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# Drivers of flash floods in the Indian sub-continental river basins

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Flash floods occur every year during the summer monsoon season in India, causing substantial damage to agriculture, infrastructure, and human life. Despite their profound implications, flash flood hotspots remain unknown, hindering adaptation efforts. Here, we use hydrological and geomorphological characteristics to map the flash flood prone sub-basins in the Indian sub-continent. Flash flood hotspots are mainly centered in Himalayas, West Coast, and Central India, with geomorphological factors driving flash floods in the Himalayas and hydrological factors (flashiness) in the West Coast and Central India. The combination of extreme precipitation and wet antecedent conditions trigger most (~ 3/4th) flash floods while the remaining (~ 1/4th) are solely driven by extreme precipitation. Several non-flash flood prone basins have experienced a significant increase in extreme precipitation frequency and intensity, highlighting that the warming climate can lead to newer flash flood hotspots in the future.

Flash floods are one of the most devastating natural hazards with over 5000 deaths annually and considerable social, economic, and environmental impacts<sup>1</sup>. Flash floods are defined as sudden floods caused by extreme rainfall events<sup>2,3</sup>. Flash floods usually occur in a very short span of time after an extreme precipitation event, usually less than six hours<sup>4</sup> and characterized by sudden rise and recession of high flow over localized areas, which makes them extremely unpredictable and disastrous<sup>5-7</sup>. Flash floods cause the highest mortality rate (ratio of death to the people affected) compared to riverine and coastal flooding<sup>1</sup>.

India is highly susceptible to floods as more than 40 million hectares of geographical area is flood prone (NDMA, <https://ndma.gov.in/Natural-Hazards/Floods>). Several river basins and urban areas (Mumbai, 2005; Leh, 2010; Uttarakhand, 2013; Jammu and Kashmir, 2014; Chennai, 2015; Kerala, 2018; Bihar, 2019; Hyderabad, 2020; Assam, Meghalaya, Arunachal Pradesh, 2022; Assam, 2024) experienced flash floods in the past decade (EM-DAT), which severely impacted infrastructure and agriculture in India. The low-lying river basins in India are highly susceptible to flash floods<sup>8</sup>. The occurrences of high intensity rainfall in a short duration causing flash floods are on the rise even in rainfall scarce regions, such as semi-arid region of western India<sup>9</sup>. The rising frequency of flash floods and substantial economic losses underscore the need to reinforce the flash flood preparedness across the nation.

The combination of meteorological, geomorphological, and anthropogenic factors attribute to the occurrence of flash floods<sup>10,11</sup>. The intense rainfall associated with tropical cyclones and the summer monsoon is a primary driver of flash floods<sup>12</sup>. Saturated soil or impervious surface

exacerbates flash flooding by causing instant runoff. Conversely, in arid regions such as desert landscapes the dry soil may lead to quick surface runoff generation<sup>13</sup>. Cloudbursts events, which are defined as precipitation events exceeding 100 mm/hour intensity, cause flash floods in hilly terrains<sup>14</sup>. In addition, dam breach or sudden release from dams can result in flash floods<sup>15</sup>. Along with the extreme rainfall, the geomorphology of the region also plays an important role in deciding the inundation extent and severity of flash floods<sup>16-18</sup>. Morphometric parameters like basin relief, drainage characteristics, and basin shape promote higher flood peaks and runoff<sup>19</sup>. In addition, basin shape can favor flash flood occurrence as circular basins cause higher runoff in less time compared to elongated basins<sup>20</sup>. Extreme rainfall at steep slopes and higher topographic relief can increase flash flood severity<sup>10,21</sup>. For instance, regions like Assam and Arunachal Pradesh are more flash flood prone due to their location at the foothills of Himalayas, which receives orographic precipitation.

The frequency of flash floods in India is projected to increase under the warming climate<sup>22,23</sup>. Rising global mean temperature is linked to increased moisture holding capacity of the atmosphere, which can result in intense and more frequent rainfall events<sup>24-26</sup>. In India, the summer monsoon season has become more erratic with prolonged dry periods followed by intense rainfall events<sup>27</sup>. Despite a long-term decline in mean precipitation, an increase in the intensity and frequency of extreme precipitation events<sup>28</sup>, can trigger flash floods. Precipitation variability, driven by climate change, poses significant challenges for managing and mitigating flash flood risks<sup>29</sup>. Unlike other hydro-meteorological hazards, flash floods are not location specific<sup>30</sup>. Every location where extreme rainfall occurs can be prone to flash

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floods, therefore, examining flash floods and their hotspots under the warming climate is essential. Moreover, identifying and mapping flash flood prone areas will help in flash flood mitigation measures and aid in regulating development in susceptible regions<sup>31,32</sup>.

Implementation of effective flash flood early warning systems is crucial for timely preparedness and evacuation<sup>33</sup>. The lack of high-resolution climate simulations makes it challenging to quantify the changes in flash flood risks<sup>34</sup>. Insufficient number of rainfall records and observing systems at hourly scale hampers effective flood detection and forecasting<sup>1,4</sup>. Furthermore, there is a need for improved integration of satellite and ground-based observations to enhance flood monitoring capabilities<sup>25</sup>. The effectiveness of flood risk management is hindered by a lack of awareness of potential flash flood risk zones<sup>35</sup>. As the vulnerability and the population exposed to floods are increasing<sup>36,37</sup>, examining the flash flood risk across the regions is crucial. As most flash floods typically originate from small catchments in complex terrains<sup>38</sup>, a sub-basin scale flash flood risk assessment is needed in India incorporating the hydro-meteorological aspects as well as the geomorphological aspects. Considering this as prominent research gap, we aim to identify the flash flood prone sub-basins in India considering meteorological and geomorphological characteristics. We find that flash floods in the Himalaya region are driven by the geomorphological factors while flash floods in central India and western ghats are mainly controlled by the flashiness index. In addition, geomorphological and hydrological factors control flash floods in the Indian sub-continent regardless of the size of the basins. Most flash floods in the sub-continent occur due to the combination of wet antecedent soil moisture and extreme precipitation. Our findings highlight that the changing rainfall characteristics can alter flash flood

