UNIVERSITY OF READING

Department of Geography and Environmental Science

HYDRO METEOROLOGICAL DRIVERS AND EXTENDED RANGE FLOOD FORECASTING FOR THE BRAHMAPUTRA RIVER BASIN IN BANGLADESH

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DECLARATION

I can confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

Md. Sazzad Hossain

ABSTRACT

While flooding is an annual occurrence in the Brahmaputra basin during the South Asian summer monsoon, there is large variability in the flood characteristics that drive risk: flood duration, rate of water level rise and peak water level. Here, three distinct objectives are adopted; first, to assess hydroclimatological characteristics of floods with respect to the key hydrometeorological drivers. Secondly, to understand flood early warning from the users' perspectives. Thirdly, to understand global model skill to simulate flood behaviour and assessment of forecast skill for different flood preparedness decisions for early action.

Historical flood records have been analysed to understand flood dynamics focusing on three extraordinary floods in 1998 (long duration), 2017 (rapid rise) and 2019 (high water level). The long duration floods in the basin have been driven by basin-wide seasonal rainfall extremes associated with the development phase of strong La Niña events, whereas floods with a rapid rate of rise have been driven by more localised rainfall falling in a hydrological 'sweet spot' that leads to a concurrent contribution from the tributaries into the main stem of the river. The recent record high water levels are not coincident with extreme river flows, hinting that other drivers such as sedimentation and morphological changes are also important drivers of flood risk that should be further investigated.

Communities are aware of the flood season as it is an annual phenomenon in the basin, but they can only anticipate floods events 2 to 3 days beforehand based on the available early warnings and their risk knowledge. This study finds that a lead time of 10 to 20 days allows better flood preparedness decisions to be taken for agricultural planning. Stakeholders specified that they would need a forecast probability of 50% and above to activate preparedness action. Capacity development of the local community is necessary to improve understanding of the probabilistic forecast and overcome communication challenges.

The Global Flood Awareness System (GloFAS) flood forecasting model has been upgraded from version 2.1 to 3.1 with a significant change to its hydrological model structure. Skillful global models can be used for anticipatory action by humanitarian agencies and also support capacity development in national hydrometeorological services to provide improved early warning. Reforecasts of two GloFAS model versions (version 2.1 and 3.1) have been assessed for the period 1999–2018. GloFAS models are skillful in simulating the hydrological behaviour of the Brahmaputra River in Bangladesh. The forecast skill shows that GloFAS 2.1 performs better than GloFAS 3.1 in predicting floods. Both versions have acceptable skill and also provide acceptable FAR and POD for decision makers in predicting low (90th percentile) and medium (95th percentile) threshold floods, with only limited skill for extreme floods (99th percentile).

The thesis provides important information on hydrometeorological drivers related to flood characteristics, users' perspectives on flood preparedness decisions and global flood forecasting model skill for the Brahmaputra basin in Bangladesh. The study results will be applied to improve existing flood early warning in Bangladesh.

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ABBREVIATIONS AND ACRONYMS

AEP	Annual Exceedance Probability
BMD	Bangladesh Meteorological Department
BWDB	Bangladesh Water Development Board
BSISO	Boreal Summer Intraseasonal Oscillation
CEGIS	Centre for Environmental and Geographic Information Services
CEMS	Copernicus Emergency Management Service
CDMP	Comprehensive Disaster Management Plan
CDS	Climate Data Store
CRPSS	Continuous Ranked Probability Skill Score
DDM	Department of Disaster Management
DAE	Department of Agricultural Extension
DHI	Danish Hydraulic Institute
DLS	Department of Livestock Services
DPHE	Department of Public Health
DWT	Discrete Wavelet Transform
ECHO	European Civil Protection and Humanitarian Aid Operations
ECMWF	European Centre for Medium-Range Weather Forecasts
EEOF	Extended Empirical Orthogonal Functions
EFAS	European Flood Alert System
ENSO	El Niño Southern Oscillation
EPS	Ensemble Prediction System
ET	Evapotranspiration
FAO	Food and Agriculture Organisation
FAP	Flood Action Plan
FAR	False Alarm Ratio
FbA	Forecast based action
FbF	Forecast based Finance
FFWC	Flood Forecasting and Warning Centre
FGD	Focus Group Discussion

