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Short to medium range impact based forecasting of heavy rainfall in India

M. MOHAPATRA, ANSHUL CHAUHAN, AVNISH VARSHNEY, SUMAN GURJAR, M. T. BUSHAIR, MONICA SHARMA, R. K. JENAMANI, KULDEEP SRIVASTAVA, PULAK GUHA THAKURTA[1], RAJIB CHATTOPADHYAY[1], MAMTA YADAV[2], RADHESHYAM SHARMA[3], A. K. MITRA, ANANDA KUMAR DAS, SANKAR NATH, NARESH KUMAR, SOMA SENROY, T. ARULALAN, AMIT BHARADWAJ, D. R. PATTANAIK, B. P. YADAV[4], RAHUL SAXENA, ASHOK KUMAR DAS, ASOK RAJA, HEMLATA B., ARUN K. V. H.[5], NITHA S.[6], ATUL K. SINGH[7], SHOBHIT KATIYAR, KRISHNA MISHRA, SURENDRA PRATAP SINGH, SHASHIKANT MISHRA, AKHIL SRIVASTAVA, GEETHA B.[8], RAHUL M.[9], K. NAGARATNA[10], H. R. BISWAS[11], MANORAMA MOHANTY[12], R. THAPLIYAL[13], SHIVINDER SINGH[14], SONAM LOTUS[15], SANDEEP KUMAR SHARMA[16], V. K. MINI[17], SUNIT DAS[5], G. K. DAS[18], ABHISHEK ANAND[19] and GAYATRI VANI K.[20]

India Meteorological Department (IMD), MoES, New Delhi – 110 003, India

[1]IMD Pune, [2]IMD Bhopal, [3]IMD Jaipur, [4]Retired Scientist IMD, [5]IMD Guwahati, [6]IMD Mumbai, [7]IMD Lucknow, [8]IMD Chennai, [9]IMD Goa, [10]IMD Hyderabad, [11]IMD Bhubaneswar, [12]IMD Ahmadabad, [13]IMD Dehradun, [14]IMD Chandigarh, [15]IMD Srinagar, [16]IMD Shimla, [17]IMD Trivandrum, [18]IMD Kolkata, [19]IMD Ranchi, [20]IMD Raipur

e mail : m.mohapatra@imd.gov.in

सार – पिछले कुछ दशकों में मॉनसून के प्रेक्षण और संख्यात्मक मॉडलिंग दोनों में महत्वपूर्ण रूप से प्रगति के कारण मॉनसून ऋतु में भारी वर्षा को समझने में काफी प्रगति हुई है। इन सभी के परिणामस्वरूप पिछले पांच वर्षों की तुलना में हाल के पांच वर्षों (2018-2022) में भारी वर्षा के पूर्वानुमान की सटीकता में 40% के सुधार के साथ लघु से मध्यम अवधि (पांच दिनों तक) में भारी वर्षा का अधिक सटीक पूर्वानुमान दिया गया। हालांकि, जान-माल की क्षति को कम करने के लिए पूर्वानुमान और चेतावनी कौशल में यह सुधार पर्याप्त नहीं है। जोखिम आधारित चेतावनी (RBW) और जीवन एवं आजीविका की रक्षा हेतु त्वरित कार्रवाई के लिए जोखिम पूर्वानुमान प्रणाली (आपदा मॉडल) और इसके प्रभाव तथा जोखिम मूल्यांकन के लिए हितधारक के साथबातचीत आवश्यक है।

इन सभी को ध्यान में रखते हुए, भारत मौसम विज्ञान विभाग (IMD) ने जुलाई 2013 से मौसम संबंधी उपखंड स्तर पर भारी वर्षा के लिए प्रभाव आधारित पूर्वानुमान (IBF) आरंभकिया और अगस्त, 2019 में जिला और शहर के स्तर पर विभिन्न क्षेत्रों में भारी वर्षा के प्रभाव और आवश्यक प्रतिक्रिया कार्रवाई लघु से मध्यम अवधि के पूर्वानुमानों और तात्कालिक अनुमानों में संभावना का संकेत दिया। इसके बाद पिछले कुछ वर्षों में भारी वर्षा के IBF में कई बदलाव हुए हैं। वर्तमान में, भारत मौसम विज्ञान विभागद्वारा कार्यान्वित किए जा रहे IBF में सभी चार घटक शामिल हैं, जैसे, (*i*) मौसम संबंधी संकट, (*ii*) भूभौतिकीय संकट, (*iii*) भू-स्थानिक अनुप्रयोग और (*iv*) सामाजिक-आर्थिक स्थितियां और यह एक वेब-जीआईएस आधारित निर्णय समर्थन प्रणाली (डीएसएस) का उपयोग करता है। इस अध्ययन में हमने भारत में भारी वर्षा के प्रभाव आधारित पूर्वानुमानके विकास के विभिन्न दृष्टिकोणों और चरणों की समीक्षा की है। भारी वर्षा के आईबीएफ की सफलता कृषि, जल और बिजली जैसे महत्वपूर्ण संसाधनों के प्रबंधन को बढ़ाएगी और जान-माल के नुकसान को कम करते हुए शहरी और आपदा प्रबंधन क्षेत्रों को सहयोग करेगी।

ABSTRACT. There have been major advances in the last few decades in our understanding of heavy rainfall during monsoon season due to substantial progress in both observation and numerical modelling of monsoon. All these resulted in more accurate forecast of heavy rainfall in short to medium range, (upto five days) with 40% improvement in accuracy of heavy rainfall forecast in recent five years (2018-2022) as compared to previous five years. However, improvement of forecast and warning skill is not sufficient to minimize damage to lives and property. It is essential to extend to hazard forecast systems (hazard models) and then to impact and risk assessment with stakeholder interaction for risk based warning (RBW) and response action to protect lives and livelihoods

Considering all these, India Meteorological Department (IMD) has introduced impact based forecast (IBF) for heavy rainfall at meteorological sub-division level since July 2013 and at district and city scale in August, 2019 in its short to medium range forecasts and nowcasts indicating the likely impact of the heavy rainfall in different sectors and required response actions. Thereafter the IBF of heavy rainfall has undergone several changes over the years. Currently, the IBF being implemented by IMD includes all the four components, *viz*., (*i*) meteorological hazards, (*ii*) geophysical hazards, (*iii*) geospatial applications and (*iv*) socio-economic conditions and it utilises a web-GIS based decision support system (DSS). In this study we have reviewed various approaches and stages of development of IBF of heavy rainfall in India. The success of IBF of heavy rainfall will enhance the management of critical resources like agriculture, water & power and support urban and disaster management sectors among others while reducing loss of life and property.

Key words – Monsoon, Heavy rainfall, Impact based forecast, Hazard, Vulnerability, Risk, Monsoon, Cyclone.

1. Introduction

Indian monsoon shows large scale intra-seasonal variation leading to wet & dry spells and hence floods and droughts during the southwest monsoon season (June to September) and northeast monsoon season (October to December) in different spatial and temporal scales (Rao, 1976). The impact of the variability of the monsoon on food-grain production and gross domestic products are well known (Gadgil *et al*., 1999) apart from the human and property losses due to heavy rainfall. In addition to it, the monsoon disturbances including lows, depressions and cyclones also occur during these seasons leading to loss of lives and properties due to mainly heavy rain leading to floods (Mohapatra, 2008; Mohapatra *et al*., 2021). The extreme precipitation events affect different parts of the country depending upon the areal coverage, duration and intensity of rainfall and the types of hazards triggered by the heavy rainfall events. With varied physiography in terms of mountain ranges including the Himalayas, Western Ghats and Eastern Ghats, other hills and mountains, coastal plains, plateaus, rivers, lakes and deserts, the heavy rainfall related hazards & their impact depend on the geo-physical features and socio-economic conditions and exposures of the region. The primary hazards associated with such events can be categorized into pluvial floods caused by surface run-offs associated only with the rainfall event. It can include flash flood, urban flood, coastal flood and riverine flood. All these can lead to landslides, mudslide, land slip/land sink, mud and debris flow, dam burst, glacial lake outburst, soil erosion and water related diseases.

The frequency of extreme precipitation events and rainstorms show a rising trend (Pai *et al*., 2015) in many parts of India. Further studies indicate that extreme precipitation events and associated floods are likely to increase under the warmer climate in India (Mukherjee *et al*., 2018; Ali *et al*., 2019; Fowler *et al*., 2022). Hence, there is an increasing risk of economic loss and damage to infrastructure. Dottori *et al*. (2018) showed that 1.5 °C increase in global mean surface air temperature from the pre-industrial level will lead to an increase in human losses from flooding by 70-80% with a higher risk in South Asia.

There have been major advances in the last few decades in our understanding of the monsoon and its variability. Substantial progress has been made on both observation and numerical modelling of monsoon (Mohapatra *et al*., 2020). All these have resulted in more accurate monsoon and associated heavy rainfall forecast in different spatial scales like meteorological subdivisions, river catchments, districts and cities upto five days (Mohapatra *et al*., 2009, 2021, 2022). However, improvement of forecast and warning skill of heavy rainfall alone is not sufficient to minimize damage to lives and property. It is essential to extend severe weather standalone forecast and warning system, to hazard forecast systems (with hazard modelling) and then to impact estimation (with impact modelling) with proper stakeholder interaction for risk based warning (RBW) and response action to protect lives and livelihoods. It is mainly due to the fact that (*i*) weather models and other hazards models are not coupled (*e.g*., landslides, storm surge), (*ii*) there is lack of scientific and technical capacity to translate hazard information into impacts leading to underestimation of impact, (*iii*) there is inadequate communication channels, which may fail also during the event, (*iv*) there is lack of appreciation and utilization of available vulnerability information (maps) at local level; (as information is either not shared or not routinely updated and not available in digital format) and (*v*) there is lack of effective Decision Support System (DSS). The institutional strengthening mechanism and improvements in observations and forecasting systems are necessary but not sufficient prerequisite to reduce impacts. There is need to understand why people do not move to safety in case of warnings issued by National Hydrometeorological Services Centre. Consistency and accuracy of forecast also matter in triggering effective response. Further it may be due to the fact that (*i*) the people do not know of the danger? (lack of awareness), (*ii*) they know it but choose to ignore it? (Pressing need/objective, *e.g.*, visit to a pilgrim place on a specific day) and (*iii*) they do not understand the scientific language?

Considering the impact of severe weather, IMD commenced providing impact based forecast (IBF) and RBW upto coastal district level for landfalling cyclones using its historical data on associated Hazard, exposure and vulnerability in beginning of 1990s (IMD, 1992). IMD introduced heavy rainfall IBF in July, 2013 after the disastrous heavy rainfall episode over Uttarakhand in June, 2013 at meteorological sub-division level by assigning different colour codes to different categories of heavy rainfall forecast based on threshold values like heavy, very heavy and extremely heavy rainfall (WMO, 2015; IMD, 2014). IMD introduced the IBF on heavy rainfall since August 2019 at the district and city scale in its short to medium range forecasts and nowcasts indicating the likely impact of the rain in different sectors and required response actions relying on the threshold based severity of rainfall determined from its past data and past knowledge of associated hazards and impacts. Since 2020 monsoon season, such IBF and RBW services were made available operationally at 25 major capital cities (IMD, 2021a) and river catchment (IMD, 2021b) considering the past matrix of heavy rainfall impact. In the monsoon season, 2021, scope of IBF & RBW was further expanded to all districts with collections and layering of exposure, hazard, vulnerability and impact data and hence development of RBW. The urban flood model, flash flood guidance system, susceptibility zonation maps for landslide and a web-based Dynamic Composite Risk Atlas (WEB-DCRA) for cyclone have been introduced during 2021-2022. Thus, the IBF currently under implementation by IMD includes all the four components, *viz.*, meteorological hazards, (*ii*) geophysical hazards, (*iii*) geospatial applications and (*iv*) socio-economic attributes. Present paper reviews various approaches and stages of Development of IBF followed by IMD for heavy rainfall events. The success of IBF initiated for heavy rainfall during monsoon season will enhance the management of critical resources like agriculture, water & power and support urban and disaster management sectors among others.

2. Need for Impact-based Forecasting (IBF) of heavy rainfall in India

The IBF aims at a fundamental change in focus from (*i*) what the weather will be to what the weather will do tomorrow. It arises naturally from a focus on users needs. It is needless to mention that weather information is normally just one "input" into decision-making by users. There is a need to increase the relevance of weather information to users and to increase the awareness of forecasters and others within the national meteorological and hydrological service of the country on users' needs and concerns.

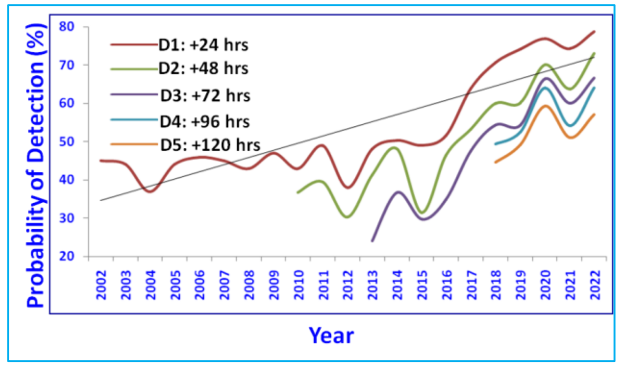


Fig. 1. Average probability of detection (%) of heavy rainfall warning at meteorological subdivision level issued by IMD during monsoon season (2002-2022)
IMD : India Meteorological Department

According to United Nations Office of Disaster Risk Reduction (UNODRR) (UNODRR, 2015), among the member countries of World Meteorological Organization / United Nations – Economic & Social Commission for Asia and Pacific (WMO/UN-ESCAP) Panel on tropical Cyclones (TC) over the Bay of Bengal and Arabian Sea, the loss is maximum in India amounting to 1,160.44 Million USD followed by Bangladesh amounting to 465,85 Million USD. Considering the latest example of heavy rainfall induced landslides in Uttarakhand in June, 2013 (IMD, 2013), which caused catastrophe with about 4000 human deaths, it was mainly due to lack of hazard and impact modelling system. There was no IBF by IMD for the flooding event in Uttarakhand in 2013. Many of the people killed were tourists/pilgrims who were not familiar with the local environment. There was inadequate coordination between meteorological service centre and the local, state and national disaster management agencies. The impact of the severe weather hazard could not be anticipated in the absence of IBF, impact modelling and risk assessment. Similarly, considering the latest example of very severe cyclonic storm (VSCS), Titli which crossed north Andhra Pradesh coast and adjoining south Odisha coast on 17th October, 2018 with a wind speed of 80 knots killed about 77 people in Odisha due to associated landslides and floods, even though there was a good quality forecast from IMD about track, intensity and landfall as well as rainfall, wind and storm surge [Regional Specialised Meteorological Centre (RSMC), New Delhi, 2019]. The disaster managers and people expected the wind and rainfall and could not anticipate the impact due to land slide and flood in south interior Odisha.

There is considerable improvement in heavy rainfall warning skill in recent years (Fig. 1) for next 72 hrs. According to Mohapatra *et al*. (2022), for 24 hrs lead period, probability of detection (PoD) has improved significantly and is 77% in year 2020 as compared to 50% in 2014. For 48 hrs forecast, it has improved from 48% to 70% and for 72 hr forecast, it has improved from 37% to 66% from year 2014 to 2020. The heavy rainfall warning issued for 120 hrs forecast in year 2020 has accuracy of 59%, whereas, it was 50% for 24 hrs forecast in year 2014. Hence, there is a gain of four days in lead period of heavy rainfall warning in 2020 as compared to 2014. Hence, with the improvement in forecast accuracy there was increasing demand for IBF.

3. IBF of heavy rainfall in India: issues & challenges

The IBF is essentially a move from information based forecast to impact based information and RBW. It is a shift from (Observations + Forecast + Warning) process to (Observations + Forecast + Expected Impacts + Risk based warning) process. The impact forecasting is more important than forecasting pure meteorological elements. The impact forecasts are more readily understood by those at risk and those responsible for mitigating those risks. The forecasters are often reluctant to predict impact which may be due to lack of confidence in the forecast in association with uncertainty, lack of knowledge of vulnerability & exposure conditions and lack of DSS. The extensive knowledge of vulnerability and exposure are a pre-requisite for developing the IBF.

The big data concept can enable IBF and decision making. Basically, it can convert the data to information which are useful, organised and structured even without knowing nothing about the raw data. The information then can be converted into contextual, synthesised knowledge for learning. This knowledge can further be converted into wisdom for understanding, integration of knowledge/ information for actionable impact based decision making.

While implementing the IBF, we have to focus on user-first design concept. Basically, it means focusing on real needs and experiences of users at different geographical domain like at national, state, district, block, panchayat, village, street & house level. The second objective is to create a geospatial digital grid to accommodate surface digital data on meteorological and hydrological parameters, geo-spatial data including land use land cover data and climatological data on normal and extremes. IMD is developing an open architecture with standard interface to accommodate different types of data with different formats so that the isolated data can be converted into an integrated system. There is willingness on the part of IMD including that of developers and forecasters to walk extra mile to integrate all required data from different sources. It is developing core algorithm for decision making on IBF and RBW. It is understood that the decision making should not be hasty, but well planned. The emergency management plan needs to be well designed at the front end. The easy design tools are being developed and clear message will be generated for IBF and RBW in the form of text, audio, video, graphics and their combination.

For communicating the IBF and RBW, there should be interaction through various broadcasting tools including mobile apps and web-GIS. These two tools enable people to report emergency case in time with accurate location. In the old system, most of people were consuming the warning information pushed by IMD. The Government focused more on improving the broadcasting of warning message to people as much as possible and as quickly as possible. In the new system, the people are generating and consuming data at the same time. The mobile internet and social media enable people to report accident or emergency related information while being warned about the severe weather also with impact and response action information. Considering all these, while the traditional communication channels still are used, the social media are also adapted by IMD. Further considering the fact that the people are not only consuming but also generating data, IMD initiated the crowd sourcing of meteorological and hazard data through web interface in 2020 and mobile app in 2022.

While there is need of flat map for data browsing, there is need of topographical map for risk analysis and high-resolution map for decision making. There could be many mathematical (Numerical Weather Prediction (NWP) models), hazard models, vulnerability models, based on which the IBF would be developed and RBW will be issued in either objective or subjective manner with intelligence navigation of data and products.

4. Methods of IBF of heavy rainfall adopted by IMD

IMD adopted the methodology described by WMO (2015) in the form of guidelines on multi-hazard IBF and warning services as shown in block diagram in Fig. 2. Relevant information from weather information is extracted and placed into the situation context to produce impact estimations. With potential impact information available, response scenarios are generated. It moved from (*i*) phenomenon based forecast to IBF, (*ii*) product based services to decision support services, (*iii*) meteorological threshold based warning to impact threshold based warning and (*iv*) deterministic forecast to probabilistic forecast with specification of uncertainty. While there have been significant progress with respect to (*i*) to (*iv*),

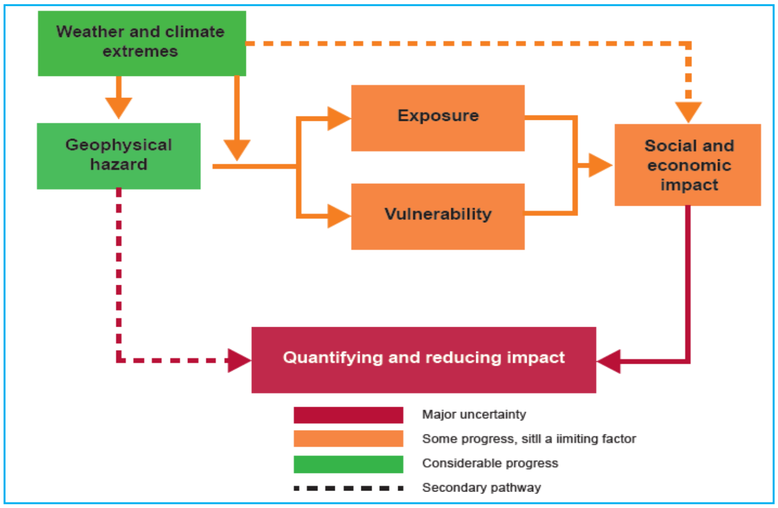


Fig. 2. Flow chart of IBF as per WMO (2015) guidelines

- *Solid arrows*: Modelling approach (each element explicitly calculated). Requires data on vulnerability & exposure, which are acquired from other agencies.
- *Dotted orange arrow*: Subjective approach (qualitative information collected from expert partners). This information represents sum of their experience & allows estimation of impact directly from magnitude of hazard.
- *Red arrows*: Traditional approach whereby the magnitude of likely impact is related directly to magnitude of meteorological hazard. This approach can help in identifying & reducing risk, but takes no explicit account of exposure or vulnerability.