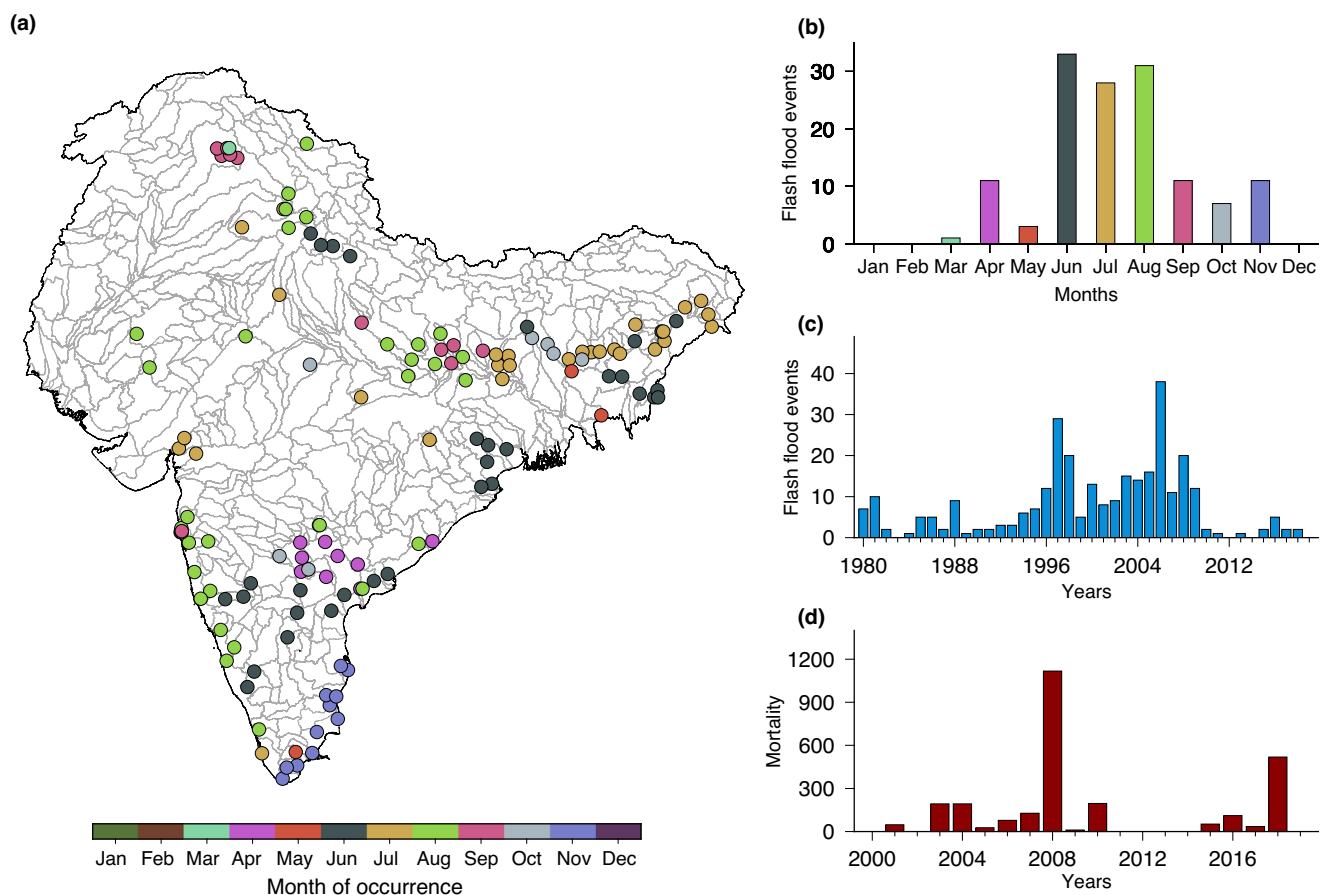
hotspots in the future under warming climate, underscoring the need for adaptation.

## Results

### Spatial and temporal distribution of observed flash flood events

First, we examine the spatial and temporal distribution of observed flash flood events across India using the observed flood events dataset from EM-DAT and India flood inventory (Fig. 1). More than 75% of the total flash floods in India occurred during the summer monsoon season (June–September). However, the south-east coast witnesses flash floods during October–December period, which is primarily affected by the Indian winter monsoon<sup>39</sup>. Unlike the other parts of the country, flash floods also occur in Andhra Pradesh during the pre-monsoon (April–May) season. Flash floods do not occur during the winter season except for the region influenced by the Indian winter monsoon. Flash floods in the summer monsoon and post-monsoon seasons are caused by the heavy rainfall and cyclonic activities that take place during the south-west and north-east monsoons, respectively<sup>40,41</sup>. The pre-monsoon season is characterized by convective thunderstorms that cause flash floods, especially near the foothills of Himalayas, south-east and south-west coasts, and eastern India<sup>42</sup>.

South-east peninsular India experiences extreme precipitation events due to the cyclonic events and depressions that take place in the southern Bay of Bengal<sup>43</sup>. Roxy et al.<sup>28</sup> reported that the change in local precipitation across central India is primarily influenced by the atmospheric dynamics rather than local thermodynamics. The increase in extreme precipitation events across central India is attributed to the surge in moisture supply caused by the variability in low-level monsoon westerlies over the Arabian



**Fig. 1 | More than 75% of the flash floods in India occurred during the summer monsoon season. a** The locations in which flash floods were observed during 2001–2018 and its month of occurrence using EM-DAT data. **b** The seasonality (month of occurrence) of observed flash flood events in the period 2001–2018 using

EM-DAT data. **c** Year-wise total number of flash flood events that occurred in the period 1980–2018 using data from India flood inventory. **d** Year-wise mortality due to flash floods in the period 2001–2018 using EM-DAT data.

Sea<sup>44</sup>. On the other hand, the Himalayan region receives moisture from different sources that can result in extreme precipitation and cloudburst events<sup>10</sup>. The cloudburst events that occur in monsoon season across lower Himalayan region (particularly in western parts) cause localized flash floods, debris flows and landslides<sup>45</sup>. In addition, cloudbursts that are driven by intense convective activity and influenced by mid-latitude and polar jet streams are observed in pre-monsoon season<sup>46</sup>.

Among the river basins, most of the observed flash floods occurred in the Brahmaputra River basin followed by Ganga and Krishna River basins (Fig. 1). We find an increase in the total number of flash flood events reported in India after 1995 (Fig. 1b). The widespread flash flood events that happened across India (majorly affecting Assam province and East Coast) in summer and winter monsoon of 2008 caused severe casualty (Fig. 1c). The yearly frequency of extreme precipitation events in India has doubled during the pre-monsoon season<sup>42</sup>. Moreover, significant increases of 56%, 40%, and 12.5% in extreme precipitation are reported during the monsoon, post-monsoon, and winter seasons, respectively<sup>42,47–49</sup>. The increase in the intensity and frequency of extreme precipitation in the Indian sub-continent can be attributed to the warming climate<sup>24,50,51</sup>. Climate change drives frequent and intense extreme precipitation events through increased atmospheric moisture, ocean warming, and altered monsoon dynamics<sup>52–60</sup>. Heavy rainfall and rainfall on saturated soil can lead to flash floods and riverine floods in the Indian sub-continental river basins<sup>61,62</sup>.

### Identification of flash flood prone sub-basins

We identify the flash flood prone sub-basins by analyzing flashiness index, geomorphology, and a combination of both factors (Fig. 2). Sub-basins in central India and west coast are highly susceptible to flash floods based on flashiness index (Fig. 2a). The sub-basins with high flash flood susceptibility have flood hydrograph slopes which highlight short time to peak flow. We find highly flash flood prone sub-basins to have an average flood hydrograph slope (flashiness) greater than 85° (Supplementary Fig. 1). Sahara et al.<sup>63</sup> reported extreme rainfall overwhelms geomorphological characteristics of the basin, making the distribution of rain and flashiness the primary driver of flash flooding. However, flashiness index does not account for the terrain's shape, slope, or drainage structure, which can considerably affect the water movement through a landscape<sup>63,64</sup>. The flashiness index quantifies the speed and variability of streamflow response to rainfall. The flashiness index connects hydrological behavior (rainfall patterns, water flow rates) to the physical landscape<sup>65</sup>. Flashiness index indicates how quickly runoff occur in a basin. Hence, it can distinguish areas prone to rapid rise in water level causing flash floods.

