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Evaluating the performance of the Flash Flood Guidance System: A Case study from Himachal Pradesh, India

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सार – आकस्मिक बाढ़, खासकर पहाड़ी और घनी आबादी वाले इलाकों में सबसे मुश्किल जल मौसम संबंधी खतरों में से एक है जिसका पूर्वानुमान लगाना भी मुश्किल है, ऐसा इसलिए है क्योंकि यह तेज़ी से शुरू होती है, जल विज्ञान प्रतिक्रिया का समय कम होता है और इसकी चेतावनी भी कम होती है। जलवायु परिवर्तन की वजह से कम समय में तीव्र वर्षा होने से ये चुनौतियाँ और बढ़ रही हैं। भारत ऐसी चरम स्थितियों के लिए बहुत ज़्यादा संवेदनशील है, खासकर पश्चिमी हिमालयी क्षेत्र में, जहाँ मुश्किल इलाके और मज़बूत मॉनसून के असर से बाढ़ का खतरा और बढ़ जाता है। आकस्मिक बाढ़ की तैयारी को मज़बूत करने के लिए, भारत मौसम विज्ञान विभाग ने विश्व मौसम विज्ञान संगठन और जल विज्ञान अनुसंधान संस्थान के साथ मिलकर अक्टूबर 2020 में साउथ एशिया फ्लैश फ्लड गाइडेंस सिस्टम (SAsiaFFGS) को चालू किया। यह प्रणाली वास्तविक समय के जल-मौसम संबंधी प्रेक्षणों और संख्यात्मक मौसम पूर्वानुमान परिणाम को एकीकृत करती है ताकि दैनिक पैमाने पर फ्लैश फ्ल्ड रिस्क(FFR) और जलग्रहण स्तर पर अल्पकालिक तात्कालिक अनुमान विंडो के भीतर आसन्न और लगातार फ्लैश फ्ल्ड का खतरा (IFFT, PFFT) उत्पन्न किया जा सके। यह अध्ययन जुलाई 2023 में हिमाचल प्रदेश में अत्यधिक वर्षा और आकस्मिक बाढ़ के दौरान SAsiaFFGS के प्रदर्शन को जांचती है। हिमाचल प्रदेश पश्चिमी हिमालय का एक ऐसा राज्य है जिसकी खासियत खड़ी ढलान और जल विज्ञान प्रतिक्रिया का समय कम है। प्रणाली से पैदा हुए खतरे और थ्रेट इंडेक्स को देखी गई वर्षा, मिट्टी की नमी में बदलाव और उपग्रह से मिलने वाले पानी के बहाव के आधार पर जांचा गया। परिणाम बताते हैं कि SAsiaFFGS ने आकस्मिक बाढ़ की स्थितियों के जगह और समय के साथ होने वाले बदलाव को कामयाबी से दर्शाया, जिससे प्रचालन शुरुआती चेतावनी के लिए एक्शन लेने लायक अग्रीम समय मिला।

ABSTRACT. Flash floods are among the most challenging hydro-meteorological hazards to forecast due to their rapid onset, short hydrological response times, and limited warning, particularly in mountainous and densely populated regions. These challenges are being amplified by climate change through increases in short-duration intense rainfall. India is highly vulnerable to such extremes, especially across the Western Himalayan region, where complex terrain and strong monsoon interactions further exacerbate flood risk. To strengthen flash flood preparedness, the India Meteorological Department, in collaboration with the World Meteorological Organization and the Hydrologic Research Center, operationalized the South Asia Flash Flood Guidance System (SAsiaFFGS) in October 2020. The system integrates real-time hydrometeorological observations and numerical weather prediction outputs to generate Flash Flood Risk (FFR) at daily scales and Imminent and Persistent Flash Flood Threats (IFFT, PFFT) within short-term nowcasting windows at the watershed level. This study evaluates the performance of SAsiaFFGS during the extreme rainfall and flash flood event of July 2023 over Himachal Pradesh, a representative Western Himalayan state characterized by steep terrain and short hydrological response times. System generated risk and threat indices are assessed against observed rainfall, soil moisture evolution, and satellite-derived runoff. Results indicate that SAsiaFFGS successfully captured the spatial and temporal evolution of flash flood conditions, providing actionable lead time for operational early warning.

Key words - Extreme precipitation, Flood forecasting, Hydrometeorology, Flash flood, Himalayan region, India.

1. Introduction

Flash floods differ fundamentally from riverine floods in their dynamics, as they are primarily triggered by short-duration, high-intensity rainfall events that generate rapid runoff responses over small catchments. These responses are often exacerbated by pre-existing saturated soil conditions and local topographic controls, resulting in very short lead times for warning and response (Doswell *et al*., 1996). Consequently, flash floods pose particularly severe risks in regions characterized by dense populations, rapid urbanization, and complex terrain.

Among such regions, the Indian Himalayan Region is especially susceptible to flash flooding due to its unique geomorphic and hydro-climatic setting. Steep slopes, narrow valleys, fragile lithology, and short river response times promote rapid concentration of runoff (Kumar *et al*., 2017). In addition, cryospheric processes such as seasonal snowmelt and glacier-fed flows modulate antecedent soil moisture and baseflow conditions, while intense orographically enhanced monsoonal rainfall frequently acts as the primary trigger. These combined controls make the Himalayan region highly sensitive to short-duration extreme precipitation events, underscoring the need for impact-based flash flood guidance systems.

In the Western Himalaya, hydro-meteorological vulnerability is further amplified by the regional rainfall climatology. The states of this region receive a major portion of their annual rainfall during the southwest monsoon season (June-September), contributing approximately 55-60% of the total, followed by winter precipitation associated with Western Disturbances (Dimri *et al*., 2015). Vulnerability increases substantially during periods when mid-tropospheric Western Disturbances interact with easterly monsoonal flow, leading to episodes of intense and spatially extensive precipitation across northwestern India (Vellore *et al*., 2015). Such interactions have been associated with several high-impact events, including the devastating 2013 North India floods, which resulted from the interaction of an upper-tropospheric trough with a strong monsoon low-pressure system (Chevuturi & Dimri, 2016; Mishra & Srinivasan, 2013).

Recent studies indicate that extreme rainfall events, both short-duration and multi-day, have increased in frequency and intensity across India over recent decades, with projections suggesting further amplification under ongoing global warming (Roxy *et al*., 2017). The Sixth Assessment Report of the IPCC attributes the observed rise in extreme events to human-induced climate change superimposed on natural climate variability (Intergovernmental Panel On Climate Change (Ipcc), 2023). These trends are of particular concern for the Himalayan region, where even moderate increases in rainfall intensity can translate into disproportionately large hydrological impacts.