IBF : Impact based forecast, WMO: World Meteorological Organisation

there is still scope to improve further. The impact is being assessed based on expected location of severe weather in terms of city and district, time of occurrence (time of the day and time of the year), recent rainfall and non-rainfall factors like associated geophysical hazard, vulnerability and exposure including Socio-Economic conditions. There are various methods adopted by IMD following WMO (2015) for implementation of IBF as mentioned below:

4.1. *Threshold method*

In this method, a forecast threshold of rainfall is defined at which people or infrastructure in a specific location is expected to be negatively impacted, based on the vulnerability of that location/infrastructure. Based on the historical events, magnitude of hazard impact is identified. The different colour codes are assigned based on the likelihood of occurrence and severity of impact (Fig. 3). It was being provided in spatial scale of meteorological subdivision since 2013. The threshold is defined in advance. The threshold defined for heavy rainfall IBF is given below:

Category	Colour code of heavy rainfall warning to indicate impact
Heavy rain (64.5 - 115.4 mm	Yellow
Very heavy rain (115.5 - 204.4 mm)	Orange
Extremely heavy rain (204.5 mm)	Red

Thus, this method is mainly based on rainfall threshold, likelihood of occurrence and expected standard impact. An example of this type of IBF is shown in Fig. 4. The standard impacts of heavy rainfall warning in association with yellow, orange and red colour are shown in Table 1. It does not take into consideration the specific vulnerability and exposure conditions of the place and time.

4.2. *Qualitative combination method*

In this method, a composite index that combines relative vulnerability with forecast hazard magnitude is created. It takes into consideration past cumulative rainfall for a few days (typically for five days) and forecast rainfall for next five days to create a relative priority score. The decision is taken through the exchange of knowledge, experience and expertise of forecasters through a video conference at 1030 hrs IST of everyday to provide IBF of rainfall for next five days (Day 1… Day 5). Thus, IMD developed a generalized impact through consensus among the forecasters based on subjective assessment of potential impacts corresponding to weather warning threshold as mentioned in section 4.1. In the process, vulnerability rankings of locations/ area within a larger region are taken into consideration from the knowledge of the forecasters. No historical data is used in this method. The IMD brings together experts to look at a weather forecast and assign colour codes to

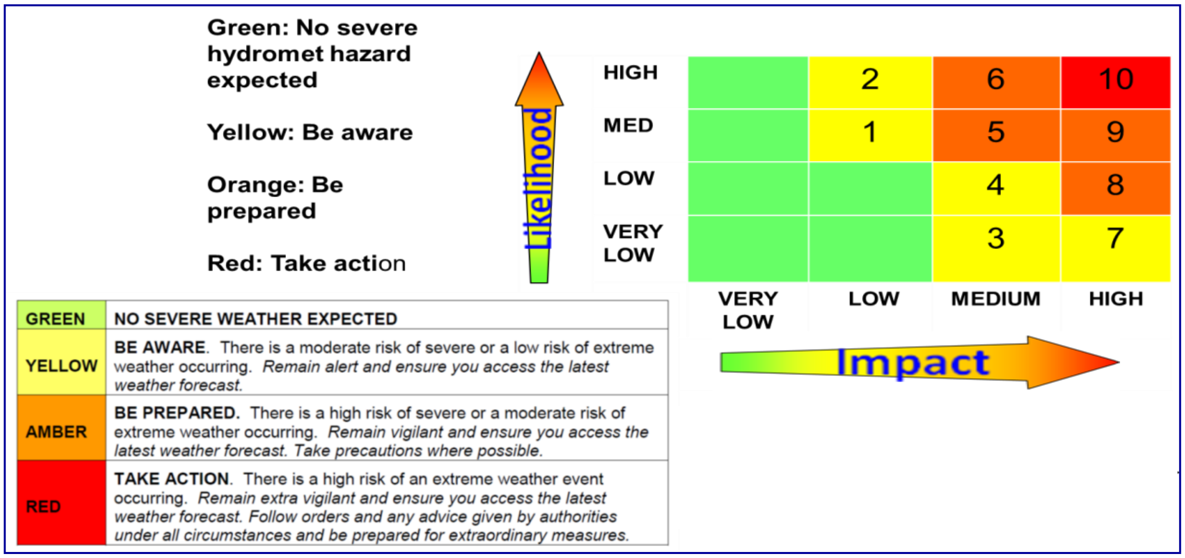
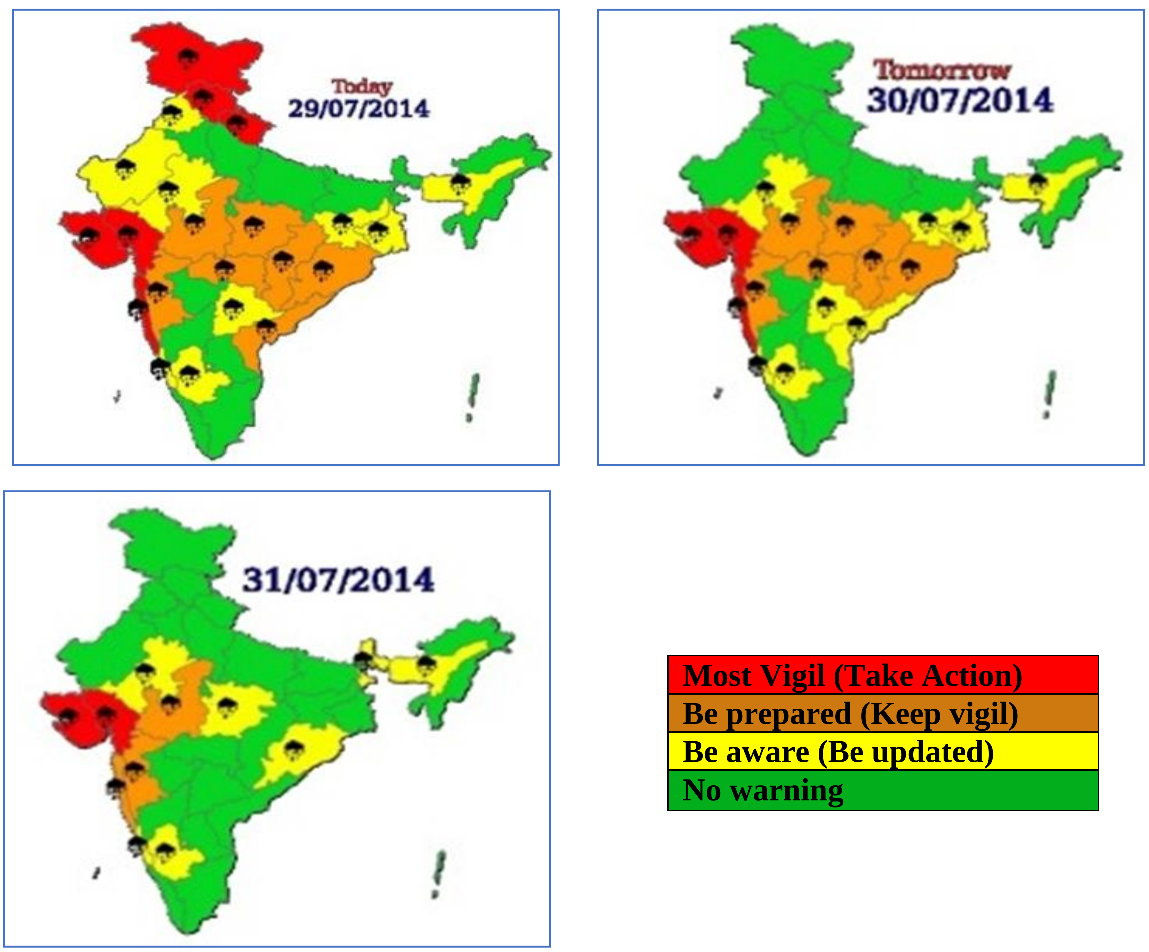


Fig. 3. Decision making on colour codes for IBF as adapted by IMD following WMO (2015) guidelines.
IBF : Impact based forecast, IMD : India Meteorological Department, WMO: World Meteorological Organisation



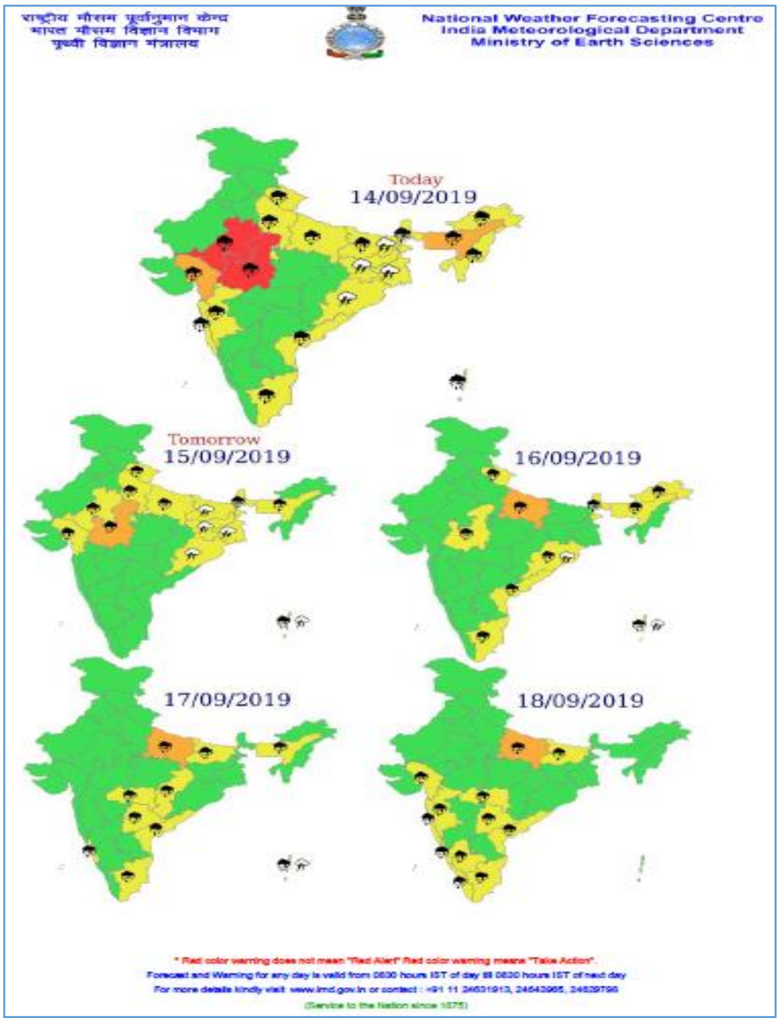
Warning is valid from 0830 hours IST of the day till 0830 hours IST of next day

Fig. 4. A typical example of IBF of heavy rainfall issued by IMD using threshold method indicating impact in terms of colour codes only. IBF : Impact based forecast, IMD: India Meteorological Department

TABLE 1

Categorisation of impact of heavy rainfall by IMD for the purpose of IBF

LOW (Yellow) Minor	MEDIUM (Orange) Significant	HIGH (Red) Severe
A few localised impact incidents, minor disruptions, no specific actions required by disaster managers. However, the disaster managers and public need to be updated	Major disruption in day to day activities, large area likely to be affected. Significant damage to property expected Disaster managers and public to be cautious and be prepared for action	Extensive and Prolonged disruption in daily activities Large scale damage to property expected Disaster managers and public to take response action



- Heavy to very heavy rainfall with Extremely heavy falls very likely at isolated places over East Rajasthan and Meghalaya.
- Heavy to very heavy rainfall very likely at isolated places over West Madhya Pradesh, Assam and Gujarat Region

Expected impact corresponding to "Red color" warning

- Localized Flooding of roads, water logging in low lying areas and closure of underpasses.
- Occasional reduction in visibility due to heavy rainfall.
- Disruption of traffic flow in major cities due to water logging in roads leading to increased travel time.
- Minor damage to Kutch roads.
- Possibilities of damage to vulnerable structure
- Localized Mudslides.
- Damage to horticulture crops

Most Vigil (Take Action)
Be prepared (Keep vigil)
Be aware (Be updated)
No warning

Fig. 5. A typical example of IBF of heavy rainfall issued by IMD using qualitative combination method
IBF: Impact based forecast. IMD : India Meteorological Department

different regions depending on a combination of probability and impact, as a part of IBF in a qualitative manner based on knowledge of forecasters. An example is shown in Fig. 5. It commenced since monsoon season of 2019. The generalized impact information in terms of water logging, inundation, traffic jam, landslide/slip, damage to huts etc. are issued corresponding to orange and red colour warning in a meteorological sub-division/district 2-3 days in advance, though yellow colour warning is issued upto five days in advance.

4.3. *Impact modeling method*

IMD introduced impact modeling method in 2020. In this method a model that combines hazard magnitude with vulnerability and exposure to predict a level of impact is developed (Hemingway and Robbins, 2020). Various data like demography, population density, rural-urban population, socio-economic conditions, topography, public utilities, industry, crop, transport, river/dam, forest cover, soil type, tourist places etc were collected from different sources and the process is still continuing. The sources included publications, websites, organizations like National disaster Management Authority (NDMA), Ministry of Power, Ministry of electronics and Information Technology, National Cyclone Risk Mitigation Project (NCRMP) of Ministry of Home Affairs (MHA), Government of India, district national Informatic Centre (NIC), State Govt., etc. For example, historical hazard and impact data were collected from Reports on disastrous weather events of India published by IMD. IMD developed partnership with other government agencies and stakeholders (emergency response agencies, mapping agencies, etc.) for data sharing among different agencies and departments. The workshop and meetings for various stakeholders within and outside IMD were conducted.

The data were collected at state, meteorological subdivision and district levels. The model could be developed based on the data availability and hence for those districts and meteorological subdivisions for which data are available. The districts for which data are not available depended on the impact model or impact matrix developed for the nearby districts. In this way the impact model or impact matrix for each city and district is developed well in advance before the season. It included inputs from:

(*i*) Crop models using rainfall estimates, to estimate scheduling of the crops, various agricultural applications, saving the crop yield from heavy rainfall hazards

(*ii*) Impact on houses and other infrastructure

(*iii*) Impact on transport

(*iv*) Impact in terms of land slide, mud slide, land slip/sink

(*v*) Urban flood and flash floods potential

(*vi*) Cyclone related heavy rainfall hazard impact forecast method of IMD (based on predefined threshold and relation between hazard and impact etc.

IMD developed a generalized impact model based on impact matrix thus developed for 25 capital cities and some districts in 2020. It was extended to all the capital cities and all the districts in 2021. An example of this method of IBF is presented in Fig. 6.

4.4. *Dynamic weather and Climate sensitive impact modeling method*

In this method, the combination of socio-economic baseline data, geophysical data, real time weather data, rainfall climatology (mean, extremes values & percentiles) data and the real time rainfall forecast data are used to assess the hazard, vulnerability and risk. The vulnerability is most closely correlated with forecast rainfall to assess the risk. This involves integrating data about potential hazards with information about the exposure of populations, assets and infrastructure and their vulnerability to hazardous event. The information about the exposure data enables more effective and efficient disaster risk management by providing stakeholders with actionable information about where and when a hazard is likely to happen, how severe it is likely to be and what impacts it is likely to have. Disaster risk managers and decision-makers in the public sector can then make informed decisions about what resources are needed, at what scales and in what location, enabling early and anticipatory response instead of responding once a disaster has occurred. This mitigates the impacts of a given hazard event on communities and ensures resilience of households, infrastructure and livelihood sectors from future hazards. The baseline socioeconomic data are collected from various sources as mentioned in section 4.3 including information about the total population, major amenities, *viz*., hospital, school, power plants, power station, tourism locations, administrative buildings, infrastructure (Airport, Railway lines, road lines), major water bodies (Dams, reservoir, lakes etc.).

This method differs from the impact modeling method in the sense that it attempts to uncover the relationship between climate risk and impacts, rather than trying to quantify anticipated impacts. It includes all the components as discussed in section 4.1-4.3. In addition, real time IBF and RBW is issued based on real time information from

- Rainfall Hazard modeling
- Associated geophysical hazard modeling
- Geo reference Coordinates
- Socio economic data base in digital form
- DSS for internal decision making and DSS for uses in web-GIS format

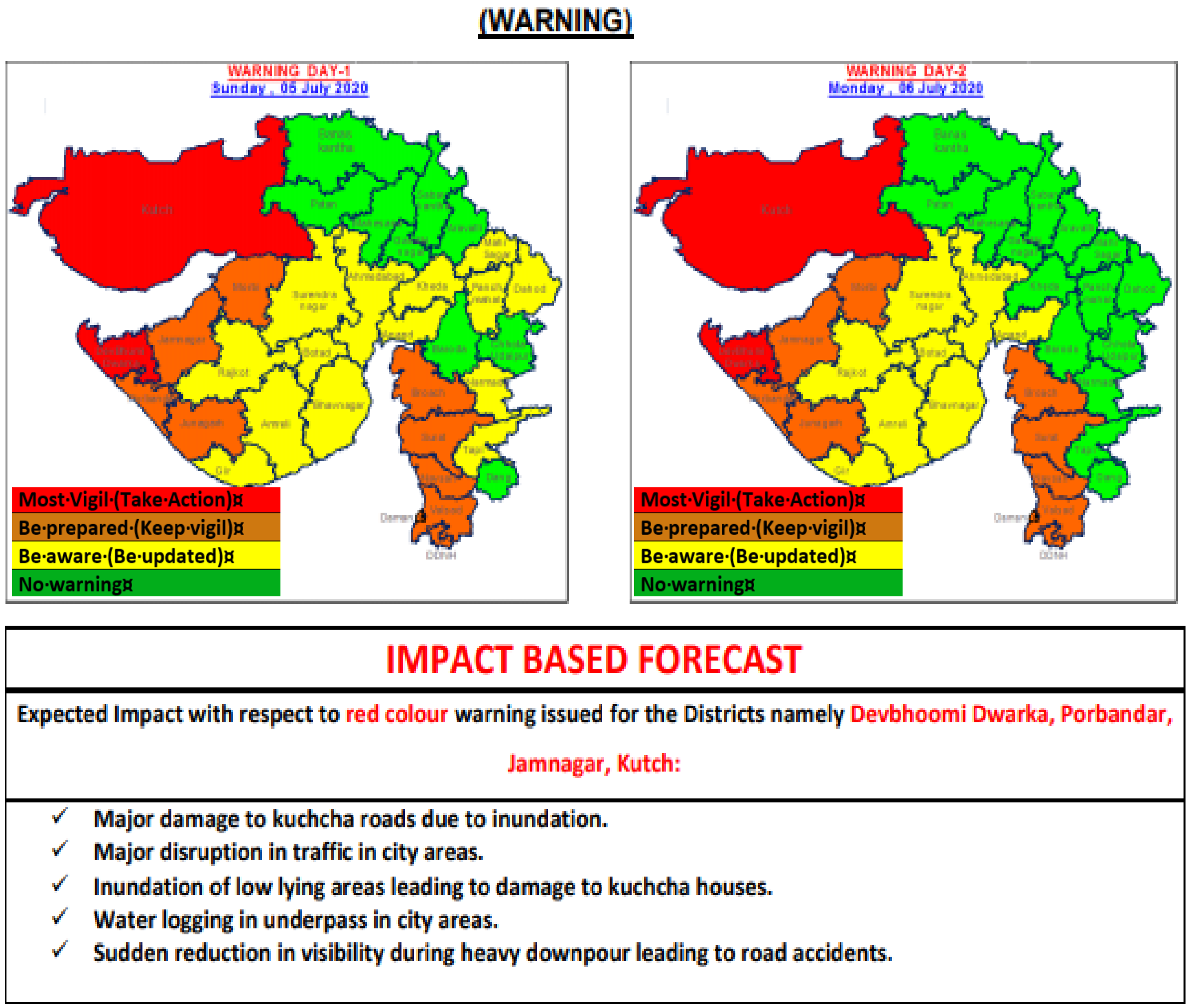


Fig. 6. A typical example of IBF of heavy rainfall issued by IMD at district level using impact modelling method
IBF: Impact based forecast, IMD: India Meteorological Department

Currently, IMD assesses the rainfall hazards from dense and frequent observations and carries out climatological rainfall hazard impact analysis for different land surface processes, *viz*., Rural/Urban, Coastal/Inland, Hilly/Plain area etc. It finalises sector specific matrices (*e.g*., health, public works, transportation etc.). It also integrates other systems like Flash flood guidance, urban flood warning system, web DCRA under NCRMP of NDMA, Govt. of India etc. The details of the data sources and methodology are presented in Table 2 and Fig. 7.