Flash flood susceptibility based on geomorphology distinguishes the hilly terrains and Himalayan region as the most flash flood prone (Fig. 2b). The geomorphological parameters including relief ratio, relative relief, drainage texture, stream number, length of overland flow and ruggedness number highlight the highly flash flood prone sub-basins (Supplementary Fig. 2). Vig et al.<sup>66</sup> reported that drainage texture and relief ratio directly impact flash flood occurrence while elongation ratio have an inverse relationship with flash flood intensity in the low mountain regions. Similarly, Ahmed et al.<sup>67</sup> reported that length of overland flow as one of the significant predictors for flash flood susceptibility. While flashiness index provides dynamic information of the water behavior in response to extreme rainfall events, geomorphological characteristics of river basins help us understand the role of physical landscape in channeling and storing water. Morphometric features like slopes, drainage networks, and soil types create local differences in flood susceptibility<sup>68</sup>. For instance, morphometric features like steep slopes and narrow valleys can concentrate streamflow, increasing flood intensity in certain areas. Similarly, complex drainage patterns, such as dense networks or poorly defined channels, influence where and how flooding occurs.

Flashiness index captures the speed of flood response but overlooks terrain features, whereas geomorphology focuses on landscape but ignores how fast runoff builds up. Hence, we identify the flash flood prone regions by considering both flashiness index and geomorphological characteristics (shape, drainage, and relief characteristics) of the sub-basins. We find that

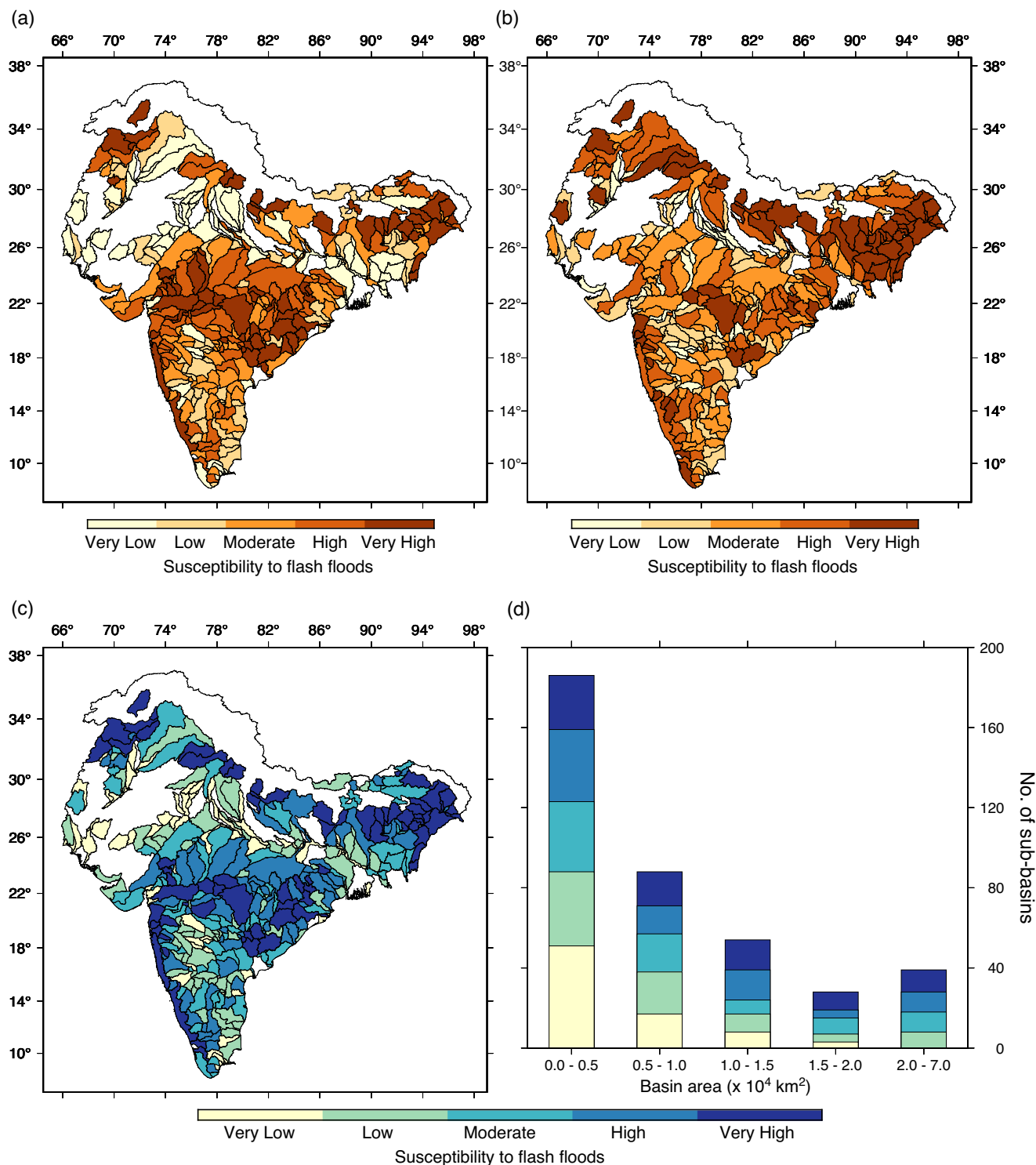
the hilly terrains, the west coast, and central India are prone to flash flooding (Fig. 2c). Despite having a high basin relief, a few sub-basins in the hilly terrains are less flash flood prone due to their low flashiness index. In contrast, a few sub-basins with low flashiness index are flash flood prone due to high elongation ratio and drainage texture. We identified the differences in the flash flood susceptibility based on the flashiness index, geomorphology, and combined indices (Supplementary Fig. 3). In some regions, like central India, flash flood susceptibility is primarily influenced by runoff characteristics as indicated by the flashiness index. In contrast, areas such as the Himalayas are more dominated by geomorphological characteristics, including slope, drainage patterns, and landforms. This spatial variation in susceptibility highlights the significance of both geomorphological and hydrological factors in accurately assessing flash flood risks across different landscapes.

