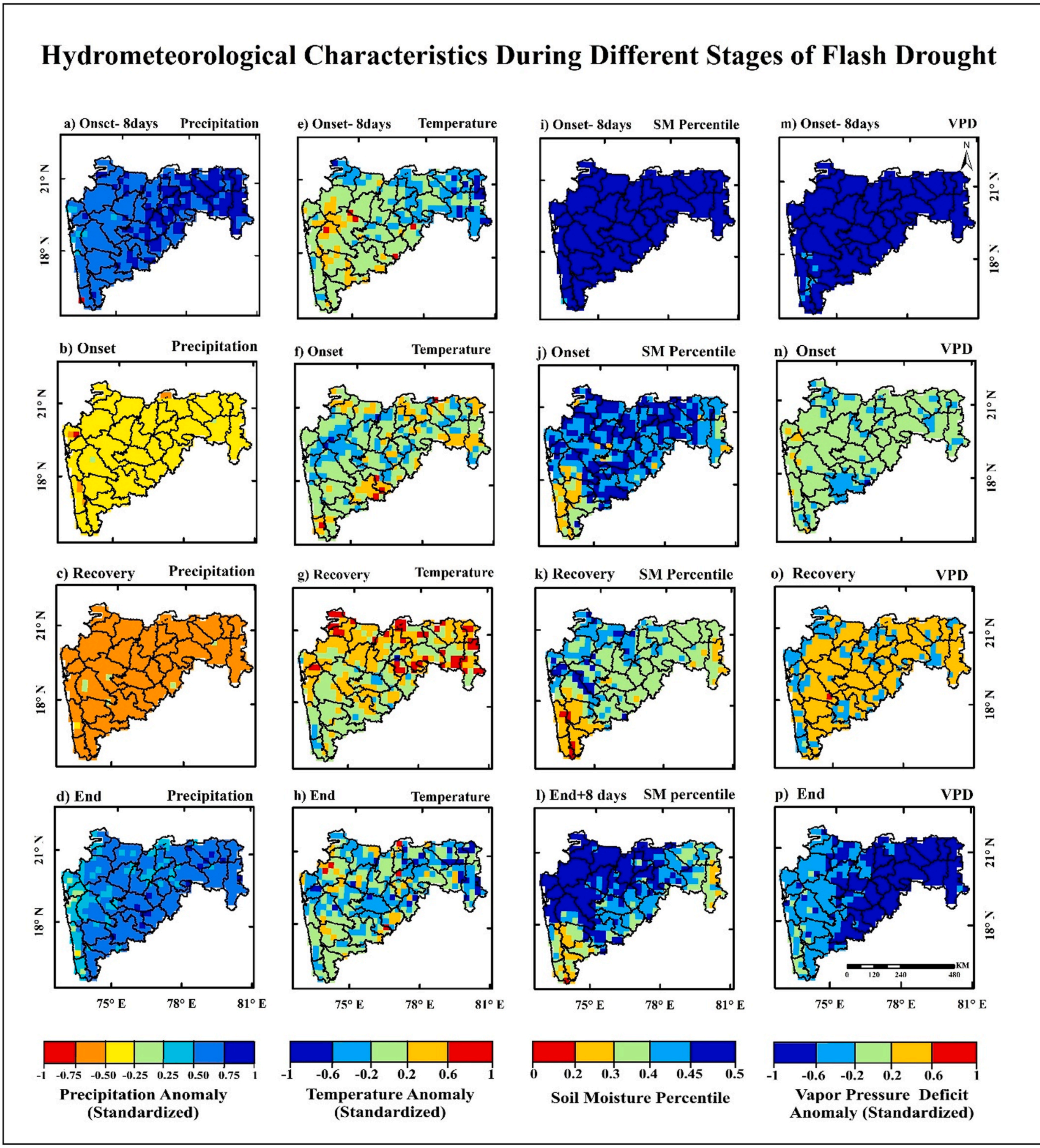


Fig. 8. Hydrometeorological characteristics during different stages of flash drought. The abbreviations SM and VPD refer to soil moisture and vapor pressure deficit, respectively.