5. Hazard and impact modelling

5.1. *Rainfall hazard assessment based on past data*

For development of rainfall hazard model, the point rainfall data are plotted from about five thousand rain gauge stations in GIS format. The complete process such as collection of the rainfall data, generation of products and dissemination through email & FTP is scheduled to run automatically. The observation products are spatial distribution of 1-7 days cumulative rainfall and 24 hour cumulative rainfall analysis, subdivision wise realized rainfall and monsoon activity (normal, active, vigorous and weak monsoon rainfall) etc. Hence, actual normal and departure from normal rainfall are prepared and analysed in GIS format. All the current weather observations on rainfall based on gauge data, satellite and radar data [quantitative precipitation estimate (QPE)] are integrated in GIS. New graphical products generated are being used in daily bulletin and daily special monsoon report, daily weather videos and social media platforms since year 2021. It has resulted in better visualization and understanding of the rainfall.

TABLE 2

Data sources used for development of heavy rainfall impact module

Past rainfall data	(1) 24 hr cumulative rainfall (R/F) (2) 3 hr cumulative R/F (3) SAFFGS based R/F (4) Past Cumulative R/F (Actual/ Normal/Departure)	(a) Analysis/ point distribution (b) Analysis/ point distribution (c) Analysis/ point distribution D1+D2, D1+D2+D3, D1+D2+D3+D4 D1+D2+D3+D4+D5	
Current rainfall data	Satellite based QPE Radar based QPE Observations (MSLP, winds at 10m, 850 hPa, 500 hPa and 200 hPa levels)		
Models based rainfall forecast	GFS, GEFS, NCEP, JMA WRF, NEPS, NCUM, MME (Including Mean R/F, Min. R/F & Max. R/F)	D1, D2, D3, D4, D5	D1+D2 D1+D2+D3 D1+D2+D3+D4 D1+D2+D3+D4+D5
Final operational rainfall forecast	D1+D2+D3+D4+D5		
Post processed data with various suitable combination of data	(1) –D1 –D2 –D3 –D4 –D5 to +D1,+D2, +D3, +D4, +D5	Suitable combination	
	Satellite and radar based precipitation estimates, Rain gauge and satellite, Radar merged dataset		
	(2) Soil Moisture		
	(3) LULC	(a) NRSC, (b) IIRS	
	(4) Socio-economic	(a) WebDCRA (b) Analog data to be converted to digital (c) Census	
	(5) Geospatial	(a) SOI (b) GSI (Land) (c) Urban Meteorology	
	(6) Climatological Hazard & extremes of rainfall	CRS Pune	
	(7) Real time flash flood guidance		
	(8) Real time urban flood model guidance		

Legends : QPE: Quantitative precipitation estimates, MSLP: Mean sea level pressure, GFS: Global Forecast System, GEFS, Global ensemble forecast system, NCUM: NCMRWF Unified Model, NEPS, NCMRWF ensemble prediction system, WRF: weather research forecast, JMA: Japan Meteorological Agency, ECMWF: European Centre for Medium Range Weather Forecasting, MME: Multi model ensemble, SAFFGS: South Asia Flash Flood Guidance System, SOI: Survey of India, GSI : Geological Survey of India, CRS Pune: Climate Research & Service Pune, NRSC: National Remote Sensing Centre, IIRS: Indian Institute of Remote Sensing, WebDCRA: Web based Dynamic Composite Risk Atlas

5.2. *Climate hazard and vulnerability due to rainfall*

Understanding and building resilience against the heavy rainfall events are very important in this ongoing climate change scenario. Currently, IMD has prepared the Climate Hazard & Vulnerability Atlas of India for the thirteen most hazardous meteorological events, including heavy rainfall, which causes extensive damages, economic, human and animal losses. This web Atlas utilizes GIS tools and is available in IMD, Pune website (https://www.imdpune.gov.in/hazardatlas/index.html). The atlas provides information on nine types of climate hazards. *viz*., Wind Hazard, Extreme rainfall, lightning,

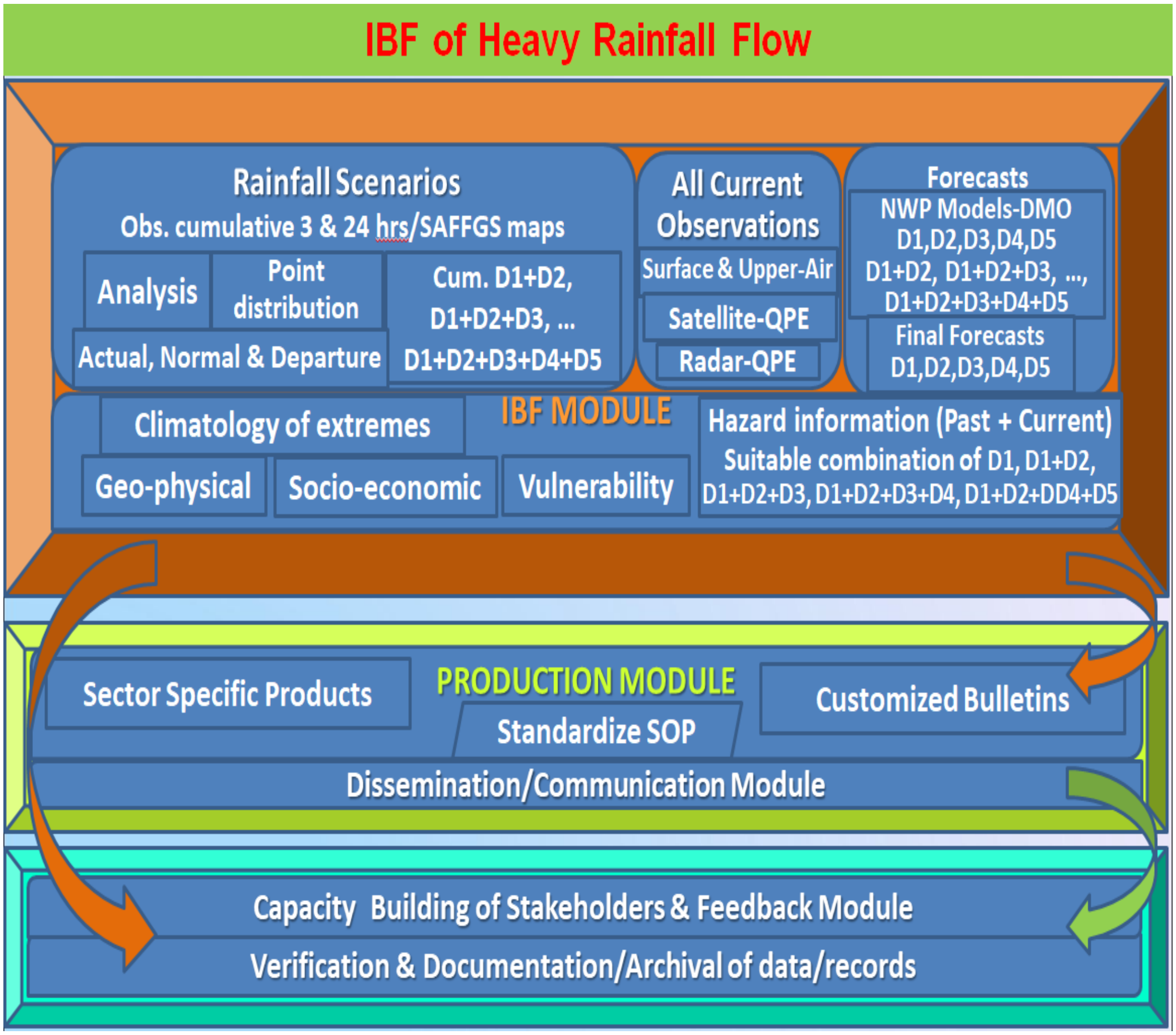


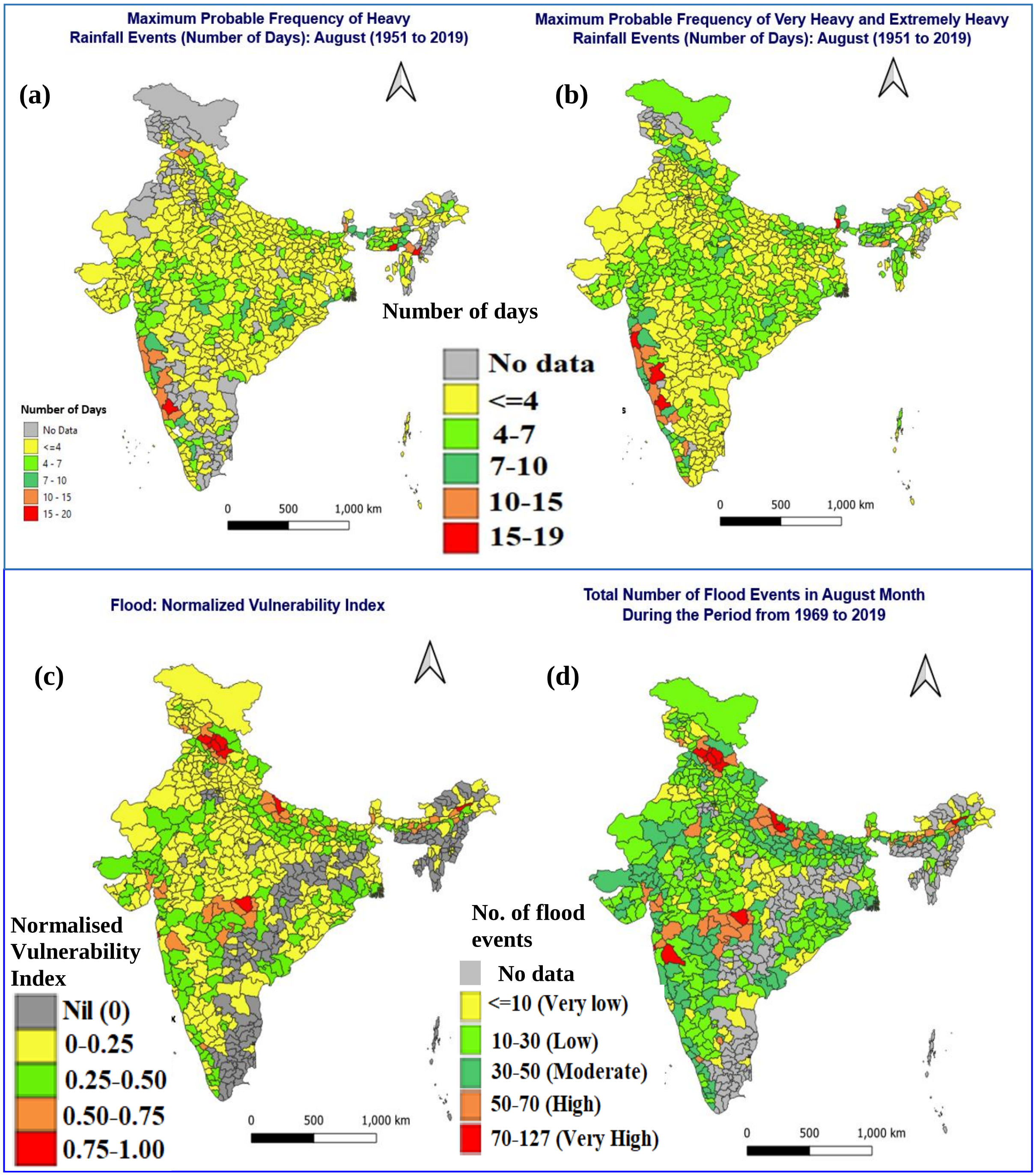
Fig. 7. Flow chart of impact based forecast module for heavy rainfall over India

dust storm, hail storm, fog, drought, cyclone and thunderstorm in terms of their spatial distribution of average number of days of occurrence of probable extreme values and normalized vulnerability index at district scale. The atlas also provides climate vulnerability information at district level on five types of hazards, namely, Cold wave, heat wave, flood, lightning and snow fall. The districts are categories as Very High, High, Medium and Low vulnerabilities for each of the climate hazards including heavy rainfall. The atlas provides pie charts representing the percentage of districts and population affected by disastrous weather events in different vulnerability categories. Thus, the hazard and vulnerability atlas can be used as reference point to issue IBF with respect to heavy rainfall. The rainfall hazard and vulnerability for the month of August are shown in Figs. 8(a-d) as examples.

5.3. *Rainfall hazard modeling*

5.3.1. *NWP model based hazard modelling*

For hazard forecasting IMD uses the rainfall forecast from various NWP models including IMD-Global Forecast System (IMD-GFS), National Centre for Medium Range Weather Forecasting Unified Model (NCUM), National Centers for Environmental Prediction-Global Forecast System (NCEP-GFS), Japanese Meteorological Agency (JMA), IMD-Global Ensemble Forecast System (IMD-GEFS), European Centre for Medium-Range Weather Forecasts (ECMWF) model (Table 2), IMD-Weather Research and Forecast (WRF) and NCUM regional models. Based on all these models a multi-model ensemble (MME) technique has been developed by IMD (Bushair *et al.*, 2023). The products have been



Figs. 8(a-d). Maximum probable frequency of (a) heavy (7-11 cm) & (b) very heavy & extremely heavy rainfall events (≥ 12 cm), (c) normalised vulnerability index for flood and (d) total number of flood events in August based on data of 1969-2019

converted into vector layers using geospatial techniques. Thus, the geospatial layers are generated and integrated to the interactive dashboard for further analysis. These model rainfall products have been classified into three categories, *viz*., heavy rainfall (≥ 64.5 mm), very heavy rainfall (≥ 115.6 mm) and extremely heavy rainfall (> 204.4 mm) at district level. The development of heavy rainfall prediction system is carried out for the above rainfall categories by considering the forecast rainfall exceeding the threshold value of rainfall [heavy ≥ 50 mm, very heavy ≥ 100 mm, extremely heavy rainfall (>150 mm)]. Normally NWP models have a tendency of under-predicting heavy rainfall events and also the gridded rainfall is the average of point rainfall inside the grid.

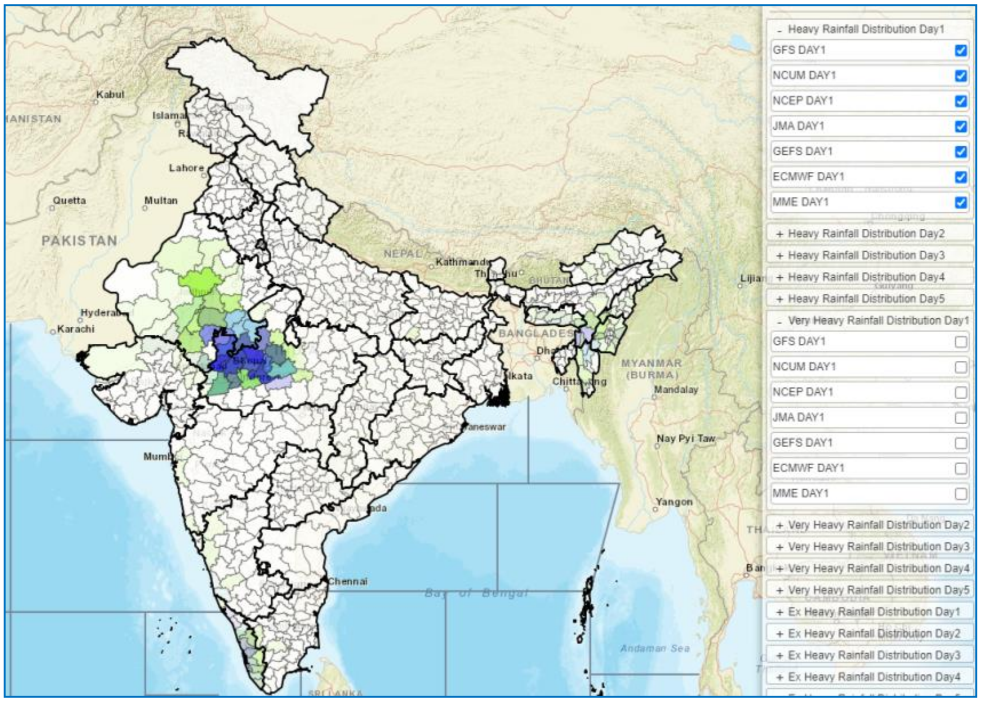


Fig. 9. Interactive dashboard for the assessment of heavy rainfall forecast by 7 numerical weather prediction models forecast of heavy, very heavy and extremely heavy rainfall in terms of intensity and spatial distribution for next 5 days

Therefore, there could be heavy rainfall at a point/location even though the grid point rainfall may be < 64.5 mm. Hence the new thresholds for heavy, very heavy and extremely heavy rainfall events are considered as mentioned above to predict the point heavy, very heavy and extremely heavy rainfall.

After integration there are seven layers from seven models available for analysis in each category (heavy, very heavy & extremely heavy rainfall). For finding the probability distribution of heavy, very heavy and extremely heavy rainfall the polygon is drawn using drawing tool over interactive dashboard by superimposing all layers together. From the drawn area of heavy rainfall the probability of heavy rainfall is calculated based on the number of models predicting heavy rain out of seven models. The probability is considered as low if drawn area is covered by 1-33% of models, moderate, if the drawn area is covered by 34-67% of models and high if drawn area is covered by 68-100% of models. The dashboard for heavy rainfall prediction issued on 22nd August, 2022 is shown in Fig. 9 as an example.

5.3.2. *Flash flood modeling*

According to WMO, flash floods are natural hydro-meteorological hazards with highest mortality rate (defined as the number of deaths per number of people affected) and cause devastating economic loss every year (Borga *et al*., 2014). Flash Floods are defined as fast surface flows with high peak discharge values, often limited in their spatial extent (Georgakakos, 2006). Flash floods are typically associated with high-intensity rainstorms with short response time. Flash Flood occurs usually in less than six hours between the occurrence of the rainfall and peak flood. The most frequent cause of this type of flood is heavy rainfall events (Thomas and Thomas, 2016). Pluvial flooding occurs when rainfall with a high intensity (high amount of precipitation during very short period) exceeds the infiltration capacity of soil, or the discharge capacity of drainage systems and water flows in uncontrolled vulnerable areas (Yin *et al*., 2016).

Recognising that flash floods have disastrous impact on lives and properties of the affected populations, the 15th WMO Congress approved the implementation of a Flash Flood Guidance System (FFGS) project with global coverage in collaboration with the US National Weather Service, the US Hydrologic Research Centre (HRC). The South Asia Flash Flood Guidance System (SASIAFFGS) is a part of Global FFGS Project Initiative by WMO designed to provide the necessary guidance information in real-time to support the development of warnings for flash floods about 6-36 hours in advance at the watershed level with spatial resolution up to 4 × 4 km for the flash flood prone areas in the south Asian countries, *viz*., India, Nepal, Bhutan, Bangladesh and Sri Lanka. WMO has entrusted India with the responsibility of the Regional Centre of SASIAFFGS for coordination, development and its implementation. On 23rd October, 2020, SASIAFFGS was launched operationally by Ministry of Earth Sciences. The system is providing early warning alerts in the form of graphical bulletins every 6 hours (4 times a day). The system as such acquired lots of changes from developmental to operational phase in the input datasets (5400 + gauge stations), new Doppler Weather Radar (DWR) based rainfall rate (19 Indian DWR's), prognostic parameters with full coverage of 5 participating member countries from 3 deterministic models.