India's climate exhibits substantial spatial and temporal variability, with the southwest monsoon contributing nearly 75% of the nation's annual rainfall. Himachal Pradesh similarly receives around 59% of its annual rainfall during the monsoon season and approximately 15% during winter due to Western Disturbances (Dimri *et al*., 2015). During certain years, interactions between westerly disturbances and monsoonal easterlies produce exceptionally heavy rainfall over the Himalayan states of Jammu & Kashmir, Himachal Pradesh, and Uttarakhand, frequently resulting in flash floods and landslides (Vellore *et al*., 2015).

Given this increasing hydro-climatic risk, the development of robust operational flash flood early warning systems is critical. To strengthen flash flood preparedness in India and the South Asian region, the South Asia Flash Flood Guidance System (SAsiaFFGS) was implemented and operationalized at the India Meteorological Department (IMD) in October 2020. The system provides real-time guidance through Flash Flood Risk (FFR) products with 24-hour validity and Flash Flood Threat indices, including Imminent Flash Flood Threat (IFFT), Persistent Flash Flood Threat (PFFT), and Forecasted Flash Flood Threat (FFFT), with six-hour validity. By integrating meteorological and hydrological inputs, SAsiaFFGS supports operational flash flood monitoring and disaster risk reduction across complex hydro-meteorological environments (Flash Flood Guidance System with Global Coverage (FFGS), 2015).

1.1 *Study Area: Himachal Pradesh*

Himachal Pradesh provides a representative case study region for evaluating the operational performance of flash flood guidance systems under complex Himalayan hydro-meteorological conditions. The state is located in the Western Himalayan region (Fig. 1) and comprises twelve districts, with elevation increasing progressively from the southern foothills toward the northern high mountains. It forms part of the upper catchments of five major rivers - Chenab, Ravi, Sutlej, Beas, and Yamuna, which contribute significantly to both the Indus and Ganges River basins. These rivers are perennial, sustained by snowfall and glacial melt during winter and spring, and by monsoonal rainfall during the summer months (Bookhagen & Burbank, 2010).

Himachal Pradesh is highly prone to flooding during the southwest monsoon season (June–September). The state frequently experiences heavy (≥64.5 mm), very heavy (≥115.6 mm), and extremely heavy rainfall (≥204.5 mm) events, as classified by IMD. Orographic lifting of moisture laden monsoonal winds often enhances convective activity, resulting in severe thunderstorms and cloudburst events (Dimri *et al*., 2017; Kumar *et al*., 2018). Such processes triggered multiple flash flood occurrences across the districts of Mandi, Kullu, Manali, and Shimla during 8–10 July 2023.

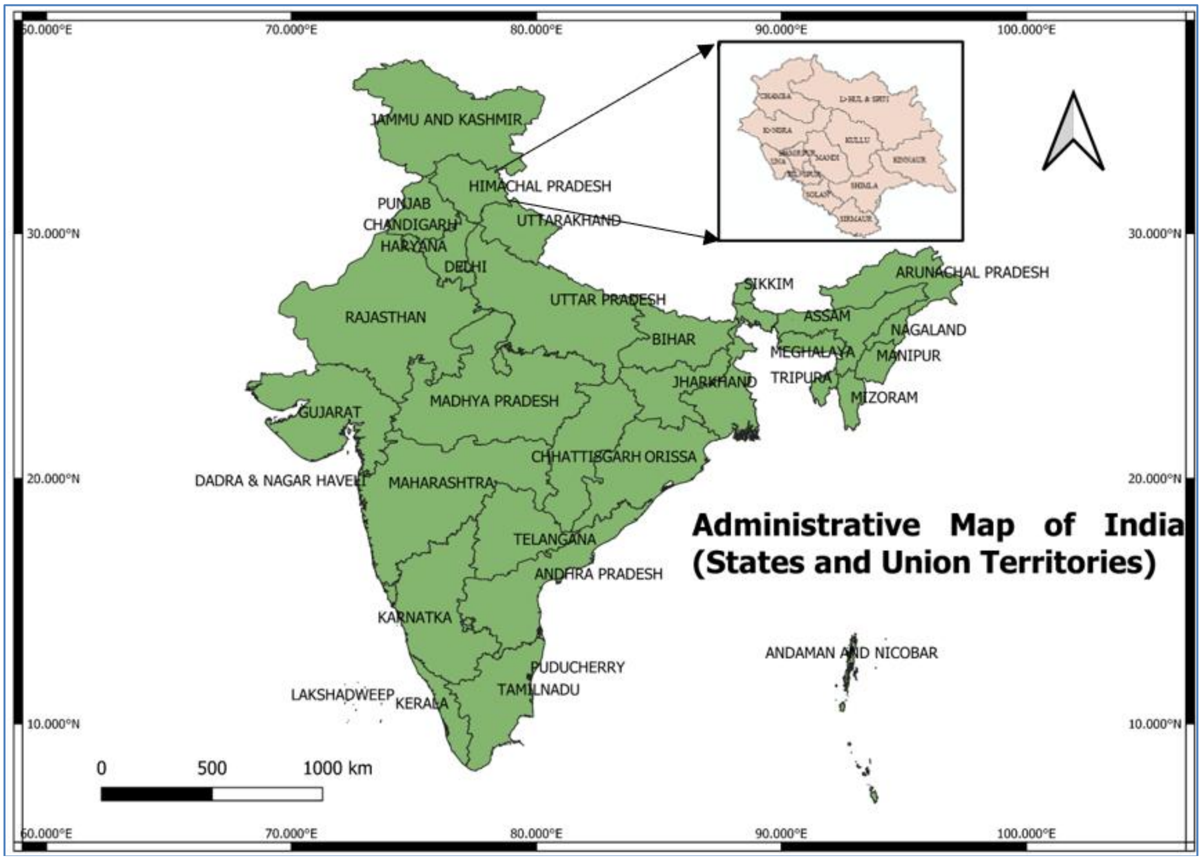


Fig. 1. Administrative map of India showing study area (Himachal Pradesh)

The year 2023 was particularly exceptional, with state recording one of its wettest July months on record. The state also experienced its wettest July day in over four decades, with 153 mm of rainfall reported by IMD, an event surpassed only by the July 1982 rainfall extremes. These conditions intensified hydrological response in steep mountain catchments, contributing to widespread flooding and flash flood episodes across several districts.