interannual variability across Maharashtra. Nevertheless, major parts of the state showing insignificant decreasing trends. The frequency of FD events insignificantly increasing at some parts of the state, particularly in central and western semi-arid districts such as Raigad, Palghar, Thane and Beed, whereas Dharashiv and Wasim showing the significant increasing trend. Similar spatial inconsistencies in FD frequency has also been reported in previous studies (Mukherjee and Mishra, 2022). The mean duration of FD events exhibited insignificantly increasing trends, particularly over central districts (Ahilyanagar, Jalna, Chatrapati Sambaji Nagar) as well as eastern districts (Akola, Amaravati, Yavatmal and Wardha). This suggested that the persistence of FD events is governed by localized hydroclimatic controls and land-atmospheric interactions rather than uniform large-scale drivers (Otkin et al., 2018). In contrast, of the FD intensification rate showed a relatively consistent increasing trend across several districts, even where the frequency and duration trends remained weak. Statistically significant increasing trends were observed in Sindhudurg and Solapur districts, possibly may be due to high temperature and sparse vegetation cover and strong soil moisture and temperature interaction, accelerate the rapid surface drying. These findings indicates that FD behavior is evolving gradually with some hotspots rather than uniform, state-wide trend.

4.3. Flash drought severity and rate of intensification

The spatial distribution of FD severity and intensification rate across Maharashtra during period 1981-2024 shows the strong spatial variability and coupling between magnitude and speed of drought development (Fig. 9). FD severity is the net change in AI percentile during flash drought event, representing the overall magnitude of moisture deficit, while rate of intensification refers to the average rate of decrease in AI percentile between successive octads (% per octad), indicating the speed of drought development (Yuan et al., 2019).

The results reveal that most parts of Maharashtra characterized by low to moderate FD severity (<4%), and intensification rates (<6%), suggesting relatively gradual moisture depletion under normal hydroclimatic conditions. However, some semi-arid districts such as Ahilyanagar, Beed, Dharashiv, Sangli and Solapur exhibit comparatively high FD intensification rates (6-9% and locally >9%) and severity levels (4-6% and locally >6%), indicating rapid moisture depletion and more severe drought conditions. Such findings are consistent with previous finding, over semi-arid regions, where rapid soil moisture decline and strong land-atmosphere interaction play a key role in drought development (Christian et al., 2019a). This indicates that when there is a co-occurrence of high severity and rapid intensification, then there is limited time for soil moisture restoration, resulting in more severe moisture stress conditions. In contrast, eastern districts such as Bhandara, Gadchiroli, Gondia, and Wardha, as well as coastal districts such as Ratnagiri, Palghar, Thane and Sindhudurg, exhibited lower severity and slower intensification rates. This can be attributed to significant rainfall distribution, humid climatic conditions, and moisture retention, which further reduce the possibility of rapid surface drying.

4.4. Flash drought triggers

In the present study precipitation, temperature and soil moisture consider as the primary climatic drivers and their individual and combined effects were analyzed to understand the FD occurrence and development across Maharashtra during period 1981-2024 (Fig. 10). These potential FD drivers generate heat stress and water stress, which can adversely affect agricultural productivity, water resources availability and vegetation dynamics (Banerjee et al., 2013; Gerken et al., 2018).

The analysis demonstrates that flash droughts across Maharashtra are predominantly precipitation deficit driven, with additional modulation from temperature and antecedent soil moisture interactions. It was observed that the precipitation deficit emerged as the main trigger for FD development across large parts of western and central Maharashtra, including districts such as Pune, Ratnagiri, Sindhudurg, Nashik, Kolhapur and Satara. (Mukherjee and Mishra, 2022; Otkin et al., 2018). This highlights the dominant role of monsoon variability and intra-seasonal dry spell in triggering FD events, consistent with previous studies over India (Jain et al., 2010; Mishra et al., 2021; Mukherjee and Mishra, 2022; Otkin et al., 2018). Temperature alone has limited impact on occurrence of FD events; however, the combined precipitation and temperature mechanism is much more evident in FD intensification, particularly across eastern and northeastern regions such as Wardha, Yavatmal and Nagpur. These results suggest that under rainfall deficit conditions, high temperature enhances atmospheric evaporative demand, accelerating soil moisture loss and intensifies FD development. Similar findings have been reported in previous studies (Bagwan, 2025; Nguyen et al., 2019; Otkin et al., 2013). Such coupled effects of precipitation and temperature have been widely recognized as critical driver of rapid drought development (Pendergrass et al., 2020; Yuan et al., 2019). A distinct hotspot was identified over central Maharashtra, especially around Solapur and its adjoining areas influence by compound interaction of all three drivers P-T-SM (Precipitation-temperature-soil moisture). This indicates that FD evolution in these semi-arid areas is strongly controlled by land-atmosphere interaction, including antecedent soil moisture conditions. Similar soil