The rainfall observations are being collected from IMD rain sensors across India and other National meteorological & Hydrological Services (NMHSs) in the region. The 24 hours cumulative gauge based mean areal precipitation (GMAP) at 0000 UTC of 22nd August, 2022 is shown in Fig. 10(a). The diagnostic merged mean areal precipitation (MAP) is computed by taking the weighted average using Inverse Distance Weighted technique based on IMD rain gauge sensors [Fig. 10(b)], quantitative satellite precipitation estimates of Infrared based Global Hydro Estimator (GHE) from NOAA NESDIS (GOES, METEOSAT and MTSAT satellites) as shown in Fig. 10(c). The resolution of the estimated precipitation from GHE is approximately 4 × 4 km^2. The microwave adjusted GHE using CMORPH algorithm from HRC [Fig. 10(d)] and real time DWR based estimates are also used to generate the flash flood guidance. Further, a lumped Sacramento soil moisture accounting model is used operationally to produce flash flood guidance estimates of a given duration from threshold runoff estimates at every watershed using these meteorological parameters.

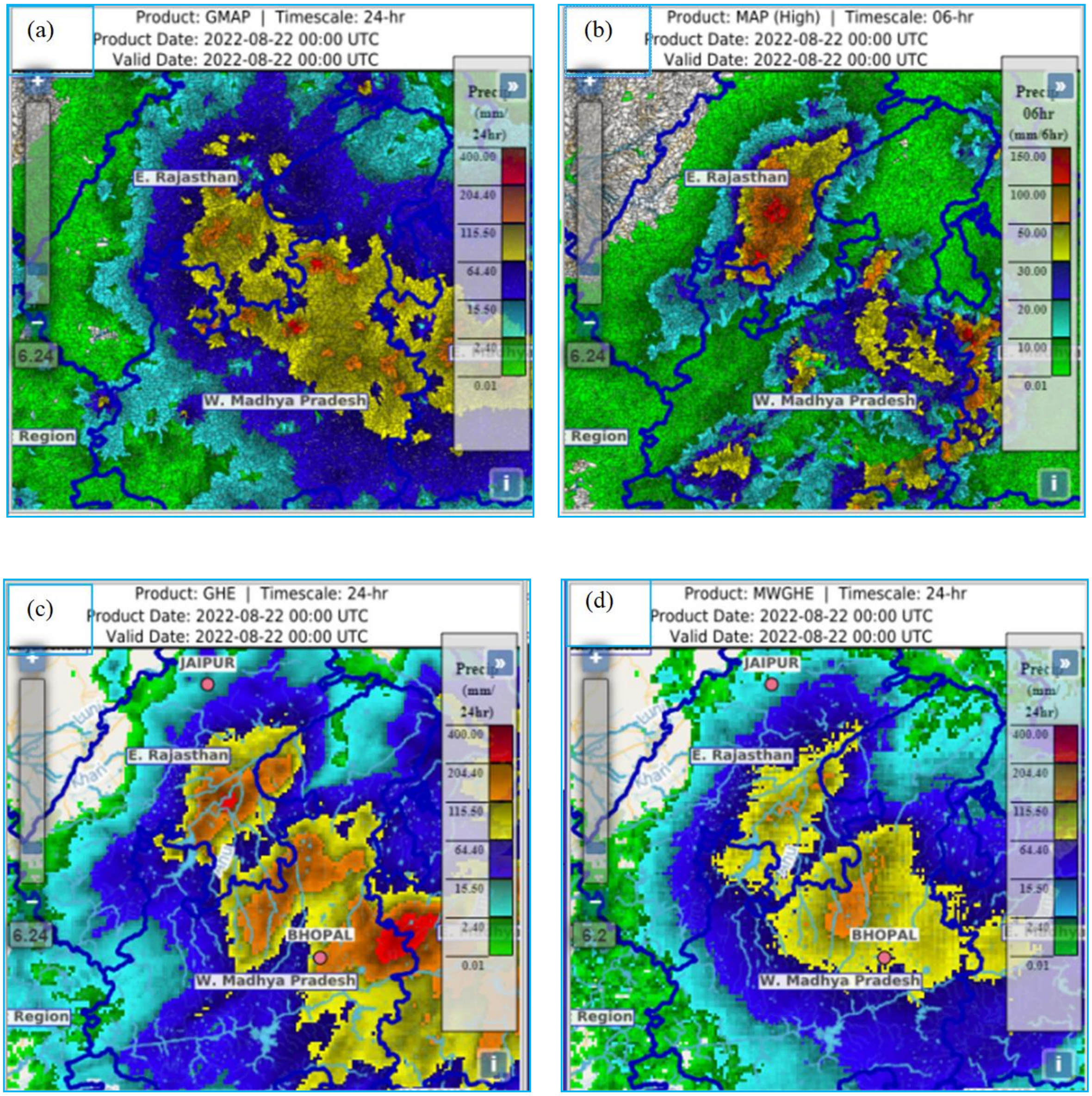
In this system, the prognostic rainfall forecasts are utilised from the operationally run NWP models at IMD & NCMRWF, *viz*., IMD-GFS T1534) (12 × 12 km), NCUM (12 × 12 km), WRF-ARW (3 × 3 km) and NCUM-R (4 × 4 km) with 4DVAR analysis system. Each processed model forecast precipitation domain is used to derive a distinct Forecast Mean Areal Precipitation (FMAP) data product over the sub-basins. Additionally, the gridded precipitation and temperature forecasts lead time are applied in the Flash Flood Risk (FFR) outlook module processing to generate the associated FFR data product index.

The FFGS ingests real-time satellite precipitation data, on-site gauge precipitation and temperature data, model-forecasted precipitation. On the basis of available spatial databases, produces flash-flood-occurrence diagnostic and prognostic indices over small flash flood prone catchments (Yadav *et al*., 2022). The indices are updated regularly and they include: mean areal precipitation from Radar and Satellite estimates (1, 3, 6 and 24 hour accumulations); GMAP (3, 6 and 24 hour accumulations); mean areal temperature (6-hour average), areal snow cover fraction, snow water equivalent, snow melt (24 and 96-hour accumulations), upper soil moisture saturation fraction; flash flood guidance (for 1, 3 and 6 hours in the future); forecast mean areal precipitation (1, 3, 6, 24 hours); imminent flash flood threat (for the last 1, 3 and 6 hours); persistence flash flood threat (for 1, 3 and 6 hours into the future), forecast flash flood threat (for 1, 3 and 6 hours into the future) and flash flood risk based on the regional deterministic model forecasts (for 12, 24 and 36 hours into the future).

The FFGS is the real-time integration of hydrological model that pre-calculates the FFG value by combining the input from the diagnostic hydro-meteorological variables with the estimated rainfall from numerical models. With the use of SRTM DEM ver. 3.0 (30 m) resolution, 30780 small watersheds of India upgraded upto 92885 small watersheds have been delineated with threshold size from 75 sq. km. to 30 sq. km. in reference to the slope and elevation. During 2021 efforts were made to enhance the delineation using GIS and digital terrain information to (a) demarcate watershed boundaries within the region of interest with specified size characteristics and (b) compute geometric characteristics of those watersheds. These geometric characteristics include watershed drainage area, stream length and stream slope, which are used subsequently in the parametrization and computation of flash flood guidance.

5.3.3. *Urban flood modelling*

Urbanization caused due to increasing migration into the floodplains has substantially increased the trend of devastation due to floods in a developing country like India. In Chennai and the surrounding suburban areas, torrential rainfall associated with low-pressure systems engulfed the city during December 2015, affecting more than 4 million people along with economic damages that cost around 3 billion USD. In view of the above-mentioned extreme event in Chennai, an expert system was designed for flood forecasting along with flood inundation maps and possible means of flood management through appropriate interventions for dealing with any such future events (Ghosh *et al*., 2019). The design of such a system involves the coupling of regional weather forecast model, tide forecast model, tidal flood model,



Figs. 10(a-d). (a) GMAP based 24 hr gauge interpolated observed rainfall, (b) MAP based 6 hr Merged Mean Areal Precipitation and (c) GHE & (d) MWGHE based 24 hr accumulated rainfall ending at 0000 UTC of 22nd August, 2022
MWGHE Microwave global hydro estimator, GHE: Global hydro estimator, GMAP: Gauge mean areal precipitation and MAP: Merged mean areal precipitation

urban overland flow model and storm-water drainage model. The expert system is multidisciplinary in nature with the involvement of multiple institutions and organizations. Initiated from the Office of the Principal Scientific Advisor to the Government of India, New Delhi, the Indian Institute of Technology (IIT) Bombay, Mumbai took the lead in developing a fully automated and multi-component urban flood forecasting system with active participation from the Indian Institute of Science (IISc), Bengaluru, IIT Madras and Anna University, Chennai in partnership with the Ministry of Earth Sciences, IMD, NCMRWF, National Centre for Coastal Research (NCCR), Chennai, Indian National Centre for Ocean Information Services (INCOIS), Hyderabad and Indian Space Research Organisation - ISRO, National Remote Sensing Centre (NRSC), Hyderabad. The developed system is now being implemented and maintained in the Chennai Flood Warning System (C-FLOWS) designed by NCCR. The developed expert flood forecasting system has six major components which are connected to each other and all the connections are automated through real-time forecast, monitoring and data sharing.

There has been similar approach demonstrated over Mumbai city (Ghosh *et al*., 2021). This state-of-art urban flood forecasting approach may be implemented in other flood-prone coastal regions as a major non-structural flood management strategy to reduce flood risk and vulnerabilities for the people dwelling in those regions. An example of urban flood warning system product over Mumbai is shown in Figs. 11(a). The corresponding satellite imagery, radar imagery and IBS issued by IMD are shown in Figs. 11(b-d) respectively.

In the SASIASSGS for urban areas, under the high-resolution re-delineation, the basin size threshold has been set at 20 km^2 for the cities whose size is more than 15 km^2. Those cities with size less than 15 km^2 are not considered for re-delineation. The goal of the delineation process is to define the flash flood basins with an average local drainage area of approximately 30 km^2 under the radar umbrellas and maintain the average local drainage area of approximately 100 km^2 outside of the radar umbrellas. Several urban cities, *viz*., Delhi NCR, Hyderabad, Patna, Bhopal, Surat, Ahmedabad, Bangalore, Lucknow, Kolkata, Dibrugarh, Guwahati, Jaipur, Chittagong, Barishal, Dhaka, Pokhara, Kathmandu, Terai, Dharan and coastal cities, *viz*., Mumbai, Mangalore, Puri, Chennai, Gopalpur, Bhubaneshwar, Colombo and Mannar have been re-delineated using high resolution stream thresholds considering its vulnerability. High resolution FFG is available for these cities.

5.3.4. *Riverine flood modelling*

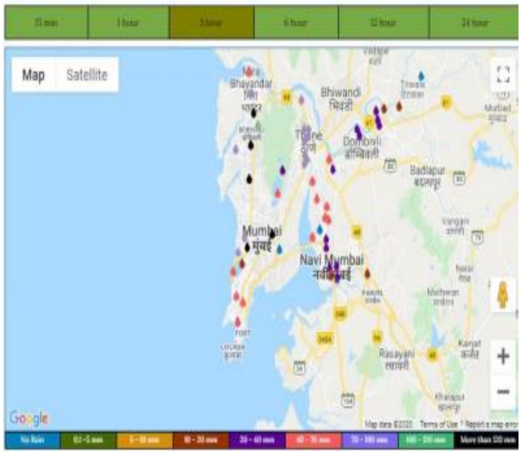
IMD's contribution in riverine flood warning is mainly in the form of Quantitative Precipitation Forecast (QPF) used in the preparation of flood warning/forecast by Flood Forecasting Division of Central Water Commission (CWC)/State Governments. IMD caters this service through its 14 Flood Meteorological Offices (FMO) situated in the different flood prone areas. The FMOs provide Hydro-meteorological support mainly in the form of sub-basin-wise QPF in the following categories: 0, 0.1-10 mm, 11-25 mm, 26-50 mm, 51-100 mm and >100 mm. Forecasts are issued by utilizing the various tools, *viz*., synoptic analysis, satellite & radar imageries & products, synoptic analogue, sub-basin-wise NWP model output and MME. These FMOs issue daily QPF during Flood Season for respective sub-basins under their jurisdiction. The information contains prevailing synoptic situation, average areal rainfall during past 24 hrs., heavy rainfall warning, observed station-wise significant rainfall (≥5cm) and the sub-basin-wise QPF for a lead time of 5-days, for 153 river sub-basins. QPF is also issued in case of cyclone during non-flood season.

Model based Sub-basin-wise QPF from dynamical model WRF ARW (3 × 3 km) for day-1 to day-3, NCUM-R (4 × 4 km) for day-1 to day-3, GFS (12 × 12 km) for day-1 to day-7, NCUM (12 × 12 km) for day-1 to day-7 are used. Also, Model based Sub-basin wise Probabilistic QPF (PQPF) using dynamical model NEPS (12 × 12 km) for day-1 today-5 and GEFS (12 × 12 km) for day-1 today-5 are calculated to provide probabilistic forecast for 153 flood prone river sub-basins. Also, WRF ARW and GFS gridded model rainfall forecast are shared with Central Water Commission (CWC) for their flood forecasting purposes. The QPF is issued in different colour codes considering the expected impact. It is decided in consultation with CWC and Disaster management division of MHA, Govt. of India.

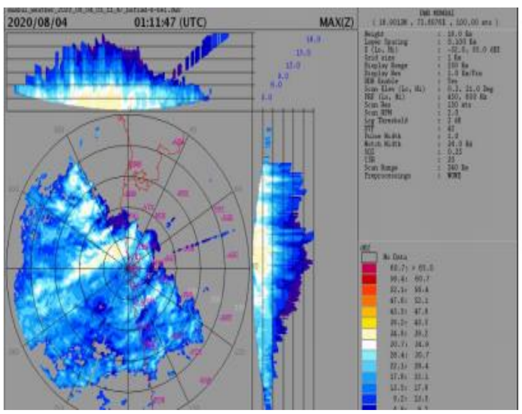
5.3.5. *Geo-spatial data base*

The IBF involves integrating data about potential hazards with geophysical layers. The geophysical layers including Land Use Land Cover (LULC), Digital Elevation Model (DEM), Normalized Difference Vegetation Index (NDVI) are considered for IBF. The DEM is used to detect the low-lying areas, catchment and development of drainage network, slope and aspects. The LULC and NDVI are used to identify the type of class which is impacted due to a heavy rainfall. IMD is developing various geophysical layers required for IBF using open source dataset or derived open source dataset. The high spatial resolution and multi-spectral images generated by Sentinel-2 and Landsat-8 satellite are available for public use. The conventional supervised classification algorithms including maximum likelihood, minimum distance to mean etc. requires the signature for each tile as spectral response varies from one tile to another tile even with the change of time. Image processing and remote sensing researchers nowadays are utilizing the state-of-art machine learning framework (Badrinarayanan *et al*., 2017; Chollet, 2017; He *et al*., 2016; Qui *et al*., 2020) to detect the pattern of LULC as it enables to detect the classes and helps in identification of the changes on large region (Fu *et al*., 2017; He *et al*., 2019; Helber *et al*., 2019; Zhu *et al*., 2017). These methodologies are further enhanced since the launch of Google Earth Engine (GEE) which gives more than 5 Peta Byte dataset access and different algorithms are built-in with the packages (Georelick *et al*., 2017). IMD developed a framework to extract the built-up layers using medium resolution satellite images based on computer vision and machine learning algorithm and aiming first for highly populated cities including Delhi, Kolkata, Chennai and Mumbai. The framework utilises GEE and

(a) Urban flood modeling over Mumbai city

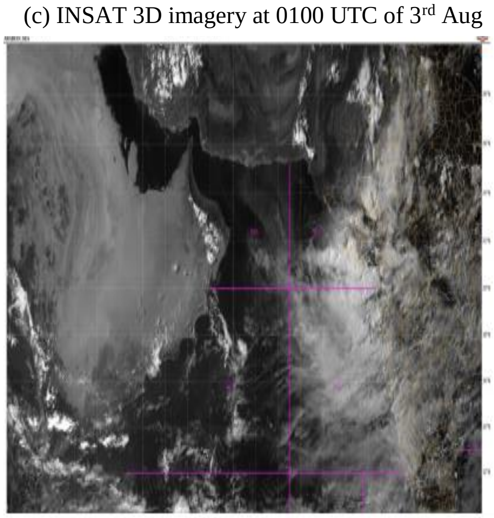


(b) Mumbai radar at 0112 UTC of 3rd Aug



Current satellite Imageries:

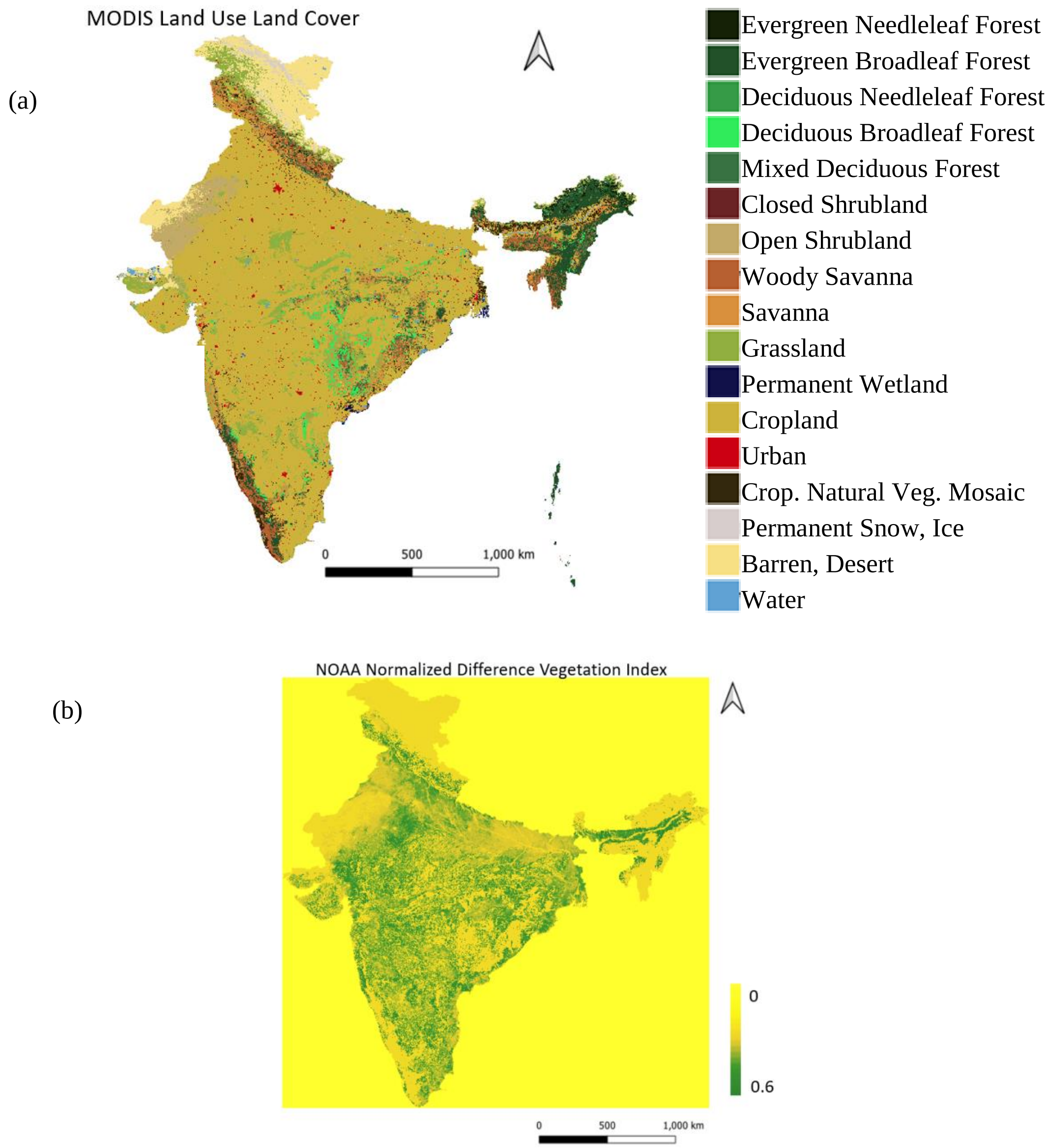
(c) INSAT 3D imagery at 0100 UTC of 3rd Aug



(d)

Date	03 Aug 2020	04 Aug 2020
Forecast & Warning	**Heavy to very heavy rainfall at isolated places**	**Heavy very heavy rainfall at a few places with extremely heavy rainfall at isolated places**
Impact Expected	• Water logging/ flooding in many parts of low lying area and river banks. • Localized and short term disruption to municipal services (water, electricity, etc.) • Major disruption of traffic flow. Major roads/local trains affected. • Possibility of danger to very old buildings and unmaintained structures, falling of trees etc. • Closure of roads crossing low water bridges.	• Widespread water logging/flooding in most parts of low lying area and also on river banks. • Major disruption of traffic flow. Major roads/local trains and travel routes. • Localized and short term disruption to municipal services (water, electricity). • Possibility of danger to very old and unmaintained structures, falling of trees etc. • Possibility of landslides in elevated hilly areas. • Closure of roads crossing low water bridges
Action suggested	• Traffic may be regulated effectively. • People in the affected area may restrict their movement.	• Traffic may be regulated effectively. • People in the affected area may restrict their movement.