FRM	Flood Risk Management
GBM	Ganges Brahmaputra Meghna
GDP	Gross Domestic Product
GEV	Generalized Extreme Value
GloFAS	Global Flood Alert System
GRC	German Red Cross
ICIMOD	International Centre for Integrated Mountain Development
ISO	Intraseasonal Oscillation
KGE	Kling-Gupta Efficiency
GRC	German Red Cross
ITCZ	Intertropical Convergence Zone
IT	Information Technology
IVR	Interactive Voice Response
LPS	Low Pressure Systems
MJO	Madden–Julian oscillations
NGOs	Non-government Organizations
NWP	Numerical Weather Prediction
QPF	Quantitative Precipitation Forecast
POD	Probability of Detection
RCCC	Red Cross Red Crescent Climate Centre
RIMES	Regional Integrated Multi-Hazard Early Warning System
SMS	Short Message Service
SST	sea surface temperature
UNOCHA	United Nations Office for the Coordination of Humanitarian Affairs
UNPFA	United Nations Population Fund
USAID	United States Agency for International Development
WFP	World Food Program
WL	Water Level

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Chapter 1 Introduction

1.1 Motivation

Flooding is the most common natural hazard in Bangladesh, occurring annually. The annual average economic loss of the country due to flooding is approximately 1.5% of gross domestic product (GDP) (Ozaki, 2016). In a normal monsoon year around 20% of the country is affected by floods (Rahman et al., 2013) and in extreme flooding years such as 1988 and 1998 more than 50% of the country's area was inundated (Mirza, 2003) (Fig.1.1). Flooding causes enormous damage to crops and physical infrastructure such as houses, roads and flood defences, with the impact controlled by timing, duration, and extent of floods; characteristics which vary across years. The most impactful floods in 1998 affected around 31 million people along with damage to: 1.5 million hectares of crops; 4500 km of embankments; 16000 km of roads (Siddique and Chowdhury, 2000); and economic losses of up to US$ 4.3 billion (EM-DAT). Several extremely impactful floods occurred between 1954 and 2019 with very variable impacts in terms of affected population and economic loss. More recently, 8.5 and 6.5 million people were affected in Bangladesh during the 2017 and 2019 floods respectively (DDM, 2017, 2019) .

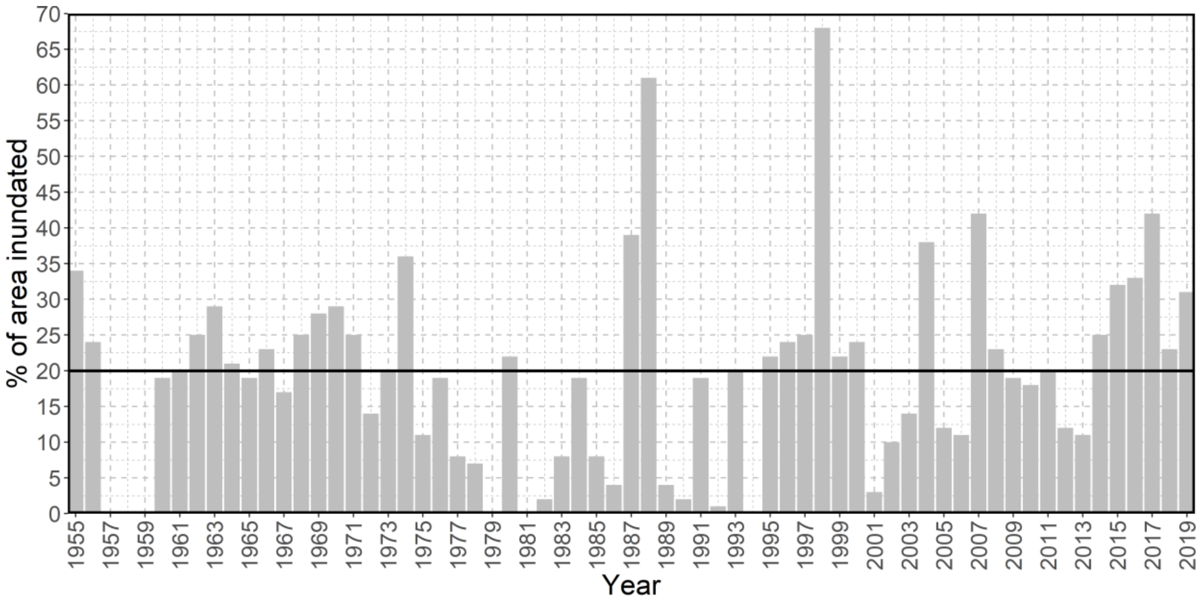

Figure 1.1. Percentage of area inundated in Bangladesh with flood water (FFWC, 2019). Horizontal black line shows 20% inundation and known as normal flooding in Bangladesh.