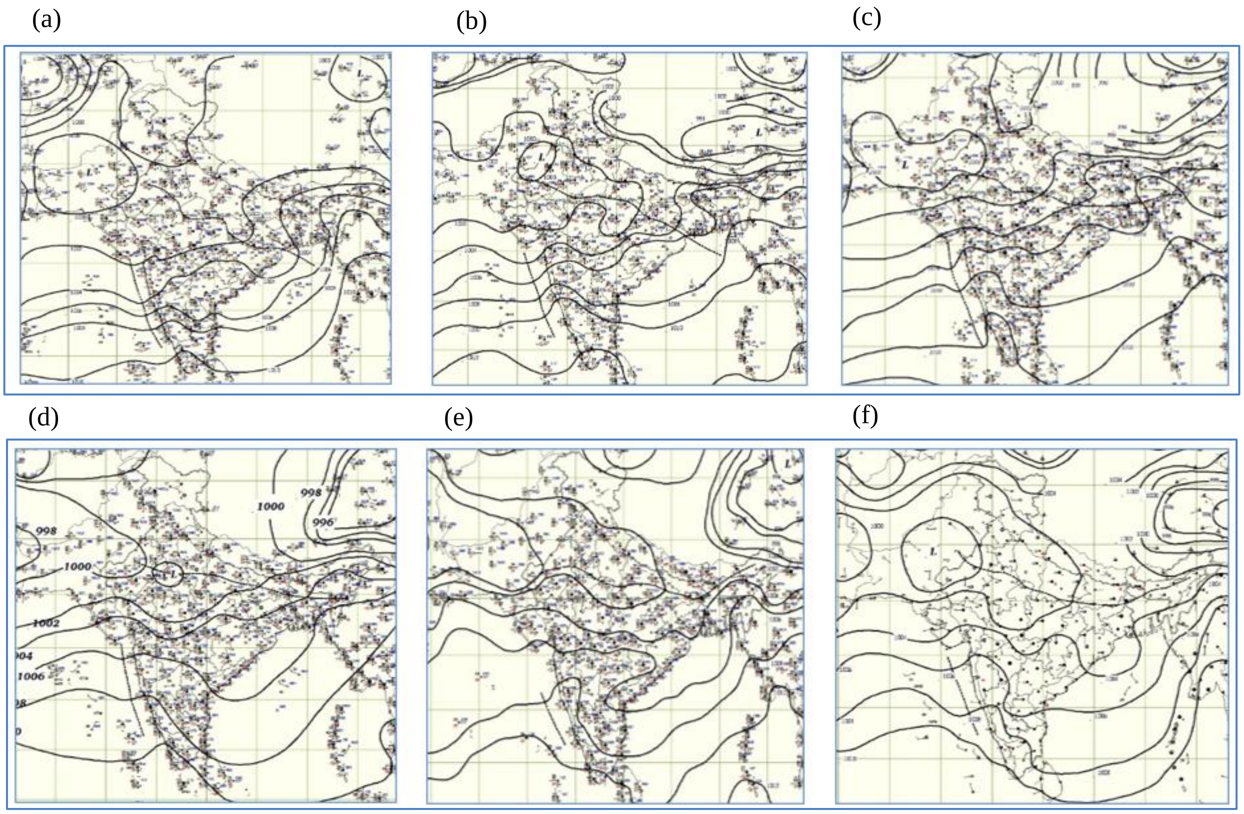
2. Data and methodology

2.1. *Overview of south asia flash flood guidance system*

The South Asia Flash Flood Guidance System (SAsiaFFGS) is an integrated hydrometeorological platform developed to support operational flash flood forecasting across India and neighboring South Asian countries. Implemented at the India Meteorological Department (IMD) in October 2020, the system synthesizes real time meteorological observations, hydrological information, land surface characteristics, and numerical model predictions to provide short term flash flood guidance at watershed and district scales (Georgakakos *et al*., 2022).

SAsiaFFGS ingests multiple rainfall inputs, including satellite-based estimates from the Global Hydro Estimator (GHE) and the Microwave Global Hydro-Estimator (MWGHE) produced by NOAA-NESDIS. The MWGHE corresponds to 24 hour accumulated precipitation derived from infrared-based GHE rainfall estimates, bias-adjusted using the CPC CMORPH microwave rainfall product. These satellite datasets are complemented by quantitative precipitation estimates from 15 Doppler Weather Radars (CAPPI products) of IMD and rainfall observations from the District Rainfall Monitoring System (DRMS), a dense network of more than 5800 surface rain gauges across India.

Forecast fields from IMD's operational numerical weather prediction models, including IMD GFS 12 km, IMD WRF 3 km, and NCUM 4 km, provide short to medium range predictions of rainfall and atmospheric conditions, which drive the Flash Flood Guidance computations. In addition, a land surface hydrological component based on the Sacramento Soil Moisture Accounting Model (SAC-SMA) accounts for soil moisture dynamics, snowmelt, and catchment response characteristics.



Figs. 2(a – f). depict the surface isobar analyses based on 0300 UTC for the period 07 -12 July respectively, illustrating the position of the monsoon trough.

By integrating these diverse datasets, SAsiaFFGS generates a suite of diagnostic and prognostic indices that support rapid detection and assessment of emerging flash flood risks under evolving synoptic and mesoscale conditions.

2.2. *Flash-flood guidance and diagnostic indices*

SAsiaFFGS produces several hydrometeorological indices that quantify flash-flood potential over different time horizons. These indices incorporate observed rainfall, satellite estimates, radar QPE, soil moisture conditions, and model forecasted precipitation to evaluate both immediate and short-range threats. The main indices used in this study are described below.

Merged Mean Areal Precipitation (MAP) - MAP provides a basin wide measure of accumulated rainfall over specified durations. It is derived using the best available estimate from bias adjusted MWGHE, bias adjusted GHE, or gauge interpolated rainfall fields.

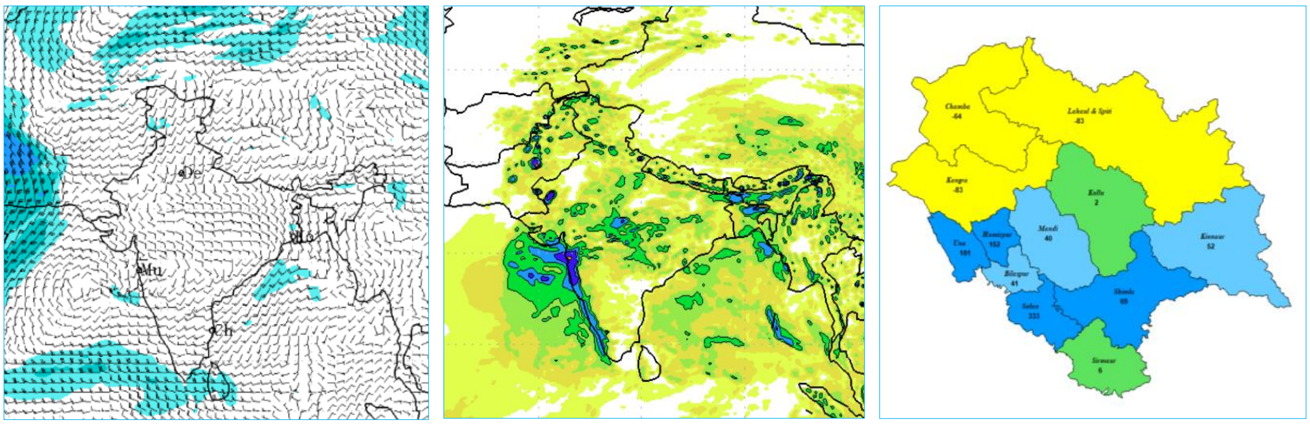
Average Soil Moisture (ASM) - ASM denotes the upper-zone soil water saturation fraction, estimated through the Sacramento Soil Moisture Accounting Model. This dimensionless parameter reflects antecedent soil moisture and is updated hourly.