Figs. 11(a-d). A typical example of (a) urban flood modeling product over Mumbai city alongwith (b) Mumbai radar imagery at 0112 UTC of 3rd August, (c) INSAT-3D imagery at 0100 UTC of 3rd August and (d) IBF for heavy rainfall over Mumbai issued for 3&4 August based on 0300 UTC of 3rd August



Figs. 12(a&b). Geophysical layers including (a) LULC and (b) NDVI
LULC : Land use and land cover, DEM: Digital elevation model, NDVI: Normalised difference vegetation index, MODIS: Moderate Resolution Imaging Spectroradiometer, SRTM: Shuttle Radar Topography Mission

python to generate the median images. Apart from the extracted built up layer, other open source data are also being used to develop the quality LULC maps. IMD is also utilizing MODIS LULC map [Fig. 12(a)] with 17 general classes for India including 11 natural vegetation classes, three human-altered classes and three non-vegetated classes. A sample of NDVI product used by IMD is given in [Fig. 12(b)].

5.3.6. *Socio economic database*

The socio-economic and exposure data includes information about the total population and major amenities, *viz*., hospital, school, power plants, power station, tourism locations, administrative buildings, infrastructure (airport, railway lines, roads), water bodies (Dams, reservoir, lakes etc.). For impact-based forecasting the various exposure data is being collected from different sources, that include open sources as well as state department authorized sources.

5.3.7. *Web-GIS based DSS*

To estimate and mitigate the impact of heavy rainfall events, an integration of atmospheric science is required along with geospatial science including remote sensing,

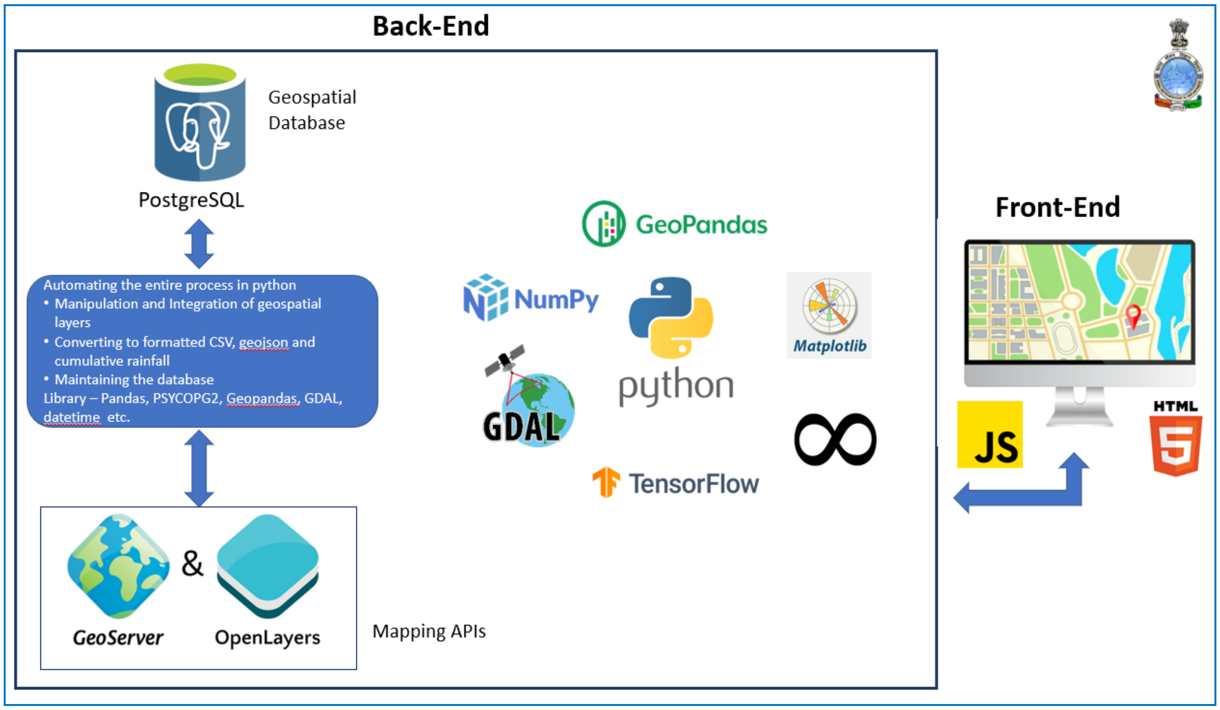


Fig. 13. Prototype framework for Web based application development for IBF

GIS, machine learning, deep learning to achieve IBF. The IMD is currently developing IBF with the development of a GIS based DSS (GIS-DSS). The aim of the GIS-DSS is to provide a single window platform for analysis and visualization of all hazards, vulnerability and exposure layers. GIS-DSS is aimed at using the open-source technology including Java Script, HTML Web Map Services, Mapping libraries and Python. This will cater the need of predicting the risk associated with heavy rainfall and will be helpful for disaster managers and public to plan the activities in advance. A prototype framework for the web based DSS being developed for IBF of heavy rainfall is presented in Fig. 13.

There is a need for displaying geospatial information interactively on the web. Open-source servers and tools such as GeoServer and Open Layers help display and share geospatial data on the web. A WebGIS based IBF portal is being developed to provide the information to the general public as well as administrators. Users will get the spatial visualization, information about the impact in case of heavy rainfall event occurred at a certain place, in terms of population affected, point of interest affected (school, hospital, industries etc.), Rail/Road network affected, type of built-up area majorly affected etc. The database is being prepared in PostGIS/PostGre SQL. The automation is being done using python and the front application is being developed using HTML, JavaScript. Geoserver is being used as mapping server. The geoserver is a prevalent open-source server created using Java exclusively for handling geospatial data. The potential of geoserver can be leveraged when dealing with massive datasets and map layers, which smoothly works in geoserver. The server follows the standards set by Open source Geospatial Consortium (OGC), further adding to the reasons for its popularity. Geoserver permits the sharing, processing and editing of geospatial data and displays it accordingly. The server also supports an extensive range of data formats and standard protocols, enabling its integration and use in different cases. GIS data stored in PostGIS, Geopackage, Shapefiles, Tiffs, Image mosaic and Web services are the input data for geoserver. These input layers are converted into web services-based outputs such as Web Map Service (WMS), Web Feature Service (WFS), Web Coverage Service (WCS) and Web Processing Service (WPS) to be used by the users. Open Layers from Open source Java Script library are used for building interactive maps. Since Open Layers can display different types of geospatial data, it is widely used with GeoServer. Using Python, Geo-spatial Data Abstraction Library (GDAL), numpy, matplotlib etc. libraries are being used for the development of GIS-DSS for IBF module for heavy rainfall.

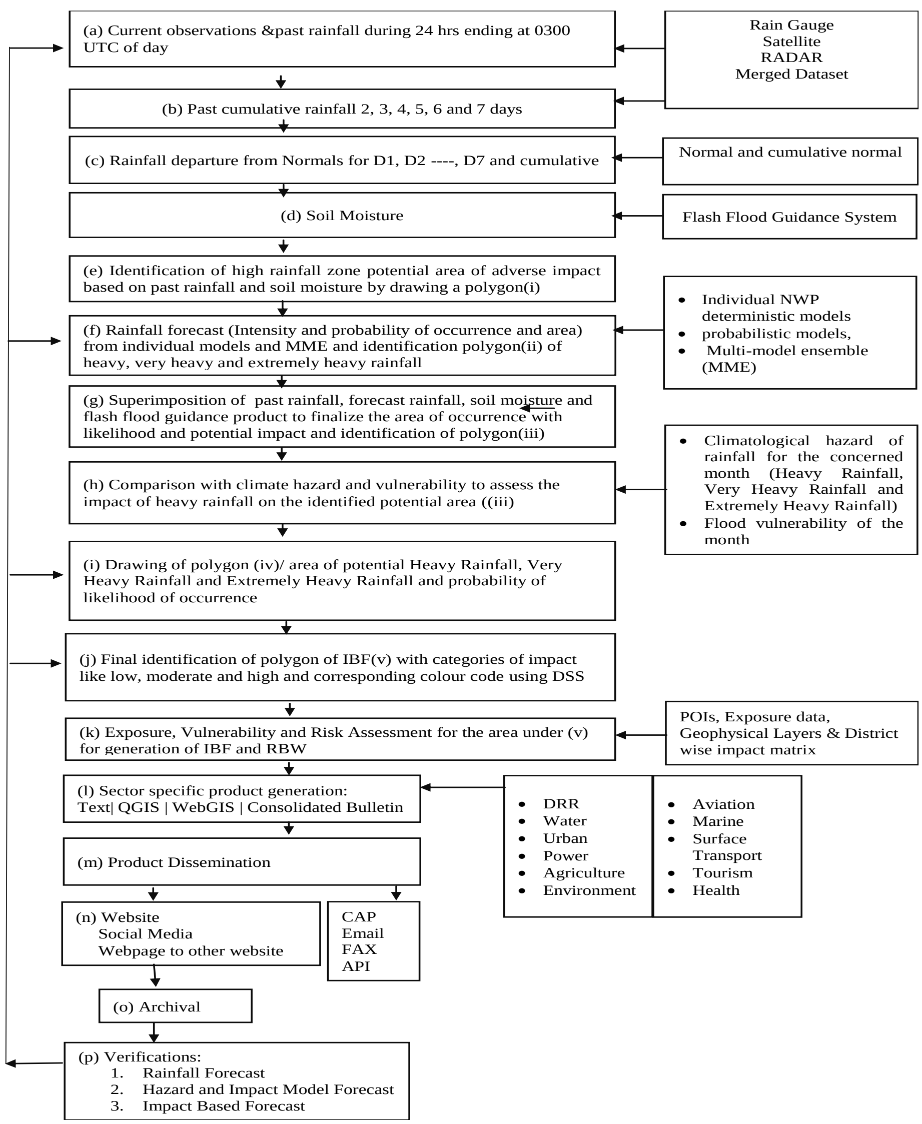
For decision making process, the forecaster and disaster management interface is being developed in two ways, *viz*., IMD + Regional Integrated Multi hazard early warning system (RIMES) + State Govt and IMD + State Govt. Data are being supplied to states. The NCRMP-DSS is being implemented through NDMA, IMD and state Govt for all coastal states. Other systems like flash flood guidance, urban flood warning system etc. are in place and need to be integrated. The web-GIS based display system has been prepared with poorer network for 50 major cities in country. The sector specific matrices, *e.g.*, health, public works, transportation are finalized for some areas and is in process of completion. The display system to share information between forecasters and disaster managers (GIS Platform) has been developed.

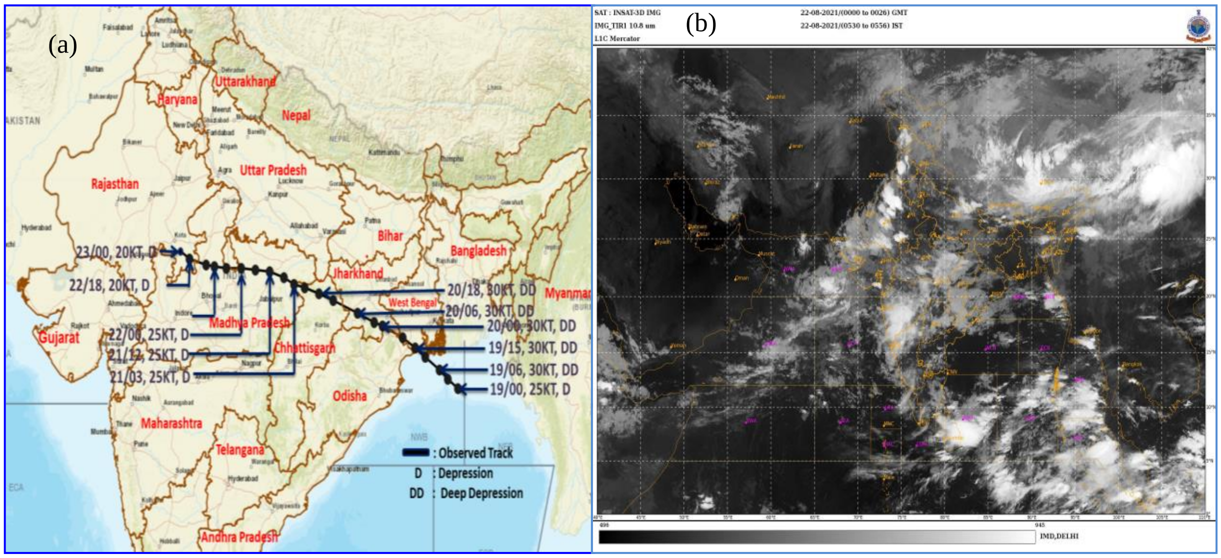
5.3.8. *Standard operation Procedure (SOP)*

The standard operation procedures (SOP) has been modified in 2021(IMD, 2022). The evaluation of SOP with hindcast data is in progress. As per modified SOP, there are four stages of heavy rainfall warning introduced in 2021.

Stage -1	:	Heavy rainfall Watch: Issued 3-4 days in advance with daily update
Stage-2	:	Heavy rainfall Alert: Issued 48 hours prior to the occurrence of event with 12 hourly updates
Stage-3	:	Heavy rainfall Warning: Issued 24 hours prior to the occurrence of event with 06/12-hourly updates)
Stage-4	:	Issued 12-Hours prior to occurrence of event with 3-hourly updates.

The steps of SOP are shown in following flow chart:





Figs. 14(a&b). (a) Observed track of deep depression over northwest Bay of Bengal during 19-23 August, 2021 and (b) INSAT 3D, infrared imagery as 0000 UTC of 22nd August, 2021

6. Case studies of IBF of heavy rainfall

A case study on development of IBF of heavy rainfall in association with monsoon depression is presented in Sec. 6.1. and another in association with heavy rainfall due to a cyclone crossing Andhra Pradesh during monsoon is presented in Sec. 6.2.

6.1. *IBF of heavy rainfall on 22nd August, 2022 over west Madhya Pradesh & east Rajasthan in association with depression*

A depression formed over northwest and adjoining northeast Bay of Bengal (BoB) at 0000 UTC of 18th August (RSMC, New Delhi, 2022). It concentrated into a depression over northwest & adjoining northeast BoB at 0000 UTC of 19th August, 2022. It moved west-northwestwards, intensified in a deep depression over same region and crossed West Bengal and adjoining North Odisha coasts between Balasore and Sagar Islands, close to Digha during 1330-1430 UTC of 19th August, 2022. It weakened into a depression over northwest Chhattisgarh at 0000 UTC of 21st August and into a well marked low pressure area over East Rajasthan and adjoining Northwest Madhya Pradesh in the forenoon (0300 UTC) of 23rd August. Under it's influence heavy to very heavy rainfall occurred over Gangetic West Bengal, Odisha, Jharkhand, Bihar, Uttar Pradesh, Uttrakhand, Madhya Pradesh and Rajasthan during 19-23 August. Extremely heavy rainfall ($\geq$ 20.45 cm) rainfall was observed over Odisha on 19th and West Madhya Pradesh & East Rajasthan on 21st & 22nd August. Observed track of depression over northwest BoB (19-23 August), is presented Fig. 14(a).

A case study has been undertaken to analyse the development of IBF over West Madhya Pradesh and east Rajasthan based on 0000 UTC initial conditions of 22nd August, 2022 valid for next 24 hours. The IR imagery from INSAT 3 D satellite at 0000 UTC of 22nd August is presented in Fig. 14(b). The cumulative rainfall during last 7 days, 6 days, 5 days,…upto last 24 hours at 0300 UTC of 22nd August is presented in Fig. 15.

The individual models guidance for 24 hr heavy, very heavy and extremely heavy rainfall forecast based on 0000 UTC of 22nd August, 2022 are shown in Figs. 16(a-c). The probability of occurrence of heavy, very heavy and extremely heavy rainfall events during next 24 hours based on 0000 UTC of 22nd August are presented in Figs. 17(a-c). The MME brought out clearly the area and intensity of heavy rainfall over West MP and east Rajasthan. The likelihood of occurrence in terms of probability derived from different models and impact in the form of intensity of heavy rainfall were estimated for west MP and east Rajasthan (Fig. 18).