Population is highly exposed to flood hazard because of the flat, low lying topography, the monsoon climate and Bangladesh lying at the lower riparian part of the three large transboundary basins: the Ganges, Brahmaputra and Meghna basin. In terms of catchment size, the Brahmaputra is about half of the Ganges and seven times higher than that of the Meghan basin (Masood et al., 2015). Bangladesh has four distinct climatic seasons: Winter (December to February), (ii) Pre-monsoon (March to May), (iii) Monsoon (June to September) and (iv) Post monsoon (October to November). Over 71% of the annual rainfall occurs during the monsoon or rainy season, also known as the flood season in Bangladesh (Khatun et al., 2016), and the monsoon rainfall is the main source of floods. The average annual flow of the Brahmaputra is about two times and five times higher the Ganges and the Meghna, respectively (BWDB, 2017b). The Brahmaputra is also located in the southern part of the Himalayan Mountain range which receives the highest annual monsoon rainfall. These hydrometeorological characteristics have made the basin geographically exposed to flooding, which occurs annually between June to September, with the river level usually peaking in July or August.

Flood characteristics such as magnitude, duration are the most important factors to anticipate damage for build environment and also emergency measures are affected by flood duration (Thieken et al., 2007). For example, flood duration increases casualty or death with flood duration (Zahran et al., 2008). Impact due to floods can be different depended on agriculture or business are affected by floods (Kreibich et al., 2007). Flood duration can be used to develop adaptation measures before flood event and post flood recovery can be reduced (Coates et al., 2019). For an agriculture dependent country like Bangladesh, flood timing (starting time of floods and duration) in a particular monsoon is essential for agriculture planning such as seedling and harvesting of crops, as well as from national to community level flood preparedness activities.

Previous studies that described hydro-meteorological characteristics of different flood seasons for the main river basins in Bangladesh (Islam and Chowdhury, 2002; Islam et al., 2010; Mirza, 2003) did not address how intraseasonal monsoon variability affected flood characteristics, despite meteorological studies linking intraseasonal monsoon variability and the Brahmaputra discharge (Jian et al., 2009). For example, monthly rainfall has been studied but this is not adequate to investigate the drivers of the rapid rise of the water levels and multiple peaks within a season such as in 2017. While in the 1998 monsoon floods had very high impact and long duration (Siddique and Chowdhury, 2000), more recent years floods with high water levels in 2017 and 2019 have severe impacts though flood duration was less than that of the 1998 floods (DDM, 2017, 2019). During the 2017 monsoon, the basin experienced two extreme flood events in July (annual exceedance probability=0.10) and August (annual exceedance probability=0.03), respectively. The extreme rainfall in August caused the water level of the Brahmaputra River and its tributaries to rise rapidly and exceed their previous historical records. The impact of floods was devastating due to rapid flooding vast area in the northwest region of Bangladesh in the Brahmaputra basin. It was a challenge for the forecasters to perceive two consecutive extreme flood events one month interval in a monsoon and predict flood event which exceeds danger level within a short period of time.

Understanding the major drivers for floods of different characteristics is a key to informing the development of reliable early warning systems and accurate predictions of future flood hazards in a changing climate. Flood preparedness and early actions of incipient flood disaster depend on correct flood forecast information and timely dissemination of early warning message to relevant organizations involved in flood management and vulnerable communities (WMO, 2003).