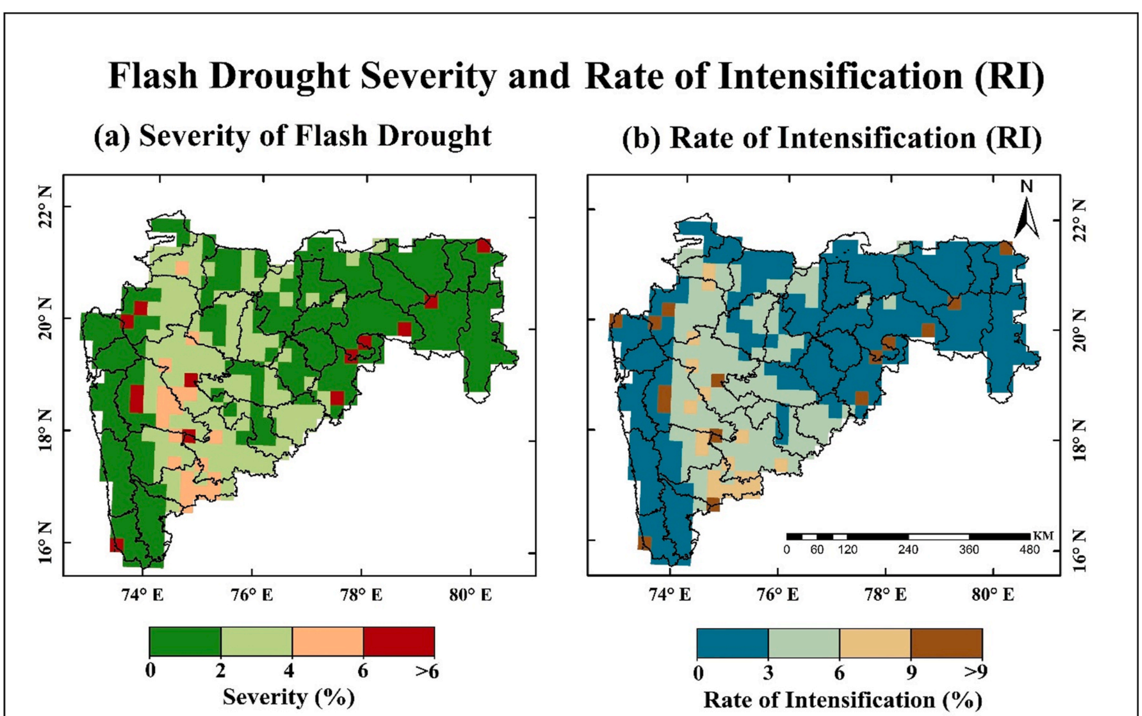


Fig. 9. (a) Severity and (b) rate of intensification of flash droughts, across Maharashtra during the period 1981–2024.