Upper and Middle Narmada, Hoshangabad to Sardar Sarovar indicated extremely heavy to very heavy rainfall on Day 1 (22.08.2022) & very heavy to heavy rainfall on Day 2 (23.08.2022). The QPF issued by Flood Meteorological Office (FMO), IMD, Ahmedabad dated 22nd August, 2022 indicated significant rainfall (51-100 mm) in 24 hours from 0300 UTC of 22nd to 0300

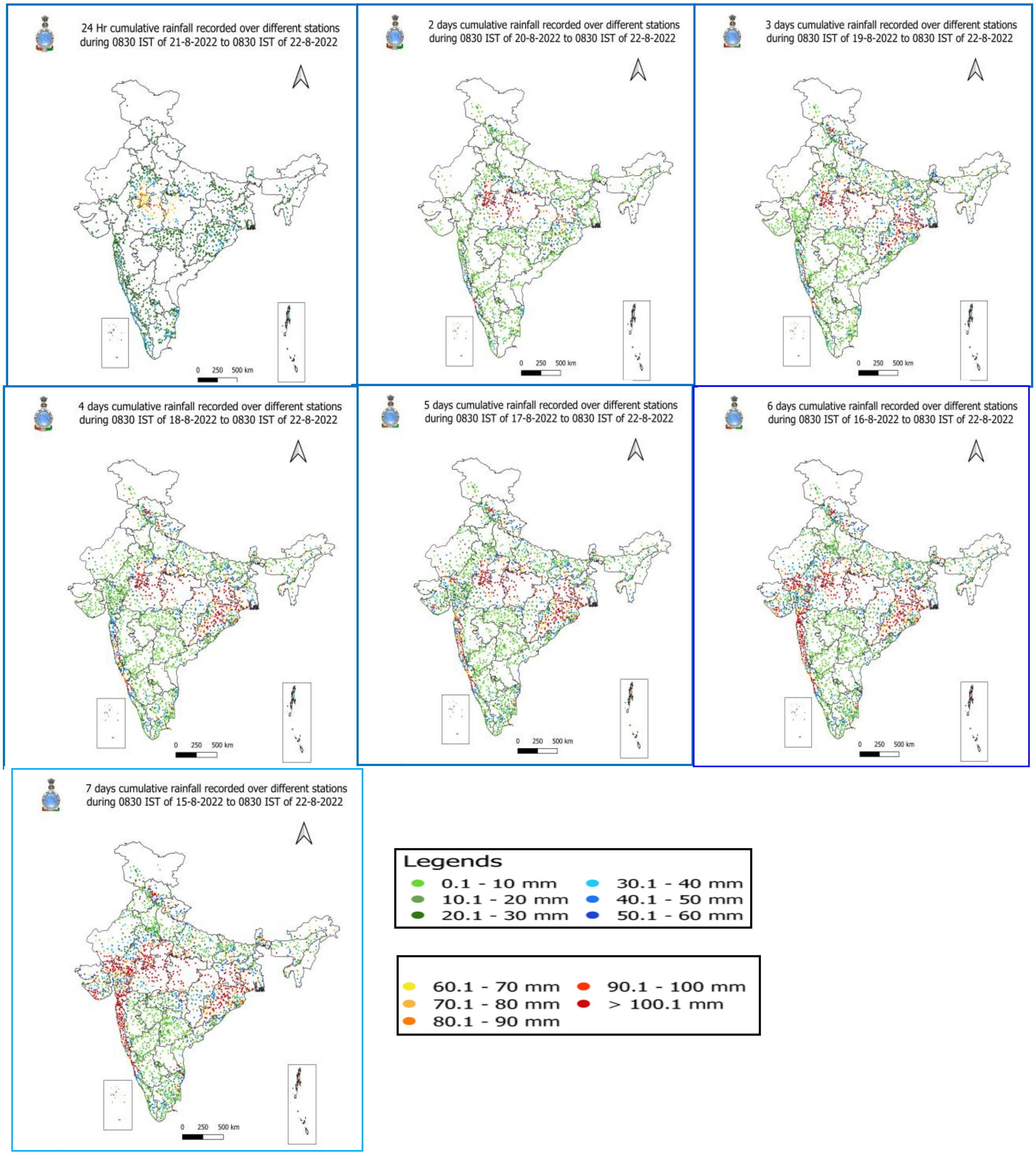


Fig. 15. 24 hr, 2 days-upto 7 days cumulative rainfall over different stations at 0300 UTC of 22nd August, 2021

UTC of 23rd August as issued on 21st August, 2022 (Fig. 19). Based on the synoptic situation, several QPF and hydrometeorological bulletins were issued on 22nd August, 2022.

Based on the estimated rainfall from different sources as shown in Figs. 14-19, the flash flood forecast guidance identified the area of concern (AOC) as west MP adjoining east Rajasthan meteorological Subdivisions. The MME approach was adapted by the forecaster in rectifying the spatial bias in the model forcing adjustments. Sacramento soil model (ASM) indicated high values on top soil saturation at 0000 UTC of 22nd August which gradually reduced in the next timelines. The high

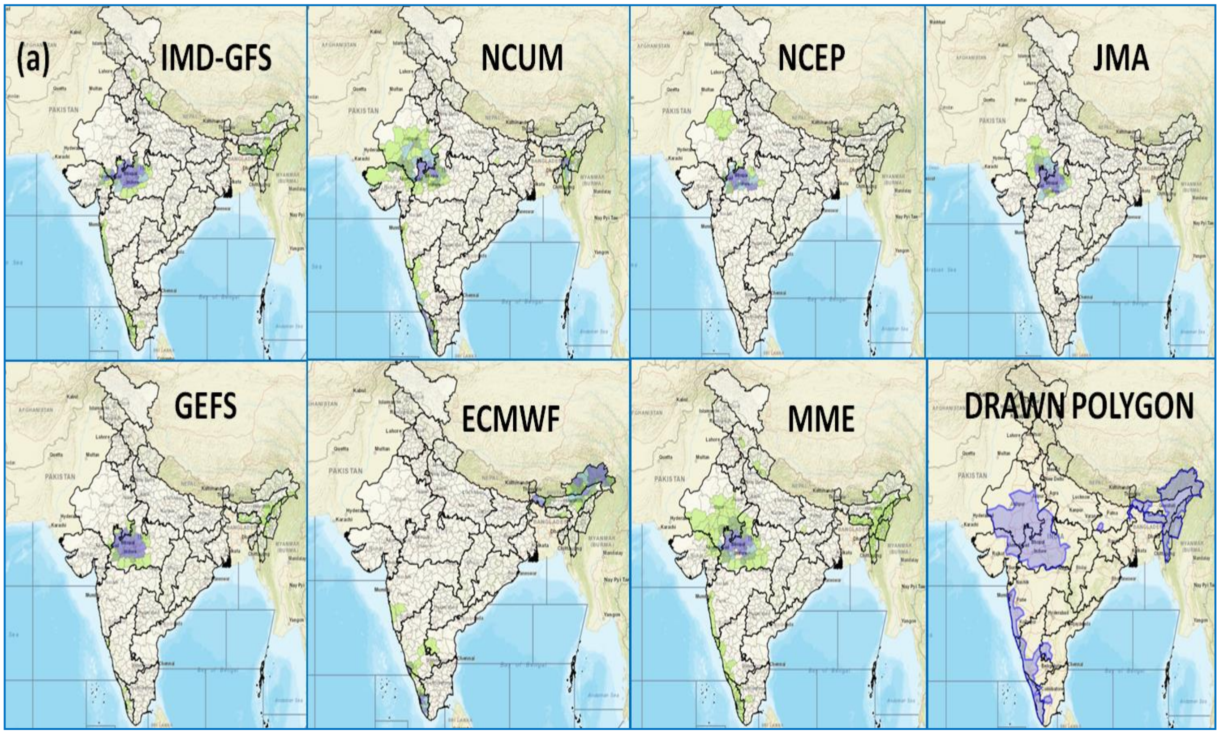


Fig. 16 (a). Individual NWP models and MME guidance for 24 hrs accumulated heavy rainfall (64.5-115.4 mm) based on 0000 UTC of 22nd August, 2022

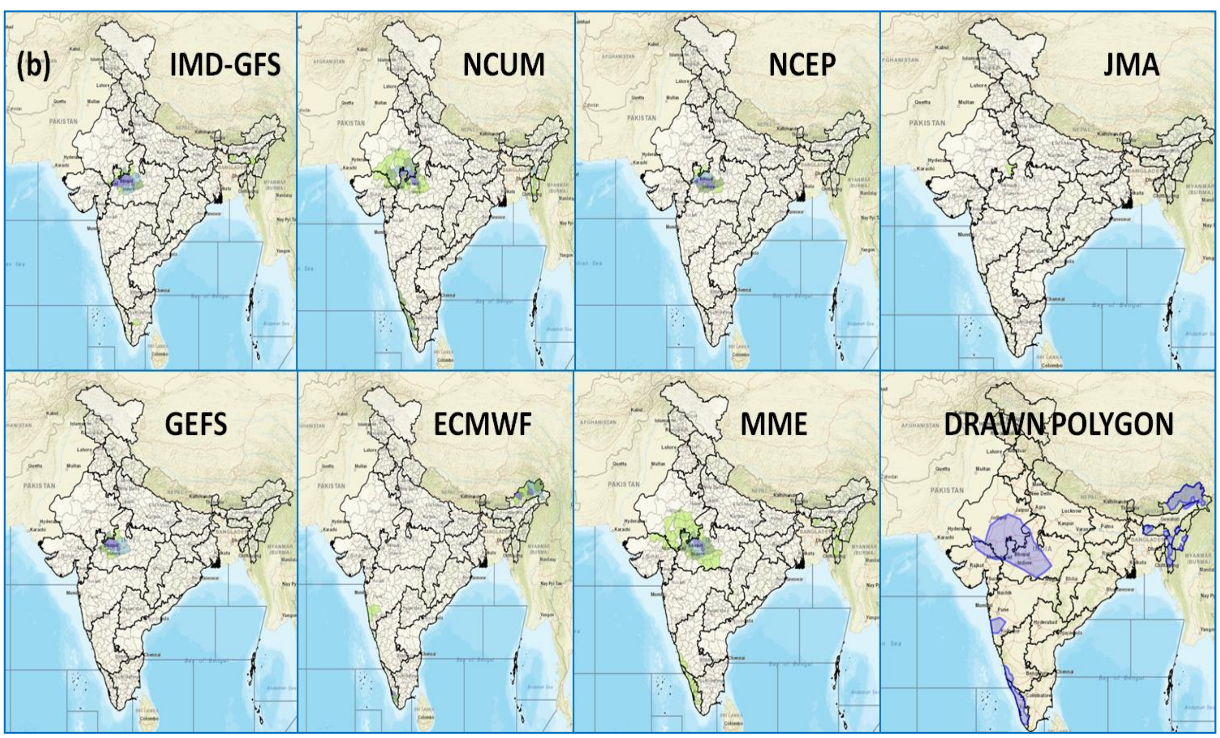


Fig. 16 (b). Individual NWP models and MME guidance for 24 hrs accumulated very heavy (115.5-204.4 mm) rainfall based on 0000 UTC of 22nd August, 2022

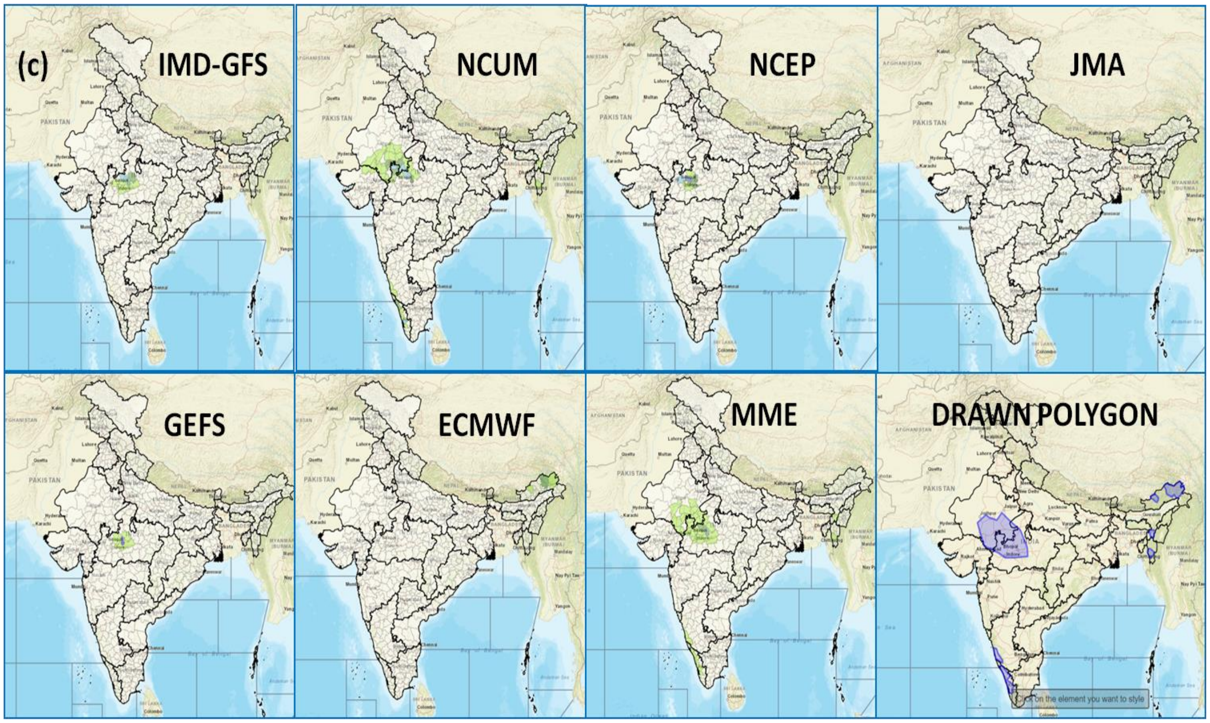
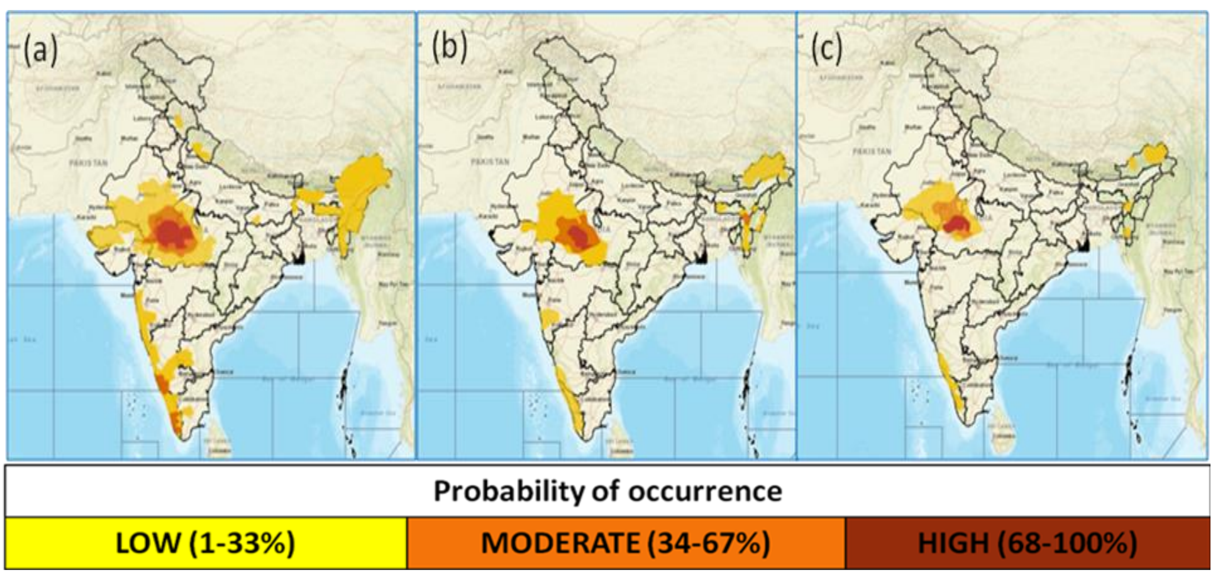


Fig. 16(c). Individual NWP models and MME guidance for 24 hrs accumulated extremely heavy rainfall (>204.5 mm) based on 0000 UTC of 22nd August, 2022



Figs. 17(a-c). Probability (%) of occurrence of (a) heavy, (b) very heavy and (c) extremely heavy rainfall during next 24 hrs based on 0000 UTC of 22nd August initial conditions of NWP models considered for IBF of heavy rainfall
IBF : Impact based forecast

Intensity heavy Rainfall was expected due to depression over central India leading to pluvial flash flood. Considering the topography of the region, the elevation ranges from 100 m to 800 m in Malwa plateau. All the models indicated heavy rainfall over AOC in next 24 hours based on initial conditions of 0000 UTC of 22nd August. The depression was predicted to further move towards south of West MP extending and adjoining East Rajasthan. The categories of alerts, *viz.*, 6 hours threat [Fig. 20(a)] and 24 hours risk [Fig. 20(b)] were indicated with alert level "high" after 0600 UTC of 22nd August over the AOC.

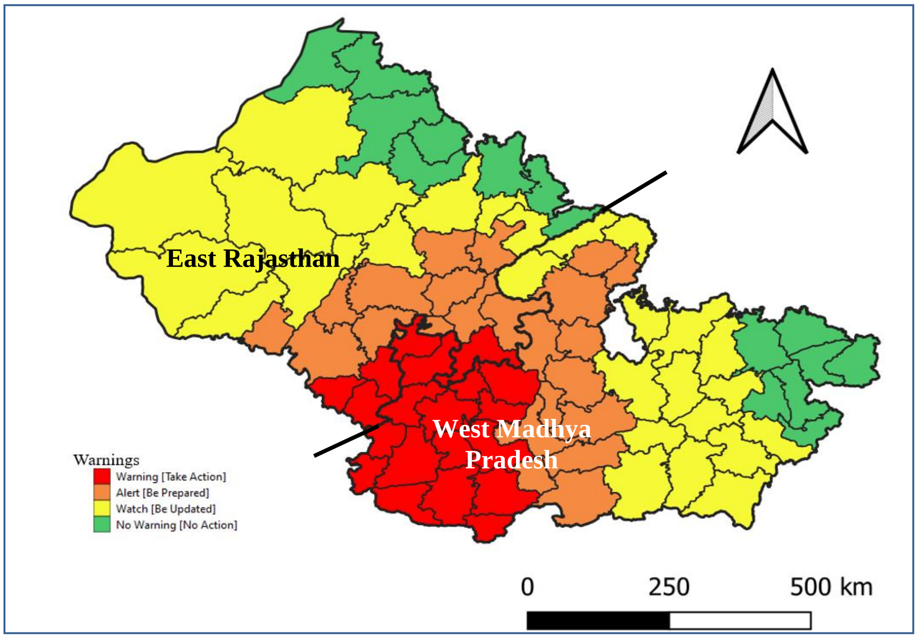


Fig. 18. Districtwise IBF issued for East Rajasthan and West Madhya Pradesh for 22nd August, 2022

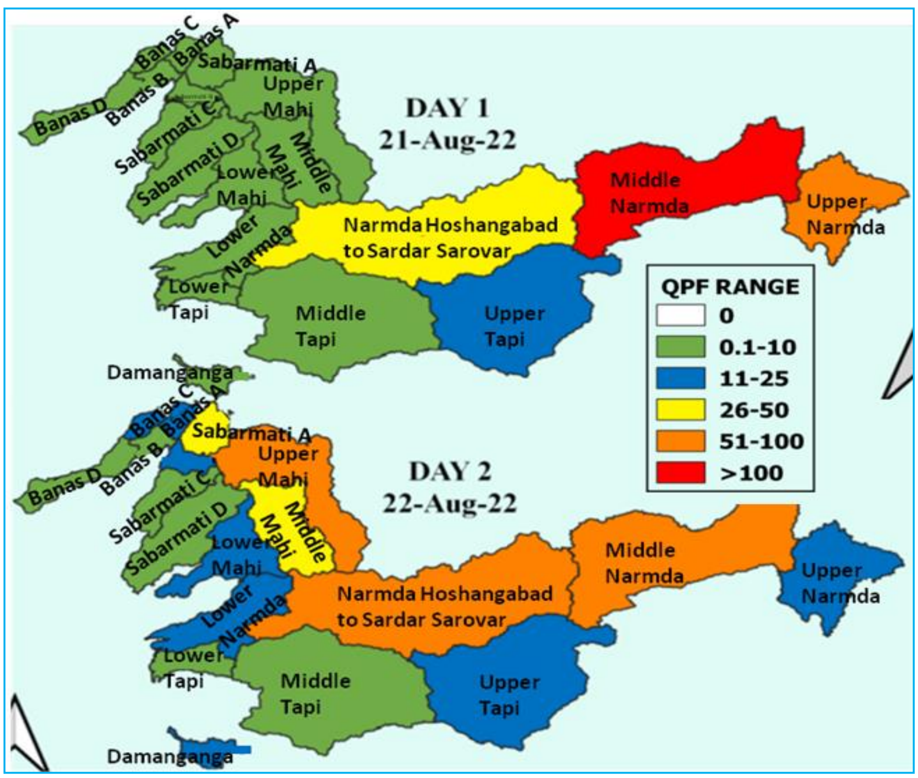
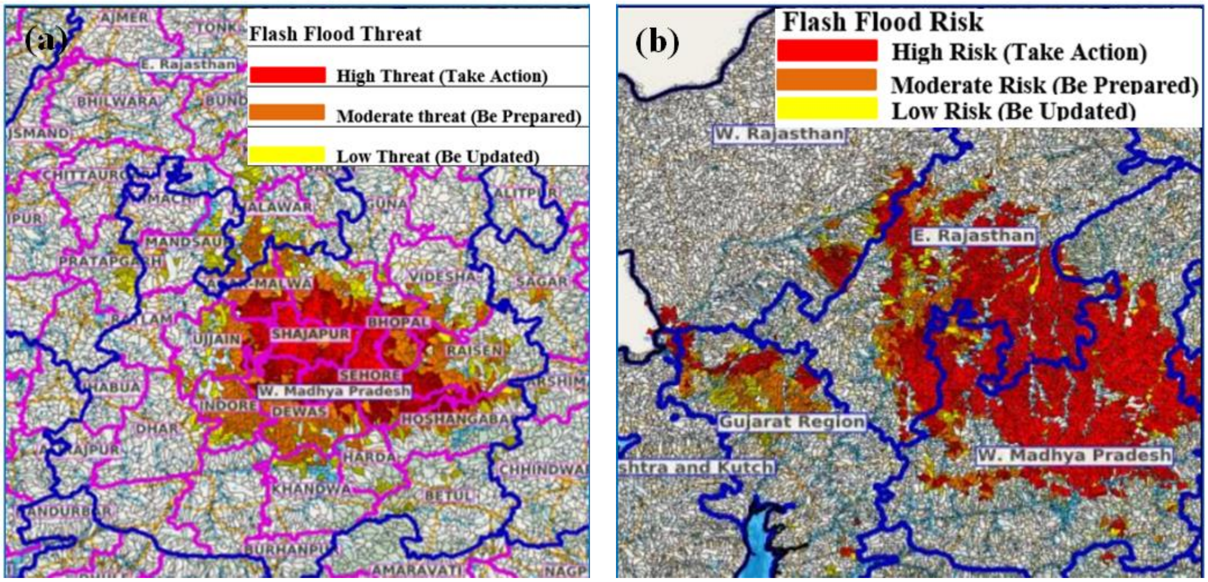


Fig. 19. The QPF issued by FMO, Ahmedabad for river catchments on 21st August, 2022 valid for 21st and 22nd August, 2022
QPF : Quantitative precipitation forecast, FMO: Flood meteorological office

The various geophysical layers and socio economic data base as discussed in Sec.5.3.5-5.3.6 were considered by superimposing these layers with the past and forecast rainfall, flash flood guidance and QPF issued for different sub-basins as well as the climatological hazard and vulnerability due to flood in the month of August (Fig. 8).