1.1.1 Personal reflection and the FFWC capacity development

As a team member of the Flood Forecasting and Warning Centre (FFWC) in Bangladesh, I was responsible for providing early warning for the river basins of the country. It was a challenge for flood forecasters who are hydrologists by training and have no formal training or academic background in meteorology to understand the weather systems that produce flood events of different characteristics i.e. rapid rise or high water levels such as 2017-style floods. The lack of understanding of key drivers that cause flood severity in the basin makes it difficult to provide correct early warning with sufficient lead time for early actions. As a result, flood impacts become worse due to less or no preparedness for responses. I felt that forecasters need to analyse carefully weather systems to understand flood types that are linked with weather phenomenon. However, the event in 2017 also allowed me to explore academic knowledge and capacity development of the FFWC to improve early warning in Bangladesh. FFWC is keen to improve early warning for floods which have a rapid rise and high water levels (e.g., 2017 floods). In addition, FFWC is mandated to provide early warning, but has less interaction with the key stakeholders to understand the early warnings from users' perspectives. For example, understanding which early warning parameters i.e., duration, flood extent, magnitude or lead time are important for preparedness decisions. Communities are interested to know the flood timing for decisions about whether they need to evacuate or harvest their crops. The implementation of forecast based actions (FbA) by humanitarian actors (Coughlan de Perez et al., 2016) can “reduce the impact of shocks on vulnerable people and their livelihoods, improving the effectiveness of emergency preparedness, response and recovery efforts, and reduce the humanitarian burden” (Tanner et al., 2019). The success of FbA depends on several factors such as the flood type, forecast skill and collaboration among the partners organizations (Stephens et al., 2015b). In Bangladesh, FbA has been piloted for the last few years in the Brahmaputra basin for humanitarian response before floods. Initially, the piloting was supported by the German Red Cross (GRC) with technical assistance from the Red Cross Red Crescent Climate Centre (RCCC) (Gros et al., 2019). There are various other actors; local NGOs, disaster managers, forecasters, community-based organizations, financial institutions as well as individual household actively involved in the implementation of FbA activities as each has a specific role in early action. Based on the result of the pilot study e.g., 2015, 2016, several others humanitarian agencies such as United Nations Office for the Coordination of Humanitarian Affairs (UNOCHA), World Food Programme (WFP), Food and Agriculture Organization (FAO), United Nations Population Fund (UNFPA), European Civil Protection and Humanitarian Aid Operations (ECHO), United States Agency for International Development (USAID) are current assisting in scaling up FbA activities in Bangladesh (Hassan, 2020). Scaling up FbA needs to overcome several challenges such as institutional, policy and interactions among different actors to respond to forecasts where conventional emergency responses are more focused at the onset of floods or during floods (Tanner et al., 2019).

Presently, the FFWC in Bangladesh is experimenting with 5 day lead time deterministic flood forecasts for the major rivers systems. This short-term forecast is quite useful for emergency management (Fakhruddin et al., 2015) however, not quite as useful for agricultural planning and long-term flood risk management. Due to improvements of numerical computational schemes, meteorological forecasts are available from week to seasonal scale. Extended lead time hydrological forecasts can be generated using this improved meteorological forecast information. For example, GloFAS provides flood forecast information using improved extended meteorological forecast for the major river basins across the world up to 30 days lead time (Alfieri et al., 2013). This global scale forecast is a source of forecast information for national flood forecasting centres or hydromet agencies for capacity development to provide improved early warning. The forecast skill needs to be evaluated to assess the model’s capability to predict events before it can be used for decision making (Stephens et al., 2015b). Therefore, it is essential to evaluate forecast skill to build confidence among decision makers to apply for early actions based on forecast. The GloFAS flood forecasting model has also undergone several versions in the last few years. In May 2021, the model has been changed in hydrological approaches in its model structure (Wiki, 2021). Figure 1.2 shows changes of model versions of GloFAS with important events such as severe flood events on the right hand side in blue, alongside this PhD research on the left hand side in green.