Sub-basins in Brahmaputra, Narmada, Tapi, Mahanadi, Brahmani, and West Coast River basins are extremely prone to flash floods. Parts of the Godavari, Ganga, Mahi, and Indus River basins are also highly susceptible to flash floods. Most of the sub-basins that are susceptible to flash floods lie in the Brahmaputra River basin followed by Ganga River basin and Godavari River basin. However, these account for only 45%, 21% and 36% of the total sub-basins that lie in Brahmaputra, Ganga and Godavari River basins, respectively. In West Coast, five out of six sub-basins are extremely flash flood prone, which is vulnerable to cloudbursts and flooding from moderate to high intensity rainfall which is followed by prolonged wet spells<sup>69</sup>. On the contrary, many of the low susceptible regions lie in Ganga, Indus, and Godavari River basins. Flash flood susceptibility varies widely within the major river basins. For instance, the sub-basins located in the Himalayan regions and southern parts of the Ganga River basin are highly prone to flash floods, whereas the sub-basins in the central regions of Ganga River basin exhibit low flash flood susceptibility. This variation in flash flood susceptibility underscores the influence of terrain and climatic factors on flood risk within different parts of the same river basin.

We examined the relation of flash flood susceptibility to basin size (Fig. 2d). Karmokar and De<sup>70</sup> reported that in hilly terrains the sub-basins of smaller to medium size are susceptible to frequent flash floods due to less time of concentration and time to peak. In contrast, Bhat et al.<sup>71</sup> found that larger sub-basins are more susceptible to flash floods compared to smaller sub-basins in the Jhelum River basin of the Himalayan region in India. We find that the larger sub-basins (greater than  $2 \times 10^4$  km<sup>2</sup> of area) are also highly susceptible to flash floods (Fig. 2d). Additionally, 47% of the smaller sub-basins (less than  $0.5 \times 10^4$  km<sup>2</sup> of area) show lower susceptibility to flash floods, whereas 54% of the large sub-basins have higher susceptibility to flash floods. For the sub-basins of size ranging from  $0.5 \times 10^4$  km<sup>2</sup> to  $2 \times 10^4$  km<sup>2</sup>, 44% of the sub-basins are highly flash flood prone, 20% are moderately flash flood prone, and 36% are less flash flood prone. The high flash flood susceptibility in larger sub-basins can be attributed to the high peak flow rate especially if they are located on high relief, which can cause high magnitude flash floods. Morphometric parameters, such as basin relief and drainage texture, which is independent of the basin size, also play a vital role in deciding the flash flood susceptibility. Nikolopoulos et al.<sup>72</sup> suggest that initial wetness conditions and rainfall intensity are more critical than basin size in triggering flash floods. While basin size can affect how these factors (antecedent wetness and rainfall) influence the flood response, it does not directly determine whether a flash flood will occur. Hence, flash floods are driven by the flashiness and geomorphological characteristics of the basins regardless of their size. Therefore, it is vital to understand the association of precipitation and flash floods within these sub-basins.

### Association between extreme precipitation and flash floods

Next, we examine the association between precipitation and flash floods by calculating the percentile of the maximum hourly precipitation prior to the streamflow peaks and its time lag (Fig. 3). We evaluated the percentile of hourly precipitation at 0-hour (at the same time as the flood) to 24 h prior to the streamflow peaks and identified the hour that recorded maximum precipitation. Similarly, we examined precipitation 0 to 72 h prior to the

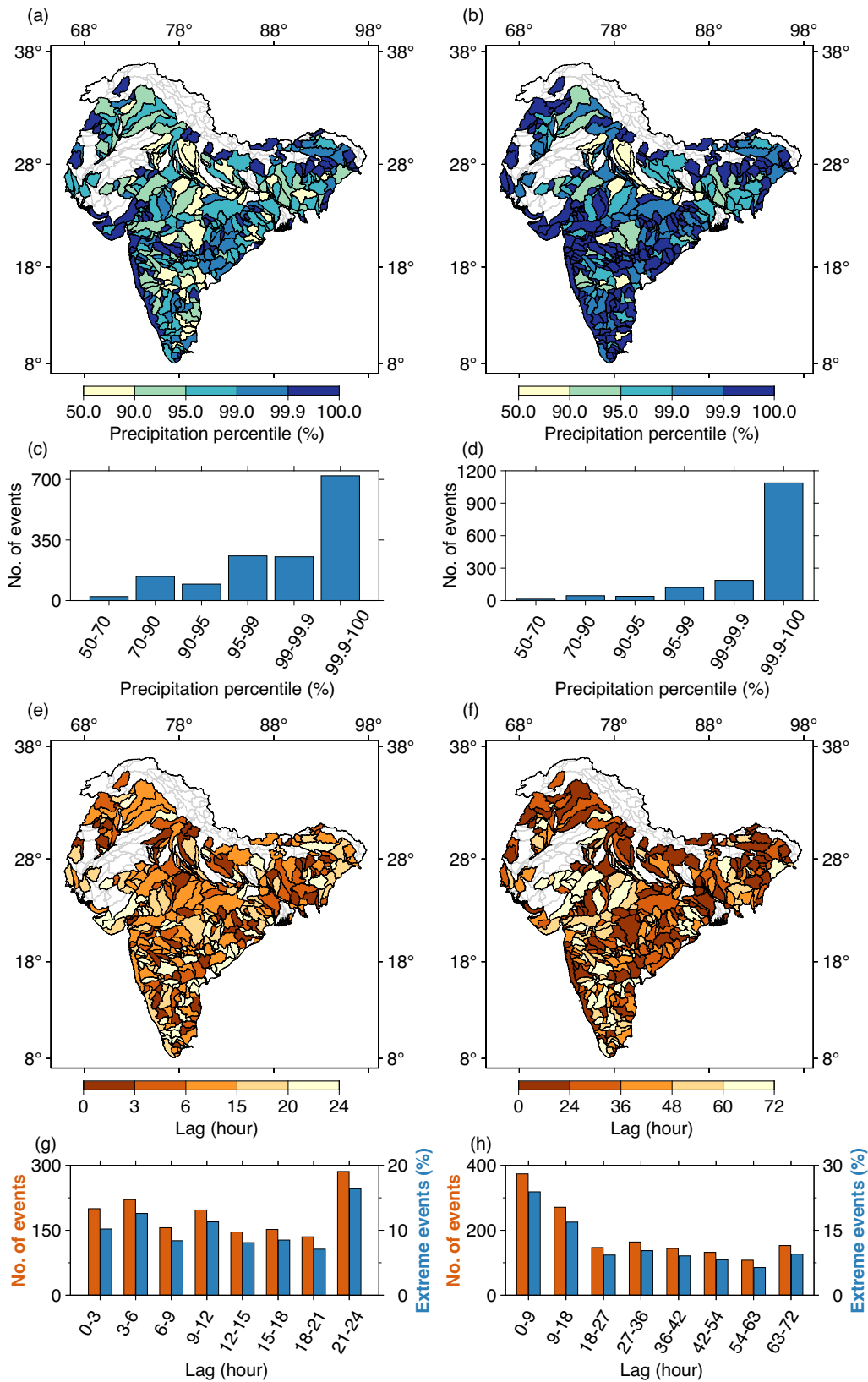


**Fig. 2 | Himalayas, west coast and central India are the most flash flood prone regions. a** Sub-basins classified according to its susceptibility to flash floods based on flashiness index. **b** Sub-basins classified according to its susceptibility to flash floods based on geomorphology. **c** Flash flood prone sub-basins based on flashiness index and geomorphology. The susceptibility scale values of all maps are normalized into

the following classes: (i) Very low susceptibility: 0–0.2 (ii) Low susceptibility: 0.2–0.4 (iii) Moderate susceptibility: 0.4–0.6 (iv) High susceptibility: 0.6–0.8 (v) Very high susceptibility: 0.8–1.0. **d** The histogram showing distribution of basin area for the sub-basins of different flash flood susceptibility based on flashiness index and geomorphology.