Figs. 20(a&b). Flash Flood (a) threat till 1200 UTC of 22nd indicating moderate to high threat over district of West Madhya Pradesh and (b) risk indicating high flash flood risk over West Madhya Pradesh, East Rajasthan, adjoining West Rajasthan and Gujarat region during 0600 UTC of 22nd August to 0600 UTC of 23rd August

TABLE 3

Summary of some of the exposure layer expected to be impacted due to heavy rain over west Madhya Pradesh and east Rajasthan on 22nd August, 2022

Impacted Exposure Layer	Count
Districts affected	**Total: 40**. **East Rajasthan (15) :** Ajmer, Banswara, Baran, Bhilwara, Bundi, Chittaurgarh, Dungarpur, Jhalawar, Kota, Pratapgarh, Rajsamand, Sawai Madhopur, Tonk, Udaipur, Lalitpur **West Madhya Pradesh (25):** Ashoknagar, Betul, Bhopal, Dewas, Dhar, East Nimar, Guna, Harda, Hoshangabad, Indore, Jhabua, Mandsaur, Narsimhapur, Neemuch, Raisen, Rajgarh, Ratlam, Sagar, Sehore, Shajapur, Sheopur, Shivpuri, Ujjain, Vidisha, West Nimar
Total Population Affected	East Rajasthan (2,35,95,959 approx) West Madhya Pradesh (3,47,46,650 approx)
Major Cities	Bhilwara, Bundi, Chittaurgarh, Udaipur, Jhalawar, Bhopal, Dewas, Ujjain, Indore
Nation Highway Affected	NH 146, 148D, 156, 158, 27, 27/48, 27/46, 346, 44, 45, 46, 47, 48, 52, 52/46, 552G, 56, 752B, 752C, 758, 927A, 934
Railway Lines Affected	Central Railway, North Central Railway, North Western Railway, Western Central Railway, Western Railway
Major Water bodies	Rana Pratap Sagar Reservoir, Gandhi Sagar reservoir, Indira Sagar reservoir, Bhopal lake
Airport	2
Hospital	26
Special Economic Zone	5
Power Station	2
Power Plant	3
Oil refinery	1
Sport Stadium	1

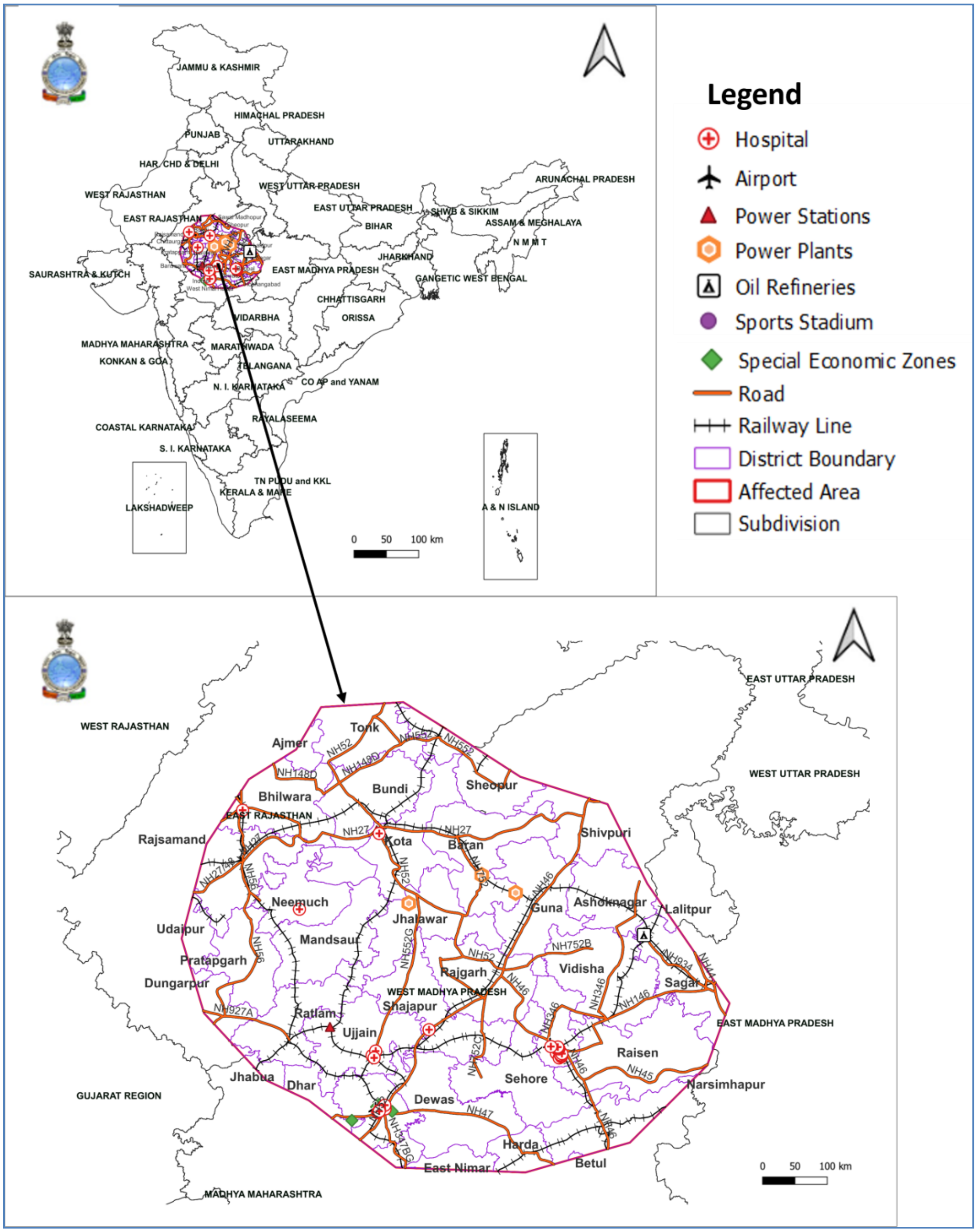
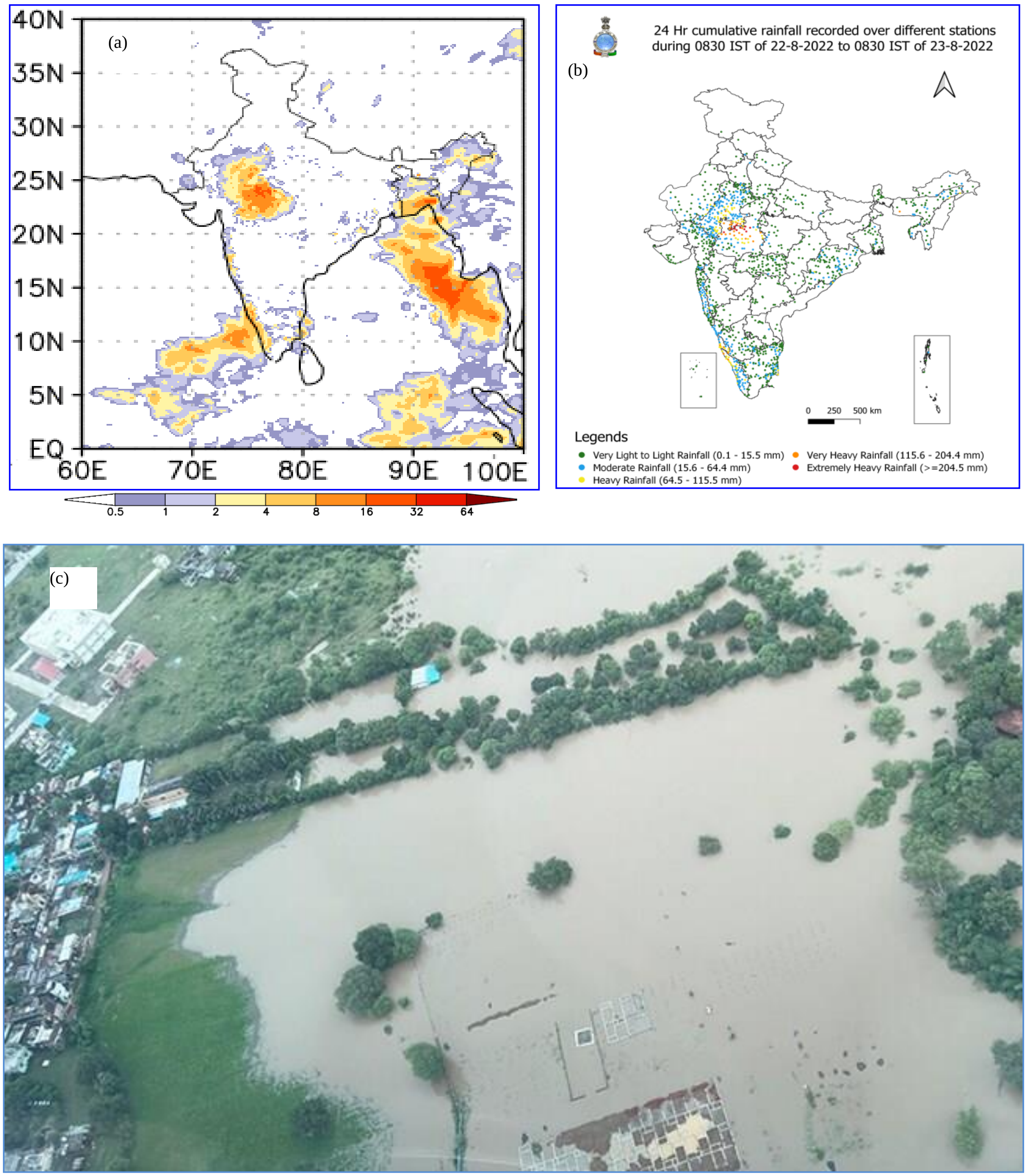


Fig. 21. Exposure expected to be impacted due to heavy to extremely rainfall on 22nd August, 2022

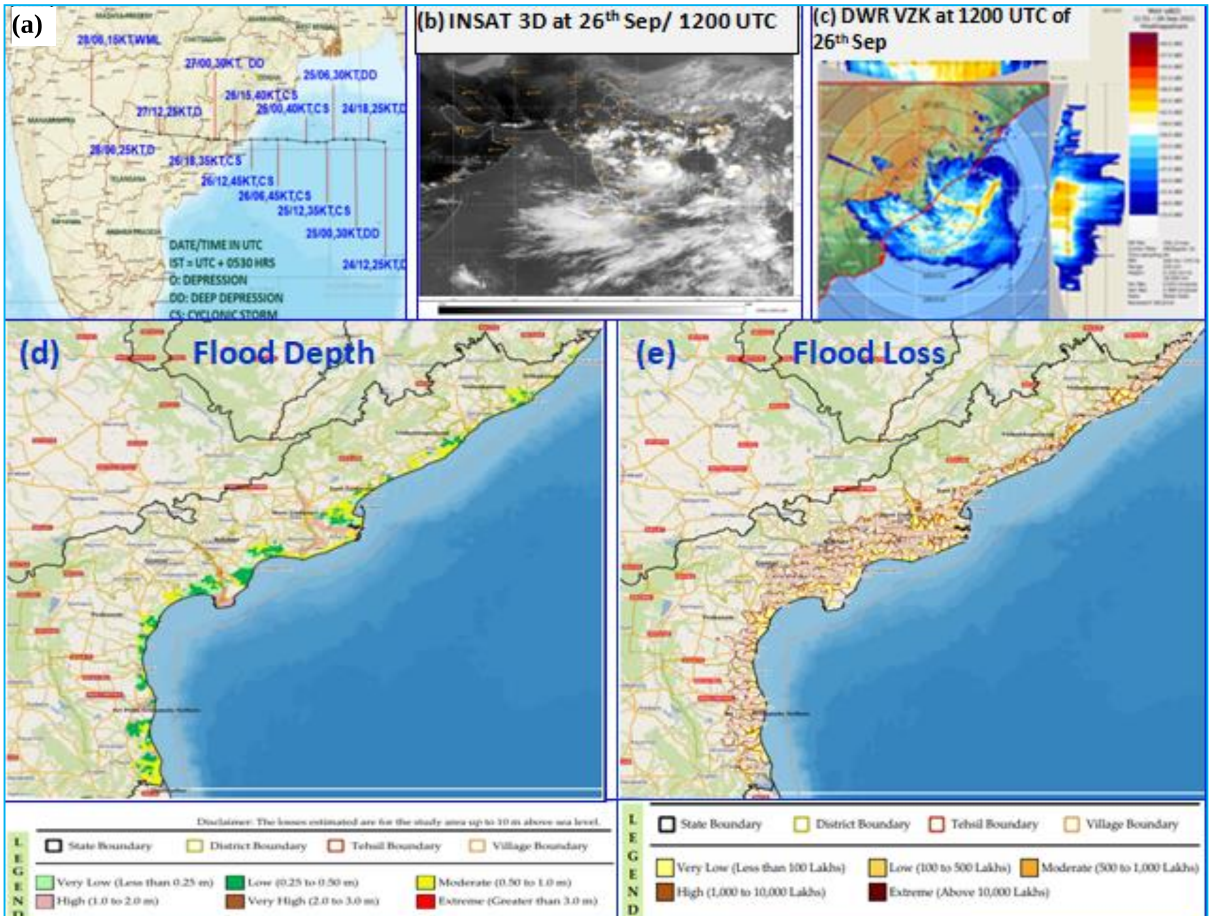
The climatology of very heavy rainfall indicates occurrence of 4-7 such events in August over the AOC. Climatologically, the region has moderate vulnerability for occurrence of flood. Considering the probability of occurrence, there was high probability of extremely heavy rainfall over west MP and moderate probability over adjoining east Rajasthan.

Considering all these, IBF in association with expected extremely heavy rainfall could be issued by IMD for the west Madhya Pradesh and east Rajasthan indicating expected inundation, flooding and related impacts as shown in Fig. 21. It also brought out the exposures to be impacted by the flood/heavy rain (Fig. 21) and Table 3. The heavy and extremely heavy rainfall was



Figs. 22(a-c). (a) IMD-NCMRWF satellite merged gauge observed rainfall, (b) 24 hour station rainfall during 0300 UTC of 22nd August to 0300 UTC of 23rd August, 2022, (c) Flooding over Madhya Pradesh (*Source* : NDTV dated 23rd August, 2021)

expected to affect approx. 185681.99 km^2 area and around 5,83,42,609 population in 15 and 25 districts of East Rajasthan and West Madhya Pradesh respectively. Some of the major cities which were expected to be impacted were Bhilwara, Bundi, Chittaurgarh, Udaipur, Jhalawar, Bhopal, Dewas, Ujjain and Indore. It was expected to impact various national highways and railway network crossing the affected district. This weather event was also



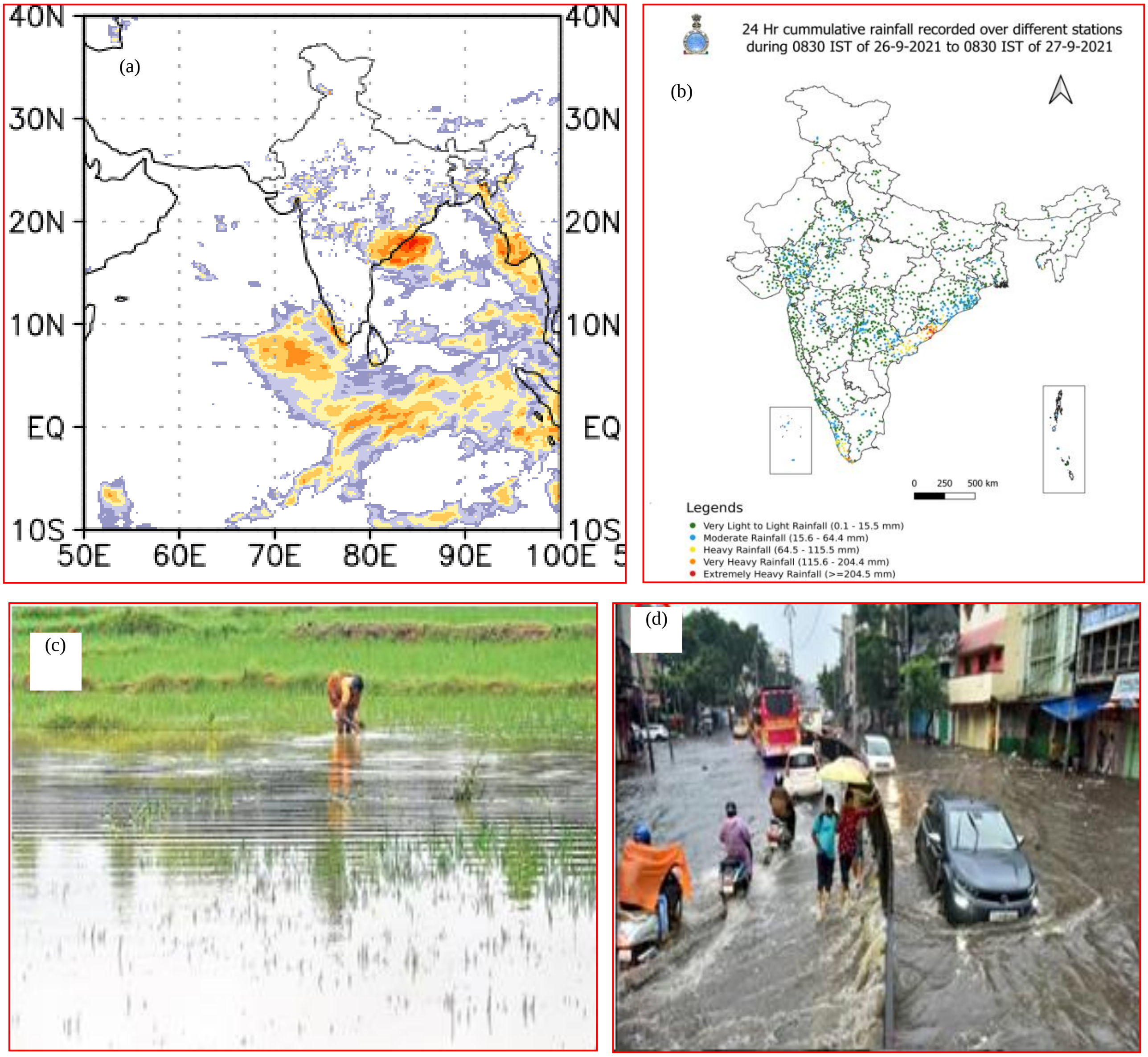
(f) Loss to various exposure elements

Exposure Type	Exposure (INR Lakhs)	Loss (INR Lakhs)	Loss %
Agriculture	17,47,337.56	72.02	0.00
Building	2,43,67,382.73	6,027.90	0.02
Essential Facilities	25,84,246.88	1,582.41	0.06
Transportation	1,58,06,558.39	6,455.01	0.04
Utilities	1,93,79,881.13	49.10	0.00

Figs. 23(a-f). (a) Observed track of cyclonic storm Gulab (24-28 September, 2021), (b) INSAT 3D imagery at 1200 UTC of 26th September, (c) Imagery from Doppler Weather radar Visakhapatnam at 1200 UTC of 26th September and Web based Dynamic Composite Risk Atlas estimated (d) Flood depth, (e) Flood loss & (f) loss by category to various exposure elements at different zones over coastal Andhra Pradesh

expected to impact the major amenities like hospitals, schools, power stations and power plants, oil refineries, etc. The presence of reservoirs and large water bodies can make the scenario more severe in case of extremely heavy rainfall and can cause floodings in low lying area, some of the major reservoirs existing in this area are Rana Pratap Sagar Reservoir, Gandhi Sagar reservoir, Indira Sagar reservoir, Bhopal. The prior information about the exposed layers could be generated to mitigate the impact of severe weather events.