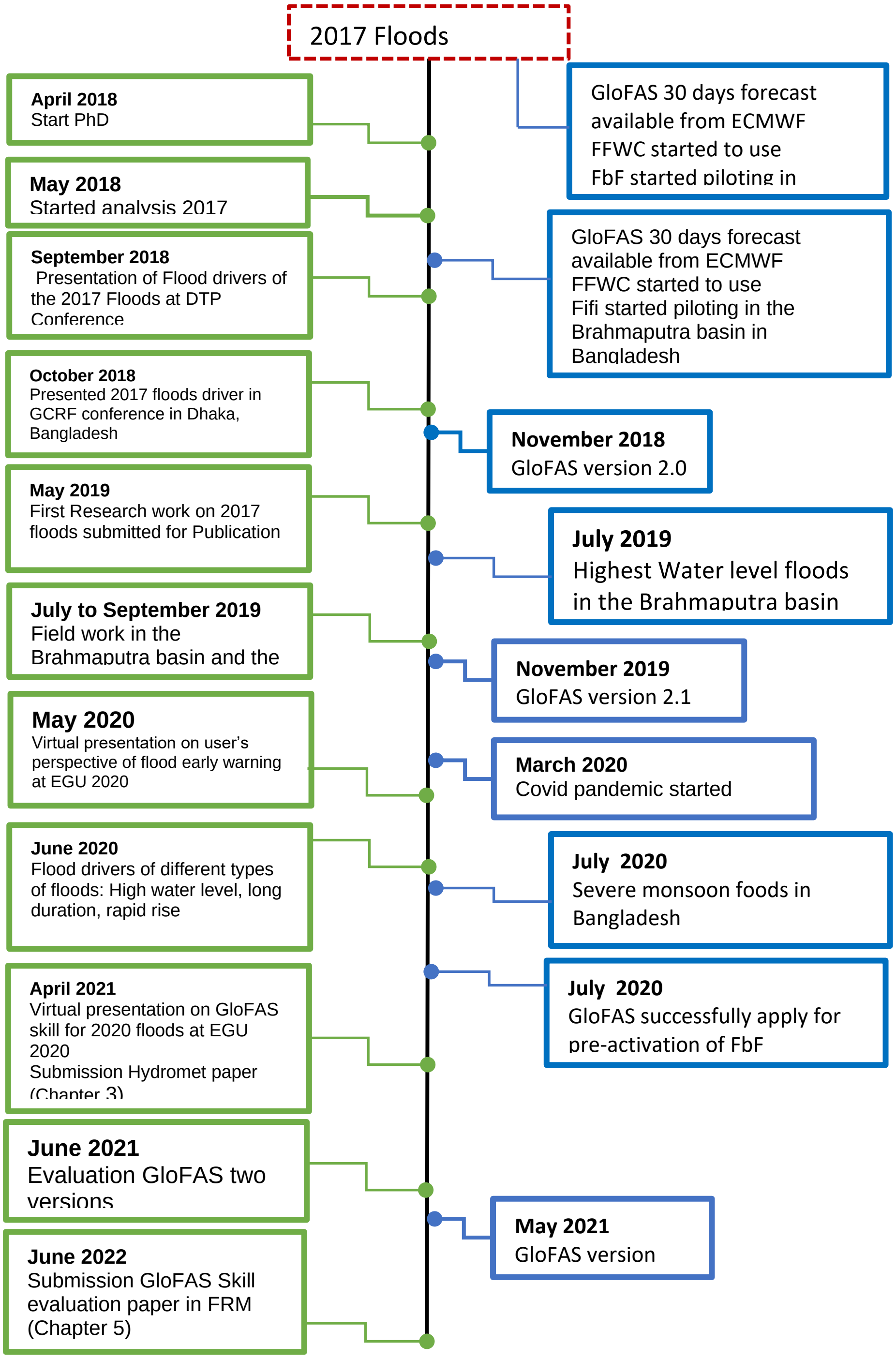

Figure 1.2. PhD research timeline (green) and GloFAS versions with important events (blue).

1.2 Aim and objectives

The aim of the study is “to support in improving flood early warning by applying extended range global forecasting for better flood preparedness for the Brahmaputra basin in Bangladesh.” The specific objectives are as flows:

(i) To assess the hydroclimatological characteristics of flooding in the Brahmaputra basin;

(ii) To study users’ perspectives on and needs for flood early warning information in the Brahmaputra basin for flood preparedness decisions;

(iii) To assess GloFAS performance and capabilities to meet user decision needs.