flash flood events. Investigating precipitation for longer durations prior to flash floods helps in evaluating the causative precipitation as well as its contribution to the antecedent moisture condition of the sub-basin. We find that flash floods in most sub-basins are caused by extreme precipitation events (> 95<sup>th</sup> percentile) occurring within a short period before peak streamflow (Fig. 3c, d). For most flash floods, extreme precipitation events

have a time lag less than 18 h from the peak streamflow (Fig. 3h). The time lag is associated with antecedent soil moisture and precipitation intensities<sup>73</sup>. We find extreme precipitation (> 95<sup>th</sup> percentile) immediately (within 6 h) cause flash floods (99.9<sup>th</sup> streamflow) only 23 percent of the time (Fig. 3g, h). In addition, extreme precipitation quickly translates to flash floods in regions where high flashiness index is observed.



We find a combination of low-intensity and high-intensity precipitation leading to flash floods in some sub-basins of central India, which is associated with a low flashiness index but high drainage texture. Furthermore, low percentile precipitation causes high streamflow in a few sub-basins located in arid and semi-arid regions. J. Yin et al.<sup>13</sup> reported that the

desert landscapes with extremely dry and parched soil repel water and cause instant runoff that results from relatively smaller precipitation events, making them flashier. Apart from the arid regions, flash flood events which are caused by a lower percentile precipitation (< 95<sup>th</sup> percentile) within 24 h have either a bigger precipitation event that occurred prior to it or had

**Fig. 3 | Only one-fourth of the flash floods are solely driven by extreme precipitation (>95<sup>th</sup> percentile), while the remaining are the result of prolonged precipitation or a combination of high-intensity and low-intensity precipitation.** **a** Sub-basin wise percentile of the maximum hourly precipitation that occurred within 24 h from the 99.9<sup>th</sup> percentile streamflow events. **b** Sub-basin wise percentile of the maximum hourly precipitation observed within 72 h prior to the 99.9<sup>th</sup> percentile streamflow events. **c** The histogram shows the distribution of maximum hourly precipitation percentile within 24 h from 99.9<sup>th</sup> percentile streamflow events. **d** Distribution of percentile of maximum hourly precipitation that occurred within 72 h prior to 99.9<sup>th</sup> percentile streamflow events. **e** Sub-basin wise time lag of the maximum precipitation that occurred within 24 h from peak streamflow. **f** Sub-

basin wise time lag of the maximum precipitation that is observed within 72 h from peak streamflow. **g** The left axis histogram (dark orange) shows the distribution of time lag of the maximum hourly precipitation within 24 h from 99.9<sup>th</sup> percentile streamflow. The right axis histogram (blue) shows the percentage of events in which extreme precipitation (> 95<sup>th</sup> percentile) were observed before 99.9<sup>th</sup> percentile streamflow within the corresponding time lag. **h** The left axis histogram (dark orange) shows the distribution of time lag of the maximum hourly precipitation within 72 h from 99.9<sup>th</sup> percentile streamflow. The right axis histogram (blue) shows the percentage of events that had greater than 95<sup>th</sup> percentile precipitation in the corresponding lag duration.

prolonged precipitation for a longer duration. For instance, in regions across peninsular India, we find extreme precipitation exceeding 95<sup>th</sup> percentile within 72 h prior to the low percentile precipitation events that led to flash floods, indicating the dependency of sub-basins in the humid regions on the antecedent soil moisture condition. In humid regions where soil moisture is high, more flash flood events with less lag time can be expected<sup>62</sup>. Ivancic and Shaw<sup>74</sup> reported antecedent soil moisture is an influential factor that causes high streamflow, and extreme precipitation does not always immediately translate to floods. Li et al.<sup>75</sup> reported that flash floods can be caused by longer duration (up to 24 h) precipitation in large basins due to long time of concentration. The duration varies across regions depending on the geomorphology, land surface, and hydro-climatological conditions of the region<sup>1</sup>. The prolonged precipitation events play a vital role in making the soil saturated, leading to flash floods resulting from a relatively smaller magnitude of precipitation<sup>76</sup>. Therefore, extreme precipitation, antecedent soil moisture, and geomorphological characteristics play an important role in the flash flood occurrence.

We find the sub-daily precipitation has the largest increasing trend in peninsular India, western India, and lower Himalayas (Supplementary Figs. 4, 5). We find an increasing temperature trend in the same regions that exhibit increased precipitation trend (Supplementary Fig. 6). Furthermore, there is a larger and significant increase in the hourly streamflow trend compared to the daily streamflow trend at upstream areas of Brahmaputra, downstream areas of Ganga, and across East Coast, Sabarmati, Narmada, Tapi and Krishna River basins. In addition, the sub-basins that are classified as moderately and highly susceptible to flash floods show an increase in the precipitation and streamflow trend (Fig. 4). However, the sub-basins that are classified as very highly susceptible to flash floods show a decline in the precipitation and streamflow trend, indicating a future shift in the flash flood hotspots under a warming climate. Therefore, we analyzed the changes in the frequency of the wet hours and wet spells above 99.9<sup>th</sup> percentile during 2001–2020 against the reference period of 1981–2000 (Fig. 5). We find that there is an increase in the wet hours in most of the sub-basins which are not currently flash flood prone. Across all the Indian river basins, 51% and 66.5% of the non-flash flood prone sub-basins show an increase in precipitation and streamflow, respectively. On the contrary, we observed that a few flash flood prone basins show a decline in the wet hours. Among the highly flash flood prone sub-basins, 50.3% and 48.7% of the sub-basins show a decline in precipitation and streamflow, respectively. We observe a significant decline in both wet hours and wet spells in some sub-basins located in the Indus, Ganga, Brahmaputra, Narmada, Brahmani, Mahanadi, and Godavari basins.