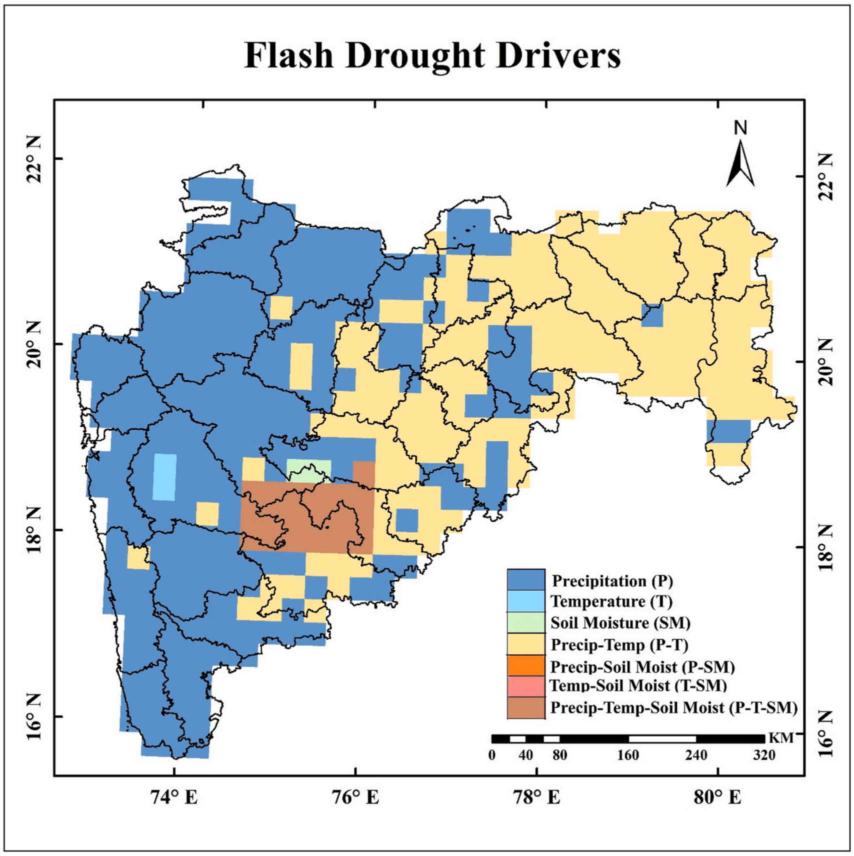


Fig. 10. Flash drought drivers across Maharashtra during the period 1981–2024.

moisture–temperature feedback mechanisms have been reported in studies (Seneviratne et al., 2006; Stacke and Hagemann, 2016).

Overall, the results suggest that FDs in Maharashtra are largely precipitation driven, their subsequent intensification and persistence are strongly influenced by temperature anomalies and soil moisture–atmosphere interactions. These findings emphasize the importance of incorporating compound hydro-climatic drivers into regional flash drought event monitoring framework that can improve the identification of vulnerable regions and strengthen early warning capabilities for rapidly developing drought events.

5. Conclusions

Flash droughts have emerged as one of the critical hydroclimatic hazard due to their rapid onset, limited predictability time and severe impacts on agriculture and crop productivity, ecosystems and water resources. In this study, a comprehensive assessment of the spatiotemporal characteristics, long-term trend, hydro-climatic controls, triggering mechanisms of flash droughts across Maharashtra using an Aridity Index (AI) based approach for the period of 1981-2024. Using High-resolution hydro-meteorological datasets, AI percentile-based framework was used to for flash droughts identification and analyze their occurrence, evolution, characteristics hotspots, drivers, and trends over 36 administrative districts across Maharashtra during monsoon, non-monsoon and their transitions period. This study will help in regional scale understanding of FD dynamics by identifying potential hotspots, seasonal variability and key hydroclimatic triggers, which will support in developing early warning systems and climatic resilient agriculture and water management.

The results revealed significant spatial and seasonal variability in flash drought occurrence across Maharashtra. The transition phase between non-monsoon to monsoon season identified as the most vulnerable phase, exhibiting highest occurrence of flash drought events and the longest durations, followed by the non-monsoon season. In contrast, FD events during the monsoon season remained relatively low and was primarily confined to semi-arid region of central Maharashtra. Spatial analysis showed that the FD events occurred more frequently in sub-humid and humid region such as Gadchiroli, Chandrapur, Bhandara are the hotspots for flash drought events, whereas the semi-arid interior districts, particularly Ahilyanagar, Beed, Dharashiv, Sangli, and Solapur, experienced comparatively more severe and rapidly intensifying FD events, highlighting their greater hydro-climatic vulnerability. The hydro-meteorological variables behavior analysis revealed that FD development is primarily governed by the combined influence of precipitation deficits, rapid soil moisture depletion, elevated temperature, and increasing vapor pressure deficit (VPD), highlighting the critical role of land–atmosphere coupling in driving the initiation and evolution of FD events. Furthermore, trigger analysis revealed that precipitation deficit is the dominant driver of FD initiation across Maharashtra, whereas temperature anomalies and antecedent soil moisture deficits play a crucial role in controlling FD intensification and severity, particularly over semi-arid regions which exhibits enhanced hydro-climatic sensitivity and rapid soil moisture depletion.

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CRediT authorship contribution statement

Vikas Poonia: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Writing – original draft. **Deepika Yadav:** Software, Visualization, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations:

FD: Flash Drought; AI: Aridity Index; GLEAM: Global Land Evaporation Amsterdam Model; IMD: India Meteorological Department; VPD: Vapor Pressure Deficit; SM: Soil Moisture; ECMWF: European Centre for Medium-Range Weather Forecasts; NM: Non-monsoon; M: Monsoon, E_P: Potential Evaporation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pce.2026.104701.

Data availability

Data will be made available on request.

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