1.3 Description of the study area

The Brahmaputra basin is located between approximately 82° E to 97° 50´ E and 25° 10´ N to 30° 30´ N, with a total area of about 580,000 km^2 (Bora, 2004). It is a transboundary river basin shared by Bangladesh (8.1%), Bhutan (7.8%), China (50.5%) and India (33.6%) (Goswami & Das, 2002). The river originates from glaciers in the Kailash range in Tibet at an elevation of about 5300 m and flows through China, Arunachal Pradesh and Assam states of India before finally meeting with the Ganges river in Bangladesh (Goswami & Das, 2002). The length of the river is about 2880 km, of which 1625 km is in Tibet (China), 918 km in India and 337 km in Bangladesh (Sarma, 2005). Figure 1.3 shows the location of the Brahmaputra basin with respect to co-riparian countries and other two river basins: the Ganges and the Meghna. In China, the Brahmaputra river is known as the Tsangpo and flows eastward at an average height of 4,000 m m.s.l (Mahanta et al., 2014). At the most eastern end of Tibet region, the river suddenly enters a deep narrow gorge at Pe at an elevation of around 3000 m (Fig. 1.4). After flowing through the high altitude Himalayan mountain ranges, it enters Indian state of Arunachal Pradesh at an elevation approximately 700 m (Goswami, 1985), where it is named as Dihang. The river travels around 220 km southern direction in the mountainous part of Arunachal Pradesh to reach Pasigaht, meets with two major tributaries Dibang and Lohit, and enters to alluvial flood plain valley of Assam (Ghosh & Dutta, 2012). The valley is surrounded by high Himalayan Mountain ranges in the north, the Patkai hill ranges in the east, the lower (Assam) hill ranges in the south, while it is connected with the floodplain of Bangladesh in the west side. The river traverses almost 720 km in the Assam valley before entering the floodplain delta in Bangladesh. The river meets with the Ganges at Goalondo in Bangladesh where it becomes known as the Padma. Finally, it meets with the Meghna River at Chandpur before flowing into the Bay of Bengal (Fig.1.3). The river bed follows a gentle slope in the lower floodplain reaches, which varies between 0.09 to 0.17 m/km, whereas a high gradient at the upstream gorge section with a maximum slope 16.8 m/km (Goswami, 1985). The river is connected to numerous tributaries from both north and south in the upstream reach of Bangladesh. The Teesta, Dharla and Dudkumar are three major tributaries inside Bangladesh. The Brahmaputra is characterised as a braided river with numerous sand bars that create several channels within the river. The river width varies from 9 to 16 km during the monsoon in Bangladesh (BWDB, 2011).

The flow regimes of the Brahmaputra have diverse physiographic environments. The physiography of the basin can be classified into three distinct zones: the Tibetan plateau (elevation exceeding 3500 m); the Himalaya belt (elevation between 100 m and 3500 m), and the agricultural floodplain (elevation up to 100 m) (Immerzeel, 2008). The lower floodplain region is the warmest among the three areas, with an average winter temperature of around 17°C and summer temperatures as high as 27°C (Immerzeel, 2008). Based on the physiographic distribution, annual precipitation varies across the different parts of the basin. Bangladesh, Bhutan and India (Sub-Himalaya region of West Bengal, Assam and Arunachal Pradesh) of the basin are located in the high monsoon precipitation regime, while the high mountainous region climate is cold and dry and receives less rainfall (Ghosh & Dutta, 2012) (Table 1.1). Average annual and monsoon flows are 20000 m3 s-1 and 40,000 m^3 s^{-1}, respectively based on measurement of stream flow at Bahadurabad stream gauging station in Bangladesh (BWDB, 2017b) (location in Fig. 1.3b). High monsoon rainfall in the basin with a dense drainage network and steep gradient at the upstream has made it the world's highest specific discharge (0.149 $m^3/s/km^2$) and high sediment yield (annual 735 million metric tonnes) river (Ghosh & Dutta, 2012; Mahanta et al., 2014). Floods are quite frequent in the floodplain of Assam valley and Bangladesh due to high intensity monsoon precipitation (Nepal & Shrestha, 2015). People’s lives and livelihoods are affected annually by floods. For example, agriculture is the main economic activity in Bangladesh contributing to about 12% of the country’s total GDP (BBS, 2023) and employing 32% of the labour force (BBS, 2020). Floods related damages such as inundation of crop fields and losses of production are common due to frequent floods (Mahanta et al., 2014).