Imminent Flash Flood Threat (IFFT) - IFFT quantifies the difference between the current MAP for a given duration and the corresponding Flash Flood Guidance (FFG). Higher positive values indicate increasing flash flood potential within the next 1–6 hours. Color-coded displays highlight the evolving threat, with yellow representing low concern and orange to red indicating progressively higher danger.

Persistent Flash Flood Threat (PFFT) - PFFT evaluates sustained rainfall conditions by comparing persisted MAP accumulations for the previous 1, 3, and 6 hours with the current FFG. It identifies prolonged heavy rainfall episodes likely to trigger flash-flooding.

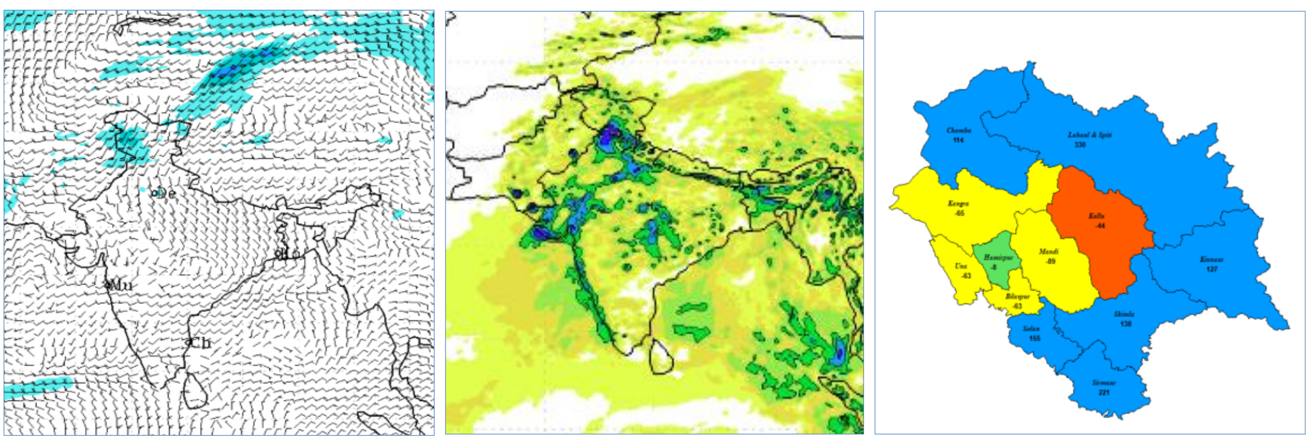
Flash Flood Risk (FFR) - FFR represents the relative likelihood of flash-flood occurrence within the next 12–36 hours, based on ensemble model guidance. The 24-hour FFR product is operationally used for short-range planning and early warning.

(a) (b) (c)



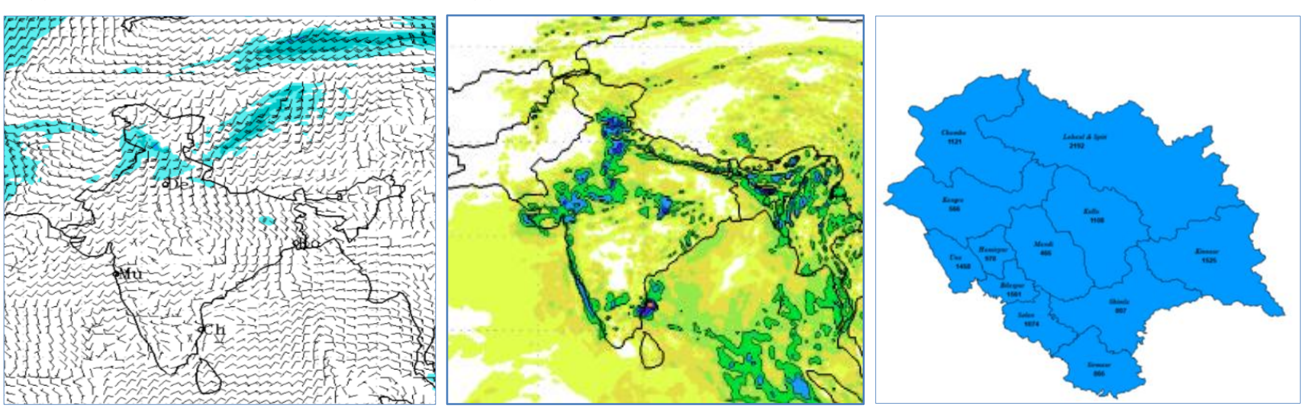
Figs. 3(a-c). IMD-GFS wind Analysis 500 HPa, IMD-GFS 24 hours rainfall forecast and Daily Rainfall % Departure (district-wise) respectively with validity from 0300 UTC 07 Jul 23 to 0300 UTC 08 Jul 23 on 07 Jul 23

(a) (b) (c)

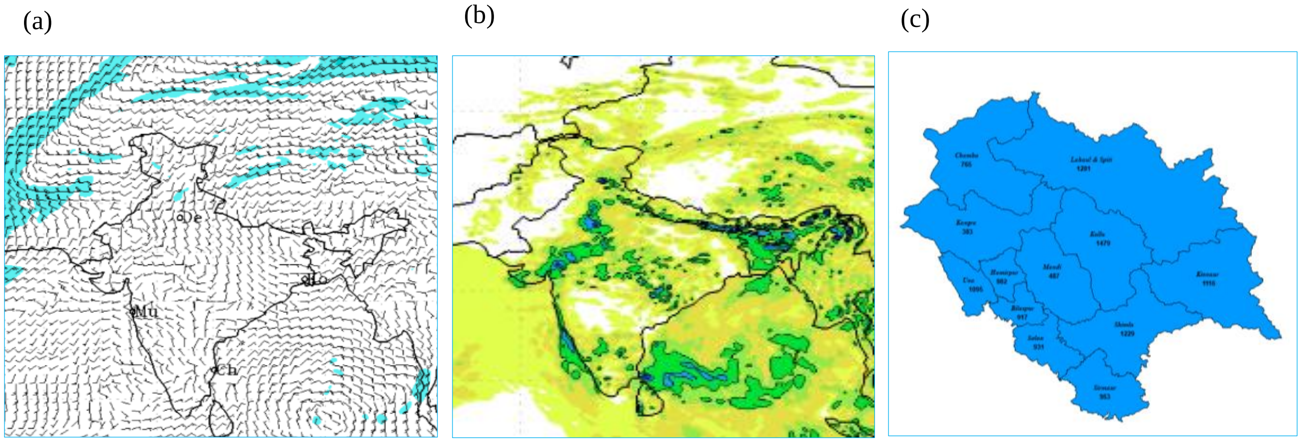


Figs. 4(a-c). IMD-GFS wind Analysis 500 HPa, IMD-GFS 24 hours rainfall forecast and Daily Rainfall % Departure (district-wise) respectively with validity from 0300 UTC 08 Jul 23 to 0300 UTC 09 Jul 23 on 08 Jul 23