## Discussions

We highlight the importance of combining both the geomorphological and hydrological factors in deriving flash flood susceptibility maps as both play vital role in estimating the flash flood risks. For instance, the flash flood prone sub-basins in the Himalayas are primarily influenced by geomorphological characteristics, while those in central India and along the west coast are mainly driven by the flashiness index. Additionally, both small and large sub-basins can be susceptible to flash floods, highlighting that flash flood risks are governed by a combination of flashiness and geomorphological features, irrespective of basin size. Most flash floods in India are

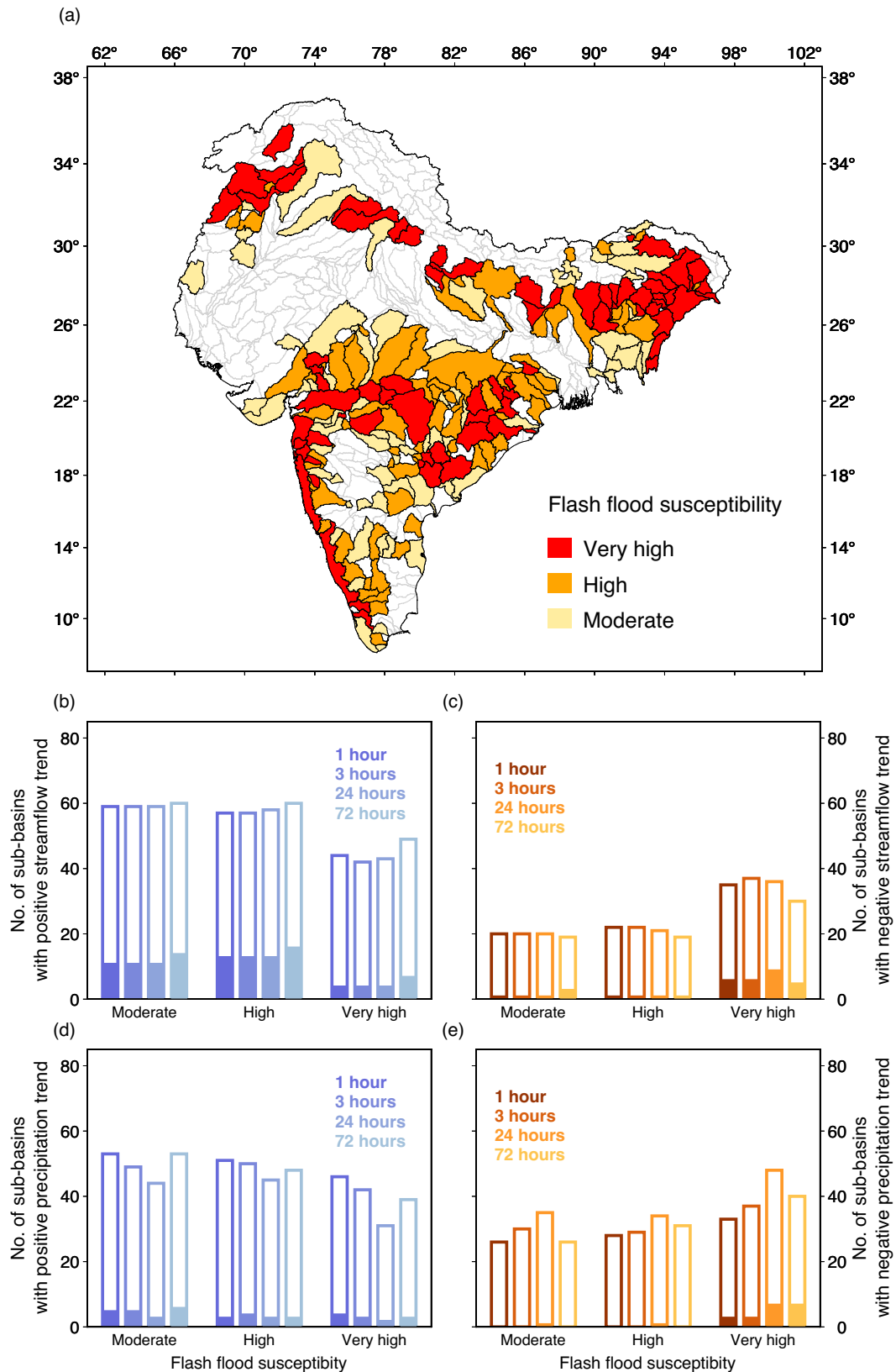
caused by extreme precipitation 18-h prior to peak flow. However, only about one-fourth flash floods are directly caused by extreme precipitation. Thus, our findings highlight the importance of antecedent soil moisture and prolonged rainfall events in flash flood occurrence. In addition, multi-day low intensity rainfall combined with saturated soil conditions can trigger flash floods. Since flash floods risk depends on the flashiness index, changing characteristics of extreme precipitation can lead to newer flash flood prone sub-basins in the Indian sub-continent.

Our findings have considerable implications for flash flood management in India. For instance, we highlight the significance of adopting region-specific adaptation strategies based on the regional topography and antecedent basin conditions as not all extreme precipitation events directly lead to flash floods. Understanding sub-basin-specific flash flood susceptibility can aid in developing early warning systems, targeted disaster preparedness, and long-term adaptation plans. A key implication of the study is the identification of emerging risk in sub-basins that are currently less vulnerable to flash floods. The increase in flash floods in low susceptible areas can incur higher loss and mortality due to under-preparedness. Hence, recognizing potential new flash flood hotspots is crucial for urban planning and infrastructure resilience in a changing climate. Our findings emphasize the need to implement climate resilient flash flood mitigation frameworks. With rising temperatures and shifting precipitation patterns, we anticipate more erratic precipitation extremes, and changes in wet spells, which can exacerbate flash flood risk in the Indian sub-continent. Thus, implementing climate resilient infrastructure, reassessing flood policies, and increasing preparedness in vulnerable and emerging hotspots are critical. Improving early warning systems, enhancing land-use planning, and targeted community awareness are also essential.