The realized rainfall from IMD-NCMRWF satellite merged gauge and 24 hour station rainfall during 0830 hrs IST of 22nd August to 0830 hrs IST of 23rd August are presented in Figs. 22(a&b). It indicated accumulated rainfall being significantly higher over West MP and east



Figs. 24(a-d). (a) IMD-NCMRWF satellite merged gauge rainfall plot (b) Realised rainfall at different stations during 0300 UTC of 26th to 27th September, (c): Submerged paddy field at Pinagadi in Visakhapatnam district (*Source*- https://www.newindianexpress.com/ dated : 29 September) and (d) Waterlogged roads in Hyderabad (*Source* : https://www.hindustantimes.com/ dated : 27 September)

Rajasthan on 22nd August creating a hazardous situation. The flood realized over the region is shown in Fig. 22(c). It indicates that the severe weather in terms of heavy rainfall and associated floods and other hazards could be predicted well with the established IBF system.

Based on the IBF and early warnings issued by Meteorological Centre (MC), IMD, Bhopal at district and city level for this heavy rainfall event, the teams of state home guards and state disaster emergency response force (SDERF) were deployed for rescue operations in flood affected areas. Additional teams were deployed to manage the flood situation during 21 to 23 August especially in Guna, Vidisha, Raisen, Ashoknagar, Bhopal, Narmadapuram districts. In accordance with warning, state government home guard and SDERF (49 numbers) were deployed at various Sethani Ghat areas of river Narmada in Narmadapuram district. A five member team carried out rescue operation in Raipura Mohalla of Vidisha district and a team of 25 members were active in Bhopal and adjoining area like Bairasiya and Huzur. Similar actions were taken by Government of Rajasthan based on the IBF and early warning issued by MC, Jaipur for this heavy rainfall event, the national disaster response force (NDRF) and state disaster response force (SDRF) were deployed at district level. Also, the state police

TABLE 4

Current status of IBF of heavy rainfall in India as compared to other countries

	IBF in India	IBF in other countries
Methodology	Subjective and Objective. Complete dynamic weather and climate sensitive impact modeling in progress	Some of the countries using subjective method except very few like UK Met office, USA, Nepal, Africa, Canada, Philippines, Germany etc who have some objective technique. Most of the impact models are not operational and are in pilot mode
Subjective Method	Fixed and Variable threshold both	Fixed and variable threshold method
Color Code	Four level color code	Mostly four level color code, some countries using 5 and 3 level color code
Temporal Range	Nowcast, Short and Medium Range	Mostly for Nowcast and Short Range
Spatial Range	Location, City, Districts and Met-sub division level	Mostly location specific and district level
Forecast	Probabilistic	Some countries using probabilistic and some deterministic also
Language	English, Hindi and local language in videos	Mostly English, some countries using bi-language also
Sector Specific	For different sectors like urban, disaster management, agriculture, transport, water sector	Mostly generalized except UK and USA where it is more sector specific
Product Generation	Semi Automatic	Mostly semi automatic
Dissemination Mode	Website, Web-GIS Email, Social Media, SMS, Fax, Print & Electronic Media, Common Alert Protocol (CAP) etc	Website, Email, Social Media, SMS, Fax, Print & Electronic Media etc in most countries and CAP and Web-GIS in some countries

coordinated with Indian Army and Indian Air Force for necessary preventive and mitigation action. The boats were also deployed in vulnerable spots. All these actions helped in minimising the loss of lives and properties.

6.2. *Heavy rainfall IBF in association with landfalling cyclone a case study*

Cyclonic Storm Gulab developed from a low pressure area that formed over east central Bay of Bengal (BoB) at 0300 UTC of 24th September, 2021. Under favourable environmental and sea conditions, it concentrated into a depression over east central and adjoining northeast BoB at 1200 UTC of 24th September. Moving nearly westwards, it further intensified into the cyclonic storm "GULAB" over northwest and adjoining west central BoB at 1200 UTC of 25th September. Thereafter, it intensified gradually and reached it's peak intensity of 75-85 kmph gusting to 95 kmph at 0600 UTC of 26th September and crossed North Andhra Pradesh and adjoining south Odisha coasts with maximum sustained wind speed of 75-85 kmph gusting to 95 kmph during 1400-1500 UTC of 26th September. Continuing to move nearly westwards, it weakened gradually into a well marked low pressure area over western parts of Vidarbha around 0600 UTC of 28th September. It caused extremely heavy rainfall over north coastal Andhra Pradesh & adjoining south Odisha on 26th September.

A case study has been undertaken to demonstrate the development of IBF of heavy rainfall on 26th September due to this cyclone. The observed track, infrared imagery from INSAT 3D at 0300 UTC of 26th September, reflectivity imagery from DWR, Visakhapatnam and Web based DCRA estimated flood depth, estimated flood loss and loss to various exposure elements at different zones over coastal Andhra Pradesh are presented in Figs. 23(a-f) respectively. The actual heavy rainfall in association with the cyclone on 26th September (24 hours accumulated rainfall from 0300 UTC of 26th to 0300 UTC of 27th September, 2021) is shown in Figs. 24(a&b). The typical images of occurrence of flood are shown in Figs. 24(c&d). It indicates that the developed system could be utilized to issue IBF of heavy rainfall on 26th September due to a landfalling cyclone. The expected losses to various sectors could be estimated and provided to various stakeholders for disaster risk reduction.

According to reports of Government of Odisha and Andhra Pradesh, based on the IBF and early warning issued by IMD in association with TC, Gulab, the NDRF and SDRF were deployed in Odisha and Andhra Pradesh including 5 NDRF and 7 SDRF teams in Andhra Pradesh. As of September 26, 2021 over 30,000 individuals in Odisha were evacuated into safety and this number further increased to 46,075 people as the storm further moved inland. More than 12,500 people were shifted to safe shelters in Andhra Pradesh. Twenty-eight trains running through the area covering Odisha and Andhra Pradesh were cancelled and five were diverted. The fishing operations were completely suspended over westcentral and adjoining northwest BoB based on the warning issued by IMD. The port operation in south Odisha and north Andhra Pradesh coasts were regulated along with the surface transport (Railways, national and state highways). Due to the accurate IBF and early warning, the number of lives lost was limited to 9 and 2 in Andhra Pradesh and Odisha respectively. Also, the loss of property could be reduced with this IBF and warning.

7. Conclusions and future scope

Considering the improvement in heavy rainfall forecast accuracy and the increasing demand from public and stakeholders including the disaster managers, IMD introduced IBF in very preliminary stage since monsoon season of 2013 based on threshold method using standard colour codes to indicate the expected impact. Thereafter, it has undergone several improvements over the years. The most noteworthy is the introduction of combination method to combine subjective assessment of impact based on consensus knowledge of forecasters with threshold criteria in 2017, impact modelling method in 2019 at some district and city scale based on impact matrix developed from historical impact data and dynamic weather and climate sensitive impact modelling method in 2021 for all districts and all capital cities. Currently the IBF under implementation by IMD is being implemented based on the dynamic weather and climate sensitive impact modelling methods. It includes all the four components, *viz*., (*i*) meteorological hazards, (*ii*) geophysical hazards, (*iii*) geospatial applications and (*iv*) socio-economic conditions and it utilises a web-GIS based DSS and an SOP. The IBF of heavy rainfall has enhanced the management of critical resources like agriculture, water & power and support urban and disaster management sectors among others while reducing loss of life and property. Comparing the status of IBF with other countries of the World, there has been significant progress in India with respect to heavy rainfall IBF (Table 4). However, there are still gap areas and scope to improve it further. Some of the future plans are mentioned below:

(*i*) Increase in the spatial and temporal resolution of meteorological observations.

(*ii*) Development and improvement of probabilistic impact models for heavy rain

(*iii*) Development of weighted MME for prediction of heavy rainfall in different spatial scales upto five days.

(*iv*) Bias correction with respect to peak rainfall, spatial error and temporal error in occurrence of rainfall, especially heavy rainfall.

(*v*) Use of Distributed Hydrological Model by replacing Lumped Hydrological Model in flash flood guidance model.

(*vi*) City specific hazard layers to be enabled in the system for all major cities.

(*vii*) Integration of other systems like Flash flood guidance, urban flood warning system etc. with DSS.

(*viii*) Collection, processing and integration of data on secondary hazards

(*ix*) Enhancement of geo-spatial information with augmentation of high resolution geophysical layers.

(*x*) Enhancement of socio-economic layers at higher resolution for effective IBF through collaboration and partnership.

(*xi*) Finalisation of sector specific matrices e.g. disaster management, health, public works, transportation etc.

(*xii*) Completion of development of dynamic weather and climate sensitive impact modeling method.

(*xiii*) Further modification and improvement of DSS(s) at both IMD and state Govt levels

(*xiv*) Evolution of SOP and guidelines for IBF of heavy rainfall.

(*xv*) Verification of IBF and evaluation.

Acknowledgements

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Disclaimer : The contents and views expressed in this study are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

References

Ali, H., Modi, P. and Mishra, V., 2019, "Increased flood risk in Indian sub-continent under the warming climate", *Weather and Climate Extremes*, **25**, 129, 100212.

Badrinarayanan, V., Kendall, A. and Cipolla, R., 2017, "Segnet: A deep convolutional encoderdecoder architecture for image segmentation", *IEEE Trans. Pattern Anal. Mach. Intell*., **39**, 2481-2495.

Borga, M., Stoffel, M., Marchi, L., Marra, F. and Jakob, M., "Hydrogeomorphic response to extreme rainfall in headwater systems: Flash floods and debris flows", *J. Hydrol.*, **2014**, 518, 194-205.

Chollet, F., 2017, "Xception: Deep learning with depth wise separable convolutions", Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition. IEEE, 1251-1258.

Dottori, F., Szewczyk, W., Ciscar, J. C., Zhao, F., Alfieri, L., Hirabayashi, Y., Bianchi, A., Mongelli, I., Frieler, K., Betts, R.A. and Feyen, L., 2018, "Increased human and economic losses from river flooding with anthropogenic warming", *Nature Climate Change*, **8**, 9, 781-786.

Fowler, Hayley J. and Haider Ali, 2022, "Analysis of extreme rainfall events under the climatic change (2022)", *Rainfall*. *Elsevier*, 307-326

Fu, G., Liu, C., Zhou, R., Sun, T., Zhang, Q., 2017, "Classification for high resolution remote sensing imagery using a fully convolutional network", *Remote Sens*., **9**, p498.

Gadgil, S., Abrol, Y. P. and Seshagiri Rao, P. R., 1999, "On growth and fluctuation of Indian foodgrain production", *Curr. Sci.*, **76**, 548-556.

Georgakakos, Konstantine, 2006, "Analytical results for operational flash flood guidance, *Journal of Hydrology*, **317**, 81-103. 10.1016/j.jhydrol.2005.05.009.

Ghosh, M., Paul, S., Karmakar, S. and Ghosh, S., 2021, "Near-real-time flood forecasting for an urban coastal catchment: An approach in combination of numerical weather and 3-way coupled hydrodynamic flood modeling", EGU General Assembly 2021, online, 19-30 April 2021, EGU21-12834, https://doi.org/ 10.5194/ egusphere-egu21-12834, 2021.

Ghosh, Subimal Subhankar Karmakar, Saha, Anamitra, Mohanty, Mohit Prakash, Ali, Shees, Raju, Satya Kiran, Vrinda, Krishnakumar, Sebastian, Maneesha, Ranjan, Manasa, Behera, R. Ashrit, Murty, P. L. N., Srinivas, K., Narasimhan, B., Tune, Usha, Ramana, M. V., Murthy, P. Thiruvengadam, Indu, J., Thirumalaivasan, D., George, John P., Gedam, S., Inamdar, A. B., Murty, B. S., Mujumdar, P. P., Mohapatra, M., Bhardwaj, Arun and Basu, Swati, 2019, "Development of India's First Integrated Expert Urban Flood Forecasting System for the City of Chennai", *Current Science*, **117**, 5, 741-745.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D. and Moore, R., 2017, "Google earth engine: planetary-scale geospatial analysis for everyone", *Remote Sens. Environ*., **202**, 18-27.

He, C., Liu, Z., Gou, S., Zhang, Q., Zhang, J. and Xu, L., 2019, "Detecting global urban expansion over the last three decades using a fully convolutional network", *Environ. Res. Lett*., **14**, 034008, DOI 10.1088/1748-9326/aaf936.

He, K., Zhang, X., Ren, S. and Sun, J., 2016, "Deep residual learning for image recognition", In: Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition, 770-778.

Helber, P., Bischke, B., Dengel, A. and Borth, D., 2019, "Eurosat : A novel dataset and deep learning benchmark for land use and landcover classification", *IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens.*, **12**, 2217-2226.

Hemingway, R. and Robbins, J., 2020, "Developing a hazard impact model to support impact based forecasts and warnings: The Vehicle Over urning (VOT) Model", *Meteorological Applications*, **27**, 1, DOI:10.1002/met.1819.

IMD, 2014, "Weather Forecasting and Warning Services: Standard Operation Procedure", Published by India Meteorological Department, New Delhi.

IMD, 2021a, "Weather Forecasting and Warning Services: Standard Operation Procedure", Published by India Meteorological Department, New Delhi.

IMD, 1992, "Damage Potential of tropical cyclones", published by IMD, New Delhi

IMD, 2021b, "Standard Operating Procedures on Hydromet Services", https://mausam.imd.gov.in/

IMD, 2013, "A preliminary report on heavy rainfall over Uttarakhand during 16-18 June, 2013", India Meteorological Department, Ministry of Earth Sciences; July 2013; http://imd.gov.in/doc/ uttrakhand_report_04_09_2013.pdf.

Mohapatra, M., Hatwar, H. R., Bandyopadhyay, B. K. and Subrahmanyamm, V., 2009, "Evaluation of heavy rainfall warning over India during summer monsoon season", *Mausam*, **60**, 4, 475-490.

Mohapatra, M., Kumar, Naresh, Sharma, Monica, Devi, Sunitha S., Soma, Senroy, Devi, K. Sathi and Singh, K. K., 2022, "Short to Medium Range Weather Forewarning System in India", *In Social and Economic Impact of Earth Sciences*, Edited by V. K. Gahalaut and M. Rajeevan, Published by Indian Academy of Sciences, 1-29. doi: 10.1007/978-981-19-6929-4_1.

Mohapatra, M., Kumar, Naresh, Mishra, Krishna and Devi, Sunitha S., 2021, "Evaluation of heavy rainfall warnings of India National Weather Forecasting Service for monsoon season (2002-2018)", *J. Earth Syst. Sci*., **130**, Article ID 0054, https://www.ias.ac.in/article/fulltext/jess/130/0054.

Mohapatra, M., Pai, D. S., Sahai, A. K., Mukhopadhyay, P., Mitra, Ashis, Bandgar, Aarti, Johny, C. J., Pattanaik, D. R., Surendran, Divya, Benke, M., Deshpande, Medha, Ganai, Malay, Sharma, Monica, Kumar, Naresh, Sreejith, O. P., Chattopadhyay, R., Phani, R., Krishna, Murali, Abhilash, S., Devi, Sunitha S., Joseph, Rao Suryachandra, Sarkar, Sahadat, Tirkey, Snehlata, Goswami, Tanmoy and Prasad, V. S., 2020, "Contribution of Monsoon Mission to Operational Advances: Short to Medium Range, Extended Range and Seasonal Forecasts", *CLIVAR Exchanges*, **79**, 15-21, DOI: 10.36071/clivar.79.2020

Mohapatra, Mrutyunjay, Sharma, Monica, Devi, Sunitha S., Kumar, S. V. J. and Sabade, Bharati S., 2021, "Frequency of genesis and landfall of different categories of tropical cyclones over the north Indian Ocean", *MAUSAM*, **72**, 1, 1-26

Mohapatra, M., 2008, "Sub-divisional summer monsoon rainfall over India in relation to low pressure systems over the Bay of Bengal and adjoining land regions during 1982-1999", *MAUSAM*, **59**, 3, 327-338.

Mukherjee, S., Aadhar, S., Stone, D. and Mishra, V., 2018, "Increase in extreme precipitation events under anthropogenic warming in India", *Weather and climate extremes*, **20**, 45-53

Pai, D. S., Sridhar, L., Badwaik, M. R. and Rajeevan, M, 2015, "Analysis of the daily rainfall events over India using a new long period (1901-2010) high resolution (0.25° × 0.25°) gridded rainfall data set", *Clim Dyn.*, **45**, 755-776, https://doi.org/10.1007/s00382-014-2307-1.

Rao, Y. P., 1976, "Southwest Monsoon", Met. *Monograph*, India Meteorological Department, p367.

RSMC, New Delhi, 2019, "Report on cyclonic disturbances over north Indian Ocean during 2018", published by Cyclone Warning Division, IMD, New Delhi.

Thomas E. Adams and Thomas C. Pagano, 2016, "Flash Flood Guidance System (3.4.5) in Flood Forecasting in the United States NOAA/National Weather Service", Academic Press, 249-310, ISBN 9780128018842.

UNODRR, 2015, "Global assessment report on disaster risk reduction", ISBN/ISSN/DOI 9789211320428.

WMO, 2015, "WMO Guidelines on Multi-hazard Impact based Forecast and Warning Services", (online), available at: https://public.wmo.int/en/media/news/wmo-updates-guidelines-multi-hazard-impactbased-forecast-and-warning-services.

Yadav, Brahm Parkash, Asok Raja, S. K., Saxena, Rahul, Bharwani, Hemlata, Das, Ashok Kumar, Giri, Ram Kumar, Manik, S. K. and Yadav, Deepak, 2022, "Recent Advances in Pluvial Flash Flood Forecasting of India", *Innovative Trends in Hydrological and Environmental Systems*, **234**, 605-643, LNCE, Springer, ISBN 978-981-19-0304-5, https://doi.org/10.1007/978-981-19-0304-5_44.

Yin, J., Yu, D., Yin, Z., Liu, M. and He, Q., 2016, "Evaluating the impact and risk of pluvial flash flood on intra-urban road network: A case study in the city center of Shanghai", China. *J. Hydrol*, **537**, 138-145.

Zhu, X. X., Tuia, D., Mou, L., Xia, G. S., Zhang, L., Xu F. and Fraundorfer, F., 2017, "Deep Learning in Remote Sensing: A Comprehensive Review and List of Resources", *IEEE Geoscience and Remote Sensing Magazine*, **5**, 8-36.