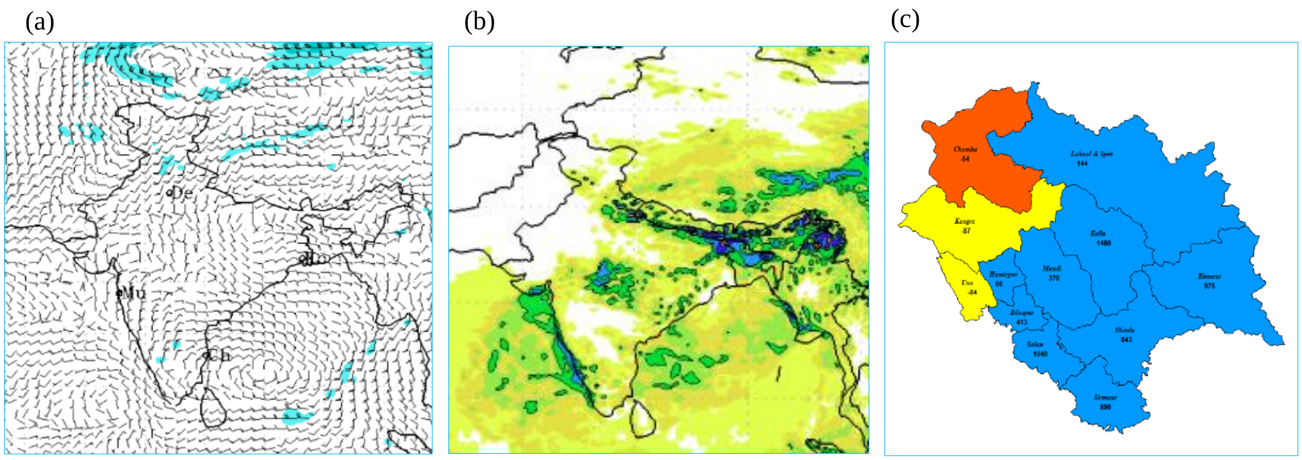
(a) (b) (c)



Figs. 5(a-c). IMD-GFS wind Analysis 500 HPa, IMD-GFS 24 hours rainfall forecast and Daily Rainfall % Departure (district-wise) respectively with validity from 0300 UTC 09 Jul 23 to 0300 UTC 10 Jul 23 on 09 Jul 23



Figs. 6(a-c). IMD-GFS wind Analysis 500 HPa, IMD-GFS 24 hours rainfall forecast and Daily Rainfall % Departure (district-wise) respectively with validity from 0300 UTC 10 Jul 23 to 0300 UTC 11 Jul 23 on 10 Jul 23



Figs. 7(a-c). IMD-GFS wind Analysis 500 HPa, IMD-GFS 24 hours rainfall forecast and Daily Rainfall % Departure (district-wise) respectively with validity from 0300 UTC 11 Jul 23 to 0300 UTC 12 Jul 23 on 11 Jul 23

3. Results and discussion

3.1. *Synoptic analysis*

Synoptic-scale atmospheric conditions prevailing during the selected flash flood event are analyzed to understand the large-scale drivers of extreme rainfall. Key synoptic features influencing moisture transport, convergence, and rainfall intensity are examined to establish the background meteorological setting for the subsequent flash flood guidance and runoff analyses.

Figs. 2a - 2f depict the surface isobar analyses based on 0300 UTC for the period 7 -12 July, illustrating the position of the monsoon trough. The analysis indicates that the axis of the monsoon trough remained south of its normal position, which typically extends through Ganganagar, Allahabad, Kolkata, and the Head Bay of Bengal. During this period, the monsoon remained in an active phase over central India, accompanied by strong easterly winds prevailing across the central and northern parts of the country.

Figs. 3a-7a present the IMD-GFS wind analyses at 500 hPa for the period 7-11 July, while the corresponding 24-hour rainfall forecasts are shown in Figs. 3b-7b. The district-wise, daily observed rainfall departure (up to 03 UTC of the following day) is depicted in Figs. 3c-7c. The 500 hPa wind analysis for 7 July (Fig. 3a) indicates the presence of a (WD) as a trough embedded in the west-erlies, extending up to 35 °N along 55 °E and approaching the Indian region. Surface analysis at 03 UTC on 7 July (Fig. 2a) similarly shows a trough at lower levels. The 24-hour IMD-GFS rainfall forecast valid until 03 UTC of 8 July (Fig. 3b) suggests that rainfall activity was initially confined to the extreme northwestern Himalayan region.

Beginning 8 July, the mid-tropospheric wind analyses at 500 hPa (Figs. 4a–6a) reveal increasing interaction between the westerlies and the easterly

TABLE 1

Cumulative district wise rainfall for 07 -11 Jul 2023

DISTRICT	ACTUAL (in mm)	NORMAL (in mm)	DEPARTURE (%)
BILASPUR	335.9	44.5	655
CHAMBA	207.9	49.6	319
HAMIRPUR	258.7	49.2	426
KANGRA	225.3	93.7	140
KINNAUR	107.6	11.2	861
KULLU	280.1	30.7	812
LAHAUL & SPITI	124.8	21	494
MANDI	245.5	68.2	260
SHIMLA	268.9	35.4	660
SIRMAUR	514	67.9	657
SOLAN	472.6	52	809
UNA	265.3	49	441
HIMACHAL PRADESH	223	41.6	436

monsoonal flow. This interaction persisted on 9 and 10 July. Comparison of the 24-hour rainfall forecasts for 7, 8, and 9 July (Figs. 3b, 4b, and 5b) indicates a progressive intensification and expansion of rainfall over Himachal Pradesh. Rainfall on 7 July (Fig. 3c) was largely confined to the southern districts, whereas on 8 July rainfall became more prominent across the northern districts, subsequently spreading across the entire state on 9 and 10 July under the influence of the WD monsoon interaction.