## Methods

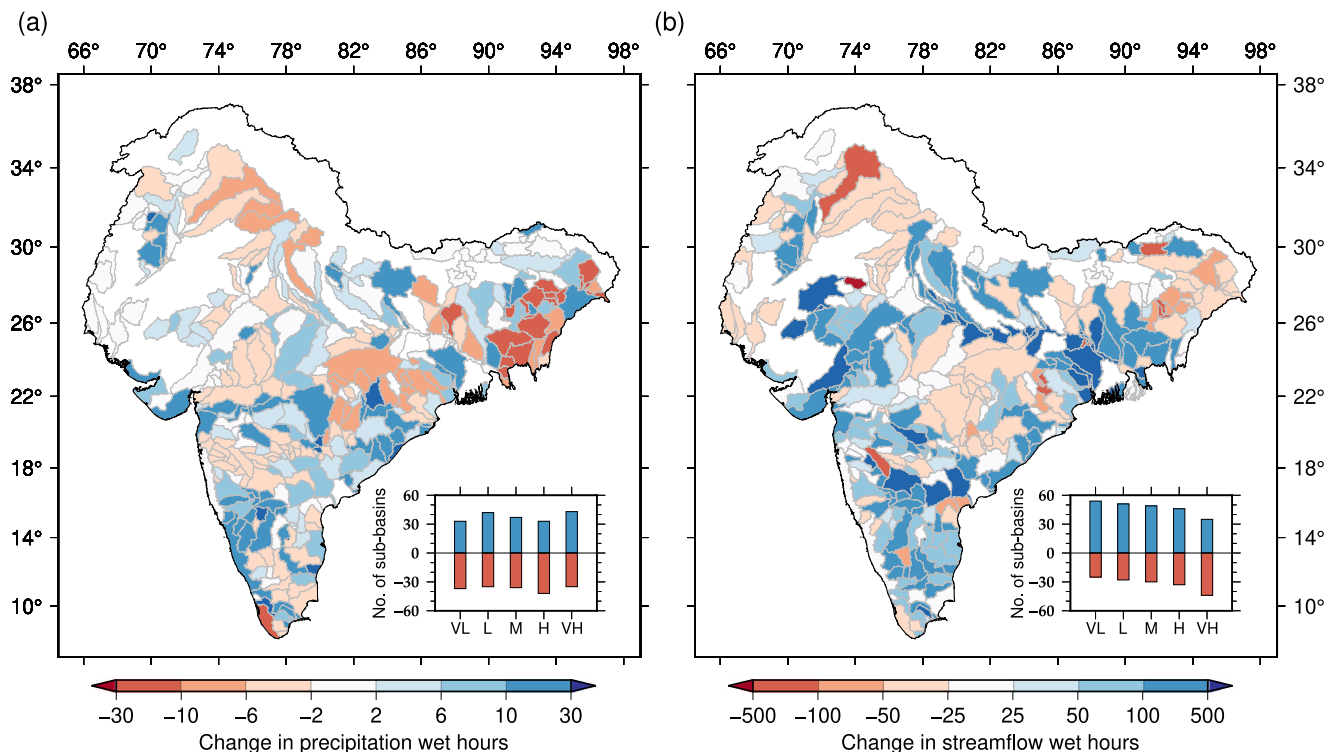
### Datasets

We obtained daily gridded maximum and minimum temperatures from IMD, which were developed using the observations from 395 quality-controlled stations for the period 1981–2020 at 1° spatial resolution<sup>77</sup>. We used hourly precipitation from IMD for 65 stations in India to evaluate the consistency of ERA5-Land precipitation. We used the HydroBASINS dataset to obtain the sub-basin boundaries across Indian sub-continent at Pfafstetter level 6<sup>78</sup>. HydroBASINS is derived from the WWF's (World Wildlife Fund) HydroSHEDS data, which is based on a 15 arc-second (~ 500 m) resolution digital elevation model. Watersheds were delineated consistently at different levels following the Pfafstetter coding system to enable topological connectivity and nested sub-basin analysis. The morphometric analysis is carried out using the digital elevation model (DEM) from the HydroSHEDS, which is available at 3 arc-seconds (~ 90 meters) resolution. Observed flash flood dataset from Emergency Events Database (EM-DAT, <https://www.emdat.be/>) and the India flood inventory developed by Saharia et al.<sup>63</sup> were used to examine the historical flash flood events. Both EM-DAT and the India flood inventory by Saharia et al.<sup>63</sup> explicitly categorize flash floods, distinguishing them from other flood types. Therefore, these datasets are essential for identifying and validating flash flood occurrences across the Indian sub-continent. Previous studies, such as Mishra et al.<sup>61</sup> and Tolani et al.<sup>79</sup>, have used the EM-DAT dataset to investigate hydrological extreme events, including flash floods in India.



**Fig. 4 | Precipitation and streamflow trends in moderate flash flood susceptible sub-basins are increasing at all durations (1 h, 3 h, 24 h, 72 h).** **a** The sub-basins that are classified as flash flood prone (moderate, high and very high) based on flashiness index and geomorphology. **b** The total number of sub-basins having different flash flood susceptibility that show a positive trend in streamflow of different durations. **c** The total number of sub-basins having different flash flood susceptibility that shows negative trend in streamflow of different durations. **d** The

total number of sub-basins having different flash flood susceptibility that show increasing trend in precipitation of different durations. **e** The total number of sub-basins having different flash flood susceptibility that show decreasing trend in precipitation of different durations. The shaded part of the histogram shows the number of sub-basins showing a significant trend ( $p < 0.05$ ). The trend analysis is done using Mann-Kendall Tau-b with Sen's Method.



**Fig. 5 | More than half of the low flash flood susceptible sub-basins show an increase in precipitation and streamflow wet hours while the high flash flood susceptible sub-basins in east and central India show decline. a** Sub-basin wise change in frequency of 99.9<sup>th</sup> percentile hourly precipitation in the period 2001–2020 compared to the period 1981–2000. The histogram shows the number of sub-basins of different flash flood susceptibility criteria (Very Low (VL), Low (L), Moderate

(M), High (H), Very High (VH) Flash Flood Prone Sub-basins) showing positive (blue) or negative (red) change in precipitation hours exceeding 99.9<sup>th</sup> percentile. **b** Sub-basin wise change in frequency of 99.9<sup>th</sup> percentile hourly streamflow in the period 2001–2020 compared to the period 1981–2000. The histogram shows the number of sub-basins of different flash flood susceptibility criteria showing positive (blue) or negative (red) change in streamflow hours exceeding 99.9<sup>th</sup> percentile.

Similarly, Aggarwal et al.<sup>80</sup> used historical flood-impact data from EM-DAT to validate the accuracy of flood risk maps in the Indian Ganga basin. However, Jones et al.<sup>81</sup> highlighted the shortcomings of the EM-DAT database, noting probable missing and inconsistently reported data. We used hourly gridded precipitation and runoff data from the ERA5-Land for 1981–2020 at 0.1° spatial resolution<sup>82</sup>. ERA5 performs better than other reanalysis products for hydrological variables in India<sup>83</sup>. Moreover, Patel et al.<sup>84</sup> studied Uttarakhand flash floods and reported that ERA5 reanalysis data can be used for flash flood assessment. We compared precipitation from ERA5-Land and IMD hourly time series at 65-gauge stations, which showed a good agreement (correlation > 0.8). We find that ERA5-Land underestimates the magnitude of extreme precipitation, however, trends and variability are well captured (Supplementary Fig. 7).

### Identification of flash flood prone sub-basins using morphometric parameters

We performed geomorphological analysis for each of the 395 sub-basins using the 17 morphometric parameters broadly classified into drainage, relief, and areal (shape) parameters (Supplementary Fig. 8). We used the ranking method to obtain the flash flood susceptibility score for each sub-basin. Morphometric ranking is an effective tool to produce flash flood susceptibility maps based on the geomorphology of the region<sup>21,85,86</sup>. We selected 17 parameters based on the previous studies<sup>85–87</sup> to assess sub-basin level flash flood susceptibility, which include bifurcation ratio, drainage density, stream frequency, stream order, stream number, stream length, drainage texture, ruggedness number, basin relief, relative relief, relief ratio, elongation ratio, length of overland flow, compactness coefficient, lemniscate ratio, form factor and circularity ratio (Supplementary Table 1). We conducted a correlation analysis among the morphometric parameters and removed those that were highly correlated (> 0.8) with others from our ranking analysis (Supplementary Fig. 9). We also examined the

geomorphological characteristics of the sub-basins that have observed flash floods and ensured the inclusion of the parameters that distinguish the flash flood observed sub-basins from others (Supplementary Fig. 10). We grouped these parameters into two categories: parameters that are directly proportional to flash flood susceptibility, and parameters that are inversely proportional to flash flood susceptibility<sup>86</sup>. For instance, the length of overland flow is inversely proportional to flash flood susceptibility, which means that a higher value of the parameter implies a lower risk of flash floods. Considering each parameter, the sub-basins are ranked from 1 to 395 based on their flash flood risk. A score of 1 is assigned to sub-basin at the lowest risk and a score of 395 to the sub-basin at the highest risk. The same score is given to sub-basins with the same parameter values. Following the morphometric ranking, the sub-basins were classified into five classes of flash flood susceptibility based on the total score obtained for each sub-basin<sup>86,88</sup>. The total score was normalized from 0 to 1 to produce the five classes of flash flood susceptibility: very low (0–0.2), low (0.2–0.4), moderate (0.4–0.6), high (0.6–0.8), very high (0.8–1).