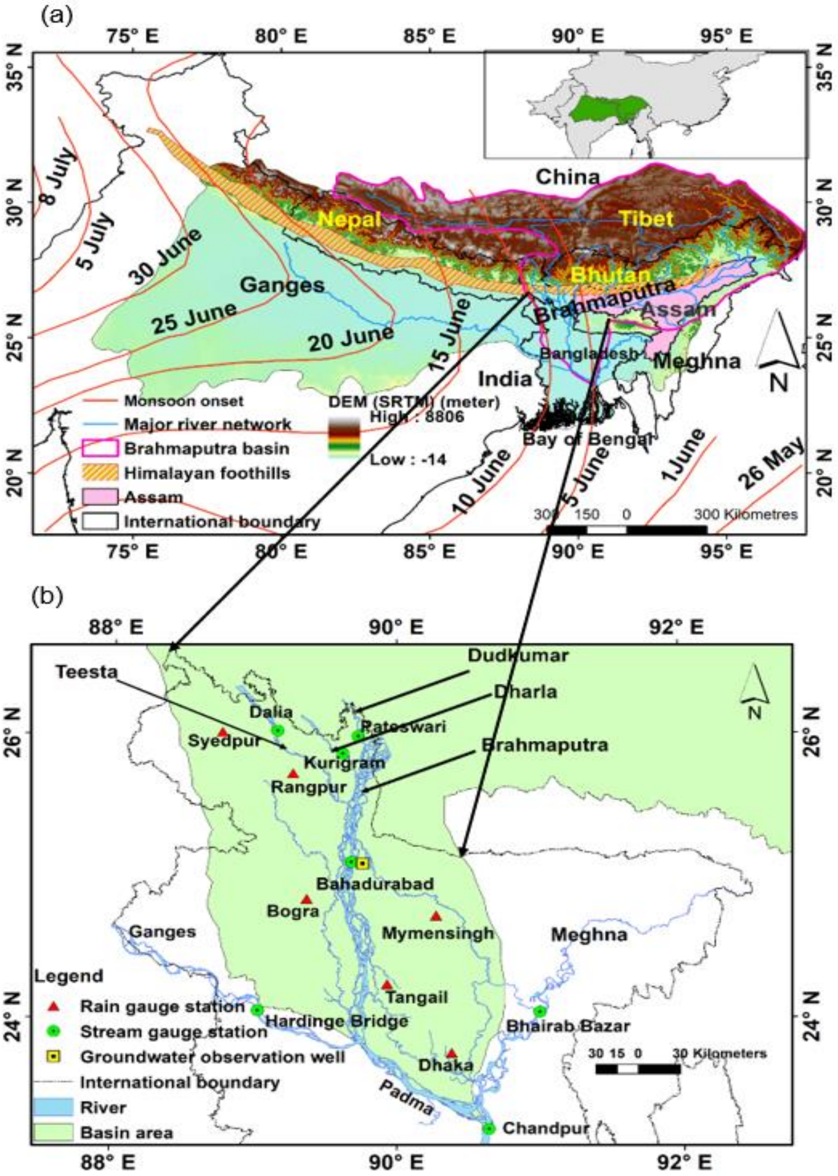

Figure 1.3. (a) Location of the Brahmaputra basin in South Asia with respect to the Ganges and Meghna basins. The Himalayan foothills and Assam areas are highlighted. Monsoon onset dates are shown in redline lines (Pai et al., 2020). (b) Basin area in Bangladesh with major river systems. The locations of the stream gauges, rain gauge stations and groundwater observation well are also shown (Source: FFWC).