District-wise observed rainfall distributions show that all twelve districts recorded either *excess* (+19% to +59%) or *large excess* (> +59%) departures from normal, demonstrating the strong impact of mid-tropospheric interactions on rainfall over Himachal Pradesh. Figs. 4c–6c illustrate the spatial distribution of observed rainfall from 8 July onward, highlighting the significant enhancement in both intensity and coverage when the westerlies interacted with the monsoonal easterlies. On 8 July, seven districts i.e., Chamba, Kinnaur, Shimla, Solan, Sirmaur, and Lahaul & Spiti, fell under the large excess category. Forecasts for 9-10 July (Figs. 5b–6b) indicated widespread heavy to very heavy rainfall over the state.

Observed rainfall on 8 and 9 July (Figs. 4c and 5c) corroborates the IMD-GFS forecasts. Single-day departures from Long Period Average (LPA) exceeded 60% in seven districts on 8 July, and by 9 July, all twelve districts experienced intense rainfall, which continued through 10 July (Figs. 5a–5c and 6a–6c). Table 1 shows that Himachal Pradesh received cumulative rainfall 436% above LPA during 7–11 July, an exceptional anomaly that contributed to flash flood occurrences on 8 and 10 July in the districts of Mandi and Kullu.

The interaction persisted until 11 July, resulting in extremely high rainfall across all twelve districts. The state received 223 mm of rainfall against a normal of 41.6 mm in four days-a deviation of 436% (Table 1), the highest recorded in the available climate record. Districts such as Kinnaur, Kullu, and Solan recorded the highest totals, with Kinnaur and Lahaul & Spiti receiving 43% and 33% of their total average annual rainfall within these four days. These extreme rainfall conditions led to flash-flood events in Mandi and Kullu on 8 and 10 July.

3.2. *Flash Flood Guidance System analysis*

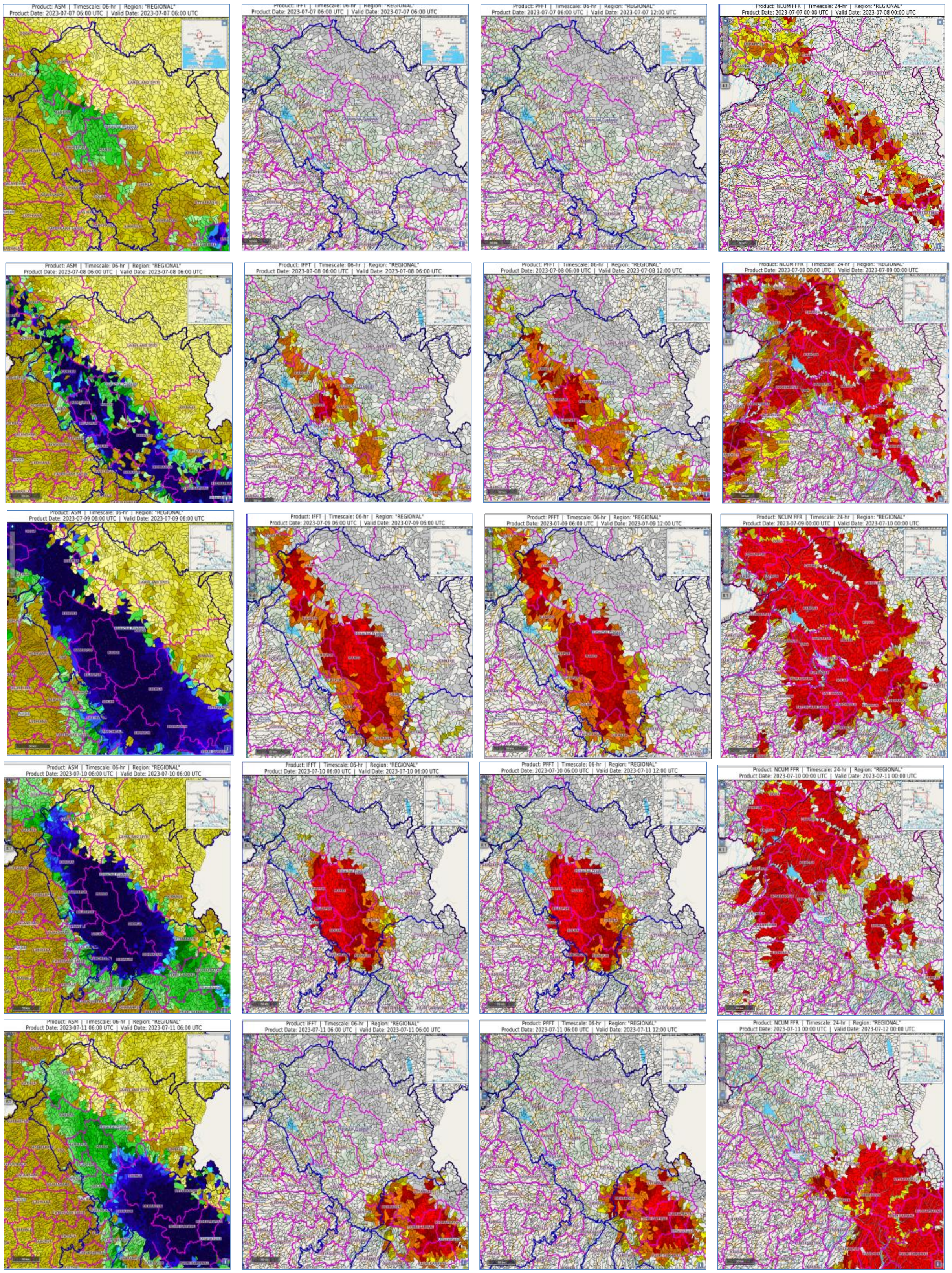
The evolution of flash-flood conditions was monitored continuously from 7 July onward. Figs. 8d–12d show the FFR forecasts with 24-hour validity generated for all districts of Himachal Pradesh. Figs. 8a–12a present the ASM estimated over 6-hour intervals using the SAC-SMA model with MAP as the primary input. ASM describes the soil saturation state as a dimensionless fraction ranging from 0 to 1, with 1 indicating complete saturation.

The IFFT and PFFT indices for the same period are depicted in Figs. 8b–12b and Figs. 8c–12c, respectively. The FFR fields were evaluated one day prior to the IFFT and PFFT products to assess whether the system captured the early signatures of potential flash-flood development 24 hours in advance. Details are captured in the Table 2.