### Identification of flash flood prone sub-basins using flashiness index

We used the Catchment-based Macro-scale Floodplain (CaMa-Flood) model to simulate hourly discharge. The CaMa-Flood hydrodynamic model accurately simulates the discharge and flood peaks<sup>89</sup>. The model offers flexibility in its temporal scale and can deliver hourly estimates when provided with hourly input data. The high temporal resolution is crucial for assessing rapid changes in water levels or flood extent during flood events<sup>90</sup>. The model is driven by runoff from a land surface model<sup>91</sup>. Liang and Zhou<sup>92</sup> reported that the CaMa-Flood model captures the fluctuations in water level due to tides and surges at hourly intervals for Zhejiang Province in China. Moreover, Vegad et al.<sup>93</sup> used the CaMa-Flood model for the major Indian river basins in simulating daily streamflow. We forced the CaMa-Flood

model with ERA5-Land runoff to simulate hourly streamflow at the outlet of the sub-basins (Supplementary Fig. 11). Streamflow observations from the India Water Resources Information System (India-WRIS) are available at a daily temporal scale, therefore, we converted the simulated hourly streamflow to a daily scale to compare against the observed flow. We evaluated the model performance at 35 gauge stations, with a satisfactory performance at the majority of the stations ( $R^2$ , NSE, KGE > 0.5) [Supplementary Fig. 12]. As we did not calibrate the CaMa-Flood model and ERA5-Land runoff is also from the uncalibrated land surface model, the performance was considered satisfactory. In addition, our aim is not to simulate absolute magnitude of flash flood peaks, so the model calibration may not play a crucial role for identifying the flash flood prone sub basins.

We obtained the streamflow peaks exceeding a return period of 10-year. We estimated the slope of the rising limb of these selected flood hydrographs to evaluate the flashiness of a sub-basin. Zian et al.<sup>94</sup> reported that flood magnitude of 10-year return period can cause a risk of flooding. Similarly, Ward et al.<sup>95</sup> suggested high probability risks can be estimated with 10-year return period floods. We fit the Generalized Extreme Value (GEV) distribution on the annual maximum streamflow values to obtain the flood magnitude of the 10-year return period. We compared the 10-year flood level estimates obtained using block maxima (annual maximum streamflow) against those estimated using the peak over threshold (PoT) method (99.9<sup>th</sup> percentile). Both estimates from the block maxima and PoT agree well except for very high streamflow estimates (Supplementary Fig. 13). We define flash floods as sudden and intense flood events that occur due to high flashiness of the sub-basins, in conjunction with their contributing morphometric characteristics. To quantify flashiness, we calculated the slope of the rising limb of the flood hydrograph using the following formula:

$$\theta = \tan^{-1} \left( \frac{Q_p - Q_s}{T_p - T_s} \right) \quad (1)$$

where  $Q_p$  is the streamflow at the peak of the flood hydrograph,  $Q_s$  is the streamflow at the onset of the flood event,  $T_p$  is the time corresponding to peak streamflow, and  $T_s$  is the time when the flood event begins. The angle  $\theta$  (in degrees) is a metric for event flashiness, where higher values correspond to steeper hydrograph slopes indicating abrupt hydrologic responses characteristic of flash flood events.

The hydrograph slope determines the flashiness of the sub-basin that implies how fast the sub-basin responds to extreme precipitation causing floods. If the flashiness of the sub-basin is high, then the flood peak is achieved quickly from the onset of an event, and the sub-basin is more susceptible to flash floods. Previous studies used the flashiness index to evaluate the flash flood severity of a sub-basin<sup>12,63,96</sup>. We ranked the sub-basins based on the flashiness index to identify the flash-flood prone sub-basins. Additionally, we identified the flash flood prone sub-basins in the Indian river basins based on both geomorphology and flashiness index. We assigned equal weightage to both factors, considering their equitable contribution to flash flood susceptibility. Some regions are more prone to flash floods due to quick hydrological response (flashiness), while others are more affected by geomorphological characteristics like terrain and drainage structure<sup>97</sup>. Hence, combining these factors can provide more robust estimates of flash flood prone sub-basins. We ranked the sub-basins based on the final score achieved by combining both factors and classified them into five susceptibility categories. Further, we compared the observed flash flood occurrences from EM-DAT with the classified sub-basins based on flash flood susceptibility (Supplementary Fig. 14). Most of the observed flash floods fall in the moderate to very high flash flood prone sub-basins validating the approach used for the flash flood identification.

### Flash flood response to extreme precipitation

We used the threshold method to obtain the streamflow peaks and identified the extreme precipitation that caused high flow to analyze the association

between precipitation and flash flood events. The Indian Meteorological Department (IMD) defines rainfall in 50<sup>th</sup>, 80<sup>th</sup>, 90<sup>th</sup>, 99.9<sup>th</sup> and 99.99<sup>th</sup> percentile as light, moderate, intense, very intense, and extreme intense spells of hourly rainfall, respectively. We checked the percentile of the hourly precipitation at different lags from the extreme streamflow events to understand the percentile and lag of the precipitation causing flash floods. We considered high flow exceeding 99.9<sup>th</sup> percentile threshold at sub-basin outlets and selected only the independent events (events at least a week apart) for our analysis. We also estimated the changes in the frequency of precipitation and streamflow extremes above a threshold of 99.9<sup>th</sup> percentile during 2001–2020 against the reference period of 1981–2000. We estimated trends in precipitation, streamflow, and temperature at each grid for the period 1981–2020 to examine changes in flash flood risks (Supplementary Figs. 4–6). We used Mann-Kendall Tau-b with Sen’s method<sup>98</sup> at a confidence interval of 95% ( $p$  value < 0.05) for the trend analysis. We used hourly precipitation from ERA5-Land and hourly streamflow simulated by the CaMa-Flood model to evaluate trends in precipitation and streamflow, respectively.

### Data availability

The data used in this study are properly cited in the relevant sections. Datasets are freely available and can be downloaded from the following links: IMD: <https://www.imdpune.gov.in>, ERA5-Land: <https://cds.climate.copernicus.eu/datasets>, HydroSHEDS: <https://www.hydrosheds.org/products/hydrobasins>, EM-DAT: <https://www.emdat.be>, India-WRIS: <https://indiawriss.gov.in>.

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### Author contributions

V.M. conceptualized the study. N.D.K. and V.M. designed the methodology. N.D.K. collected data, performed the analysis, and wrote the original draft. U.V. conducted the CaMa-Flood simulations. N.D.K. and V.M. contributed equally to editing and finalizing the manuscript.

### Competing interests

The authors declare no competing interests.

### Additional information

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