Day 1 – 07 Jul 2023:

Low to moderate FFR values (valid up to 0000 UTC of 8 July) were generated for some districts of Jammu &

(a) (b) (c) (d)



Figs. 8 to 12. (a-d). 06 Hours accumulated ASM, IFFT, PFFT and FFR products at 06 UTC for 07 to 11 Jul 2023 respectively

TABLE 2

Spatial and temporal details of the Risk and Threats generated by SAFFGS for the period 07 to 11 Jul 2023

Date	Districts under Flash Flood Risk (24 Hours Validity)			Threat generated at (UTC)	Districts under Imminent Flash Flood Threat (IFFT) >40%	Districts under Persistent Flash Flood Threat (PFFT) > 40%
	WRF	NCUM	GFS			
07 Jul 23	Mandi	Mandi Chamba Shimla Sirmaur	Chamba Mandi Chambal Shimla Hamirpur Kinnaur	06, 12	NIL	NIL
08 Jul 23	Chamba Kangra Mandi Kinnaur Lahaul & Spiti Shimla	Chamba Kangra Mandi Shimla Hamirpur Kinnaur Lahaul & Spiti Shimla	All the Districts	06, 12	Hamirpur Mandi Bilaspur Hamirpur Mandi Bilaspur Chamba Kangra	Hamirpur Bilaspur Mandi Kangra Chamba Kangra Mandi
09 Jul 23	All the districts except UNA Lahaul & Spiti Kinnaur	All the districts	All districts except UNA	06, 12	Kangra Kullu Mandi Hamirpur Shimla Sirmaur , Solan Mandi Kullu Shimla Sirmaur	Kangra Kullu Mandi Hamirpur Bilaspur Sirmaur Solan Mandi Kangra Shimla Hamirpur Solan
10 Jul 23	Sirmaur	Kangra Hamirpur Mandi UNA Lahaul & Spiti Kullu Shimla Kinnaur	Mandi Kullu Chamba Shimla	06, 12	Kangra, Kullu Mandi, Bilaspur Hamirpur Shimla Sirmaur, Solan Mandi Hamirpur Bilaspur Sirmaur	Kangra ,Kullu Mandi , Bilaspur Hamirpur Shimla Sirmaur , Solan Hamirpur Bilaspur Sirmaur
11 Jul 23	Shimla	Solan Sirmaur Shimla Kinnaur	Sirmaur	06, 12	Sirmaur No IFFT generated	No PFFT generated No PFFT generated

Kashmir and Himachal Pradesh, indicating a lower probability (≤ 50%) of flash-flood risk over the watersheds of Chamba, Mandi, and Kullu (Fig. 8d). Rainfall was reported only in a few districts of Himachal Pradesh (Fig. 3c), and soil saturation levels also remained below 90 percent (Fig. 8a). Consequently, no IFFT or PFFT indices were generated for this day (Figs. 8b & 8c).

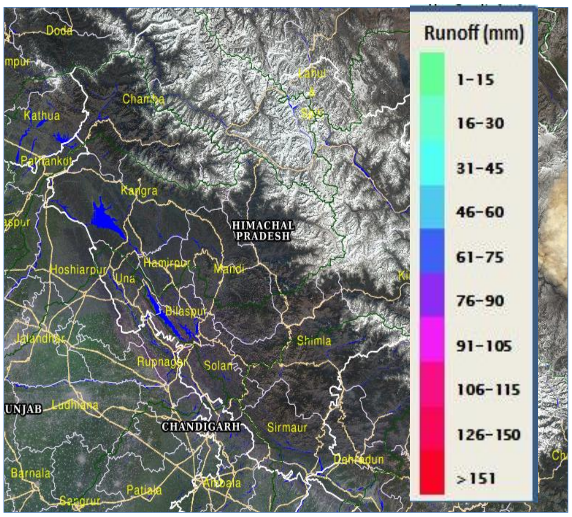
Day 2 - 08 Jul 2023:

The IMD-GFS 24-hour rainfall forecast issued at 0000 UTC on 7 July indicated increased precipitation for 8 July, with the main activity expected over Himachal Pradesh and Uttarakhand. Nearly half of the districts in Himachal Pradesh i.e., Chamba, Lahaul & Spiti, Kinnaur, Solan, Shimla and Sirmaur, recorded daily rainfall in the "excess" category on 8 July (Fig. 4c). By 12 UTC, most watersheds in Kangra, Kullu and Mandi had reached 90 to 100 percent soil saturation (Fig. 9a).

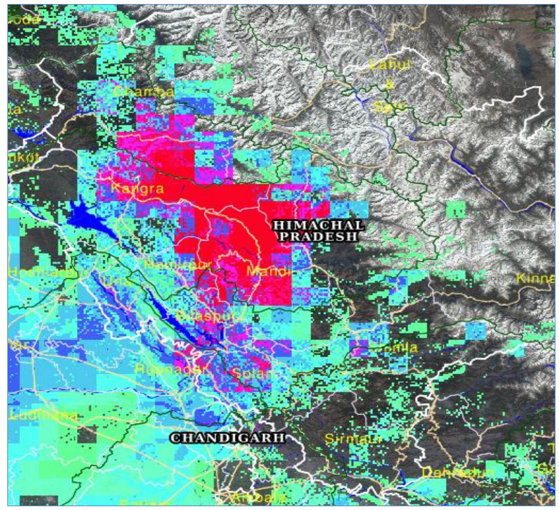
The 24-hour FFR showed a moderate probability (50 to 100 percent) of flash-flood occurrence over the districts of Bilaspur, Hamirpur and Mandi at 0600 UTC. In addition, a high probability (> 60 percent) of PFF, indicating the likelihood of flash flooding during the next six hours was generated for Mandi and Hamirpur.

Day 3 and 4 - 09 and 10 Jul 2023:

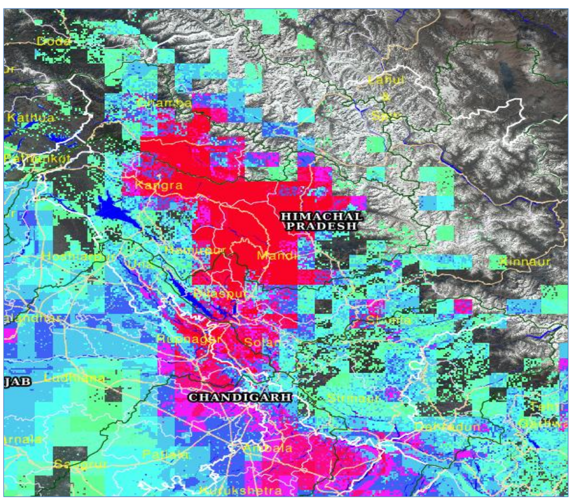
The 24-hour IMD-GFS rainfall forecasts issued for 9 July (0000 UTC) and 10 July (0000 UTC) indicated continued and intensified precipitation activity over



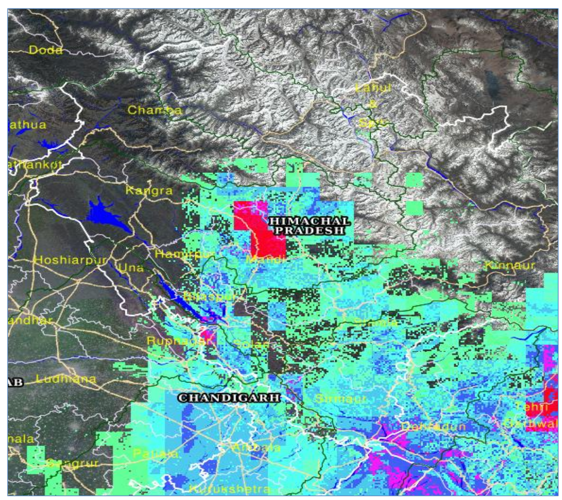
(a) 08 Jul 23



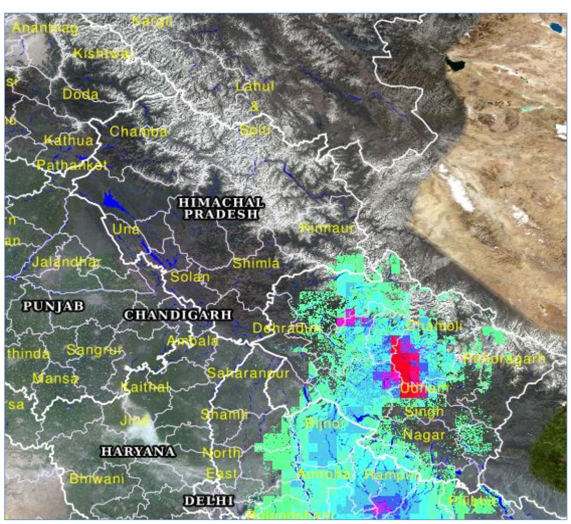
(b) 09 Jul 23



(c) 10 Jul 23



(d) 11 Jul 23



(e) 12 Jul 23

Figs.13. (a-e). Cumulative Runoff from 08 Jul to 12 Jul 2023 respectively

Himachal Pradesh and Uttarakhand. All districts of Himachal Pradesh-Chamba, Kangra, Lahaul & Spiti, Kinnaur, Mandi, Kullu, Solan, Una, Bilaspur, Shimla and Sirmaur-recorded daily rainfall in the “large excess” category (> 59 percent departure from LPA) on both 9 July (Fig. 5c) and 10 July (Fig. 6c). Soil saturation across all district watersheds reached 100 percent during this period (Figs. 10a and 11a).

The 24-hour FFR exhibited positive flash-flood signals across multiple sub-basins. The Imminent Flash Flood Threat, represented in red on the system outputs, indicated heightened concern over several sub-basins on both days (Figs.10b and 11b). Flash-flood risks remained elevated for the subsequent six hours as well, as reflected in the persistent threat fields (Figs. 10c and 11c).

Day 5 - 11 Jul 2023:

The main rainfall activity shifted toward the Uttarakhand region as the interaction between the westerlies and the monsoonal flow moved eastward (Fig. 7a), associated with the progression of the westerly trough around 76°–77° E. As a result of decreasing rainfall over Himachal Pradesh, soil saturation levels reduced noticeably (Fig. 12a). The FFR did not indicate any positive flash-flood signals for this day (Fig. 12d), and consequently, neither IFFT nor PFFT indices were generated for the state (Figs. 12b and 12c).

3.3. *Runoff analysis*

To understand the hydrological response to intense rainfall, daily cumulative runoff over Himachal Pradesh is analyzed for the selected flash flood event. The spatial and temporal variability of runoff provides insight into catchment response and flood persistence across the region.

Figs. 13a–13e present the daily cumulative runoff over Himachal Pradesh derived from the National Database for Emergency Management (NDEM), NRSC–ISRO, for the period 8–12 July. Minimal runoff was observed on 8 July (Fig. 13a), consistent with limited rainfall activity on that day.

On 9 July, runoff exceeding 106 mm (24-hour accumulation) was recorded over several sub-basins in the districts of Kangra, Mandi and Kullu (Fig. 13b). Runoff in the range of 61–105 mm was observed across the remaining sub-basins covering Bilaspur, Chamba, Solan and Shimla, indicating widespread flooding conditions across much of Himachal Pradesh.

By 10 July, areas with runoff exceeding 106 mm were restricted mainly to the districts of Mandi, Kullu and Hamirpur (Fig. 13c), while other districts continued to record runoff between 61 and 105 mm, reflecting the persistence of flooding conditions across the state. On 11 July, notable runoff was still observed over parts of Kangra and Mandi, particularly along the sub-basins of the Beas River.

By 12 July, the primary zone of rainfall activity had shifted toward Uttarakhand, leading to a gradual reduction in soil moisture over Himachal Pradesh. Correspondingly, the highest runoff values were recorded over Uttarakhand on this day (Fig. 13e), consistent with the observed eastward shift in the heavy rainfall pattern.

4. Conclusions

This study evaluated the performance of the South Asia Flash Flood Guidance System (SAsiaFFGS) in capturing the flash flood events over Himachal Pradesh during 8–11 July 2023. The key findings are summarized below.

(i) SAsiaFFGS effectively captured the evolving flash flood conditions over Himachal Pradesh during the study period, both temporally and spatially. The system consistently reflected the intensifying hydrometeorological conditions associated with the observed extreme rainfall events.

(ii) The 24-hour Flash Flood Risk (FFR) products showed progressively increasing positive threat signals, indicating heightened potential for flash-flood occurrence. The Imminent Flash Flood Threat (IFFT) and Persistent Flash Flood Threat (PFFT) indices, each with six-hour validity, were generated with good spatial accuracy for the specific watersheds that experienced flooding.

(iii) The integrated Average Soil Moisture (ASM) estimates, updated every six hours, were well simulated and closely aligned with the observed rainfall distribution and intensity across the region. The temporal evolution of ASM corresponded effectively with the progression of the heavy rainfall episodes.

(iv) Fully saturated soil moisture conditions (ASM = 1.0) do not necessarily guarantee the occurrence of surface runoff or flash flooding. The generation of flash-flood threats depends not only on antecedent soil saturation but also on the magnitude, spatial distribution and temporal accumulation of rainfall.

The Flash Flood Threat (FFT) and Flash Flood Risk (FFR) outputs rely on rainfall forecasts from numerical weather prediction (NWP) models, as FFT is computed from the difference between Flash Flood Guidance (FFG) and accumulated model-forecast precipitation for the required duration. Consequently, uncertainties inherent in the NWP model forecasts are propagated into the SAsiaFFGS generated threat and risk products.

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