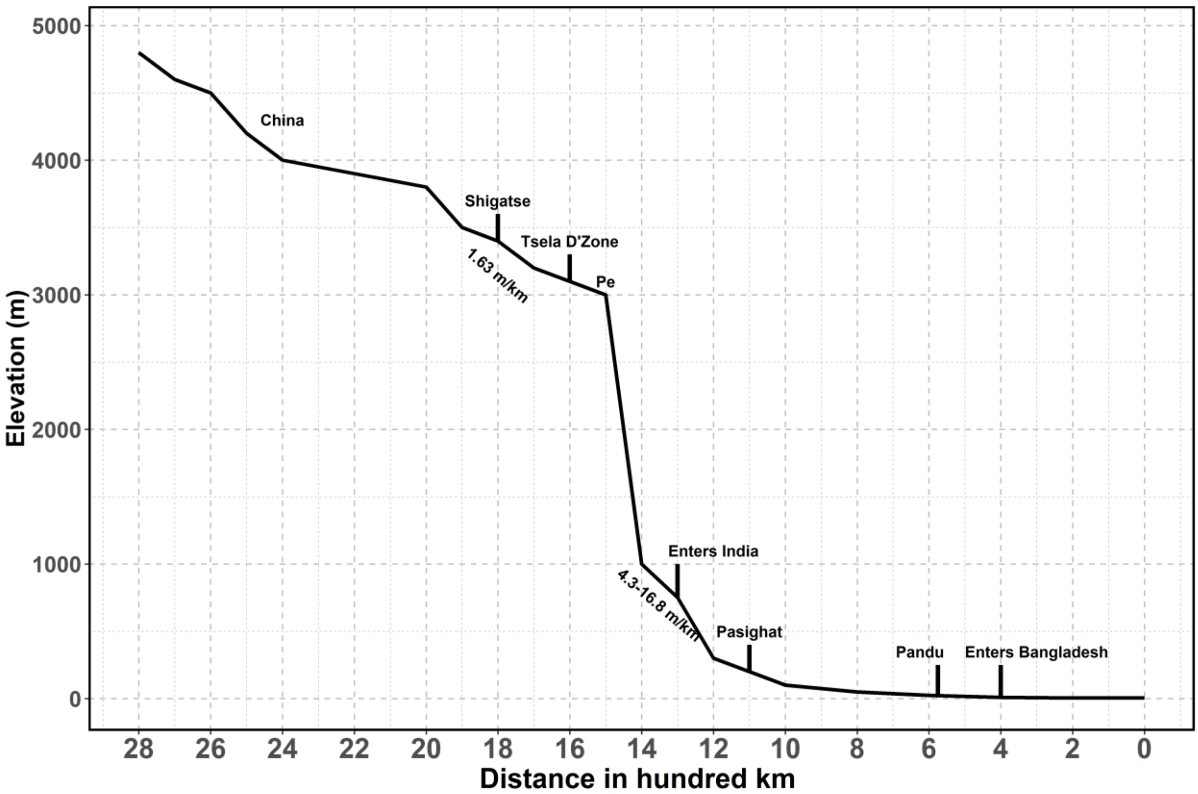

Figure 1.4. Longitudinal profile of the Brahmaputra River. Starting at 30°21', 82°51' in China and 90°38', 23°16'' in Bangladesh (Goswami, 1985).

Table 1.1. Mean annual precipitation different countries of the Brahmaputra basin (Mirza et al., 2003).

Basin	Country	Mean annual precipitation (mm)
Brahmaputra	Tibet (China)	400-500
	Bhutan	500-5000
	India	2500
	Bangladesh	2400

1.4 Structure of the thesis

The thesis is structured in the following chapters based on three research topics: Assessment of hydroclimatological characteristics floods, Users' perspectives flood early warning and GloFAS forecast skill from flood preparedness decisions for the Brahmaputra basin in Bangladesh.

Chapter 2

Chapter 2 includes a literature review of the South Asian summer monsoon and its relation to floods over the Brahmaputra basin at different time scales: synoptic, intraseasonal and seasonal. The second part of the literature review includes the development of flood forecasting from the global to regional level and stakeholders decisions using early warning of the Brahmaputra basin in Bangladesh.

Chapter 3

This chapter presents assessment of hydroclimatological characteristics of flooding in relation to key flood drivers in the Brahmaputra basin as a case study. It contains data, methods and results of different meteorological and hydrological drivers causing flood characteristics such as long duration, high flood and rapid rise.

Chapter 4

This chapter focuses on the analysis of users' perspectives of flood early warning in Bangladesh. The research is based on qualitative data: semi-structured interview, focus group discussion and household survey which was collected during the 2019 monsoon floods. The study includes stakeholders from national, sub-national and community levels. The major findings answer the key questions of how flood forecast is used for preparedness. Users need in terms of lead time for better response to early action, including challenges for probabilistic forecast in early action decisions.

Chapter 5

Chapter 5 includes forecast skill of GloFAS flood forecast for model versions 2.1 and 3.1. The evaluation focuses forecast skill with respect different decision criteria including model's capability to simulate annual flood behaviour.

Chapter 6

Overall discussion of the research work.

Chapter 7

The final chapter contains concluding remarks of the research.

Chapter 2 Literature Review

Monsoon and flood hydrology of the Brahmaputra basin

2.1 Introduction

The monsoon, originating from the Arabic word *'Masum'* meaning season, refers to a seasonal change of wind flow from the pre-monsoon direction (north-easterly to south-westerly) (Gadgil, 2003; Goswami, 2012; Rao, 1976). This results in a differential heating of large land and sea areas, altering with the season (McIntosh, 1972) (Fig. 2.1). During the winter (December–January–February), cold dry wind flows from the northeast direction (also known as north-east monsoon). The temperature rises from March to May, and the high summer temperature warms the land mass, creating well marked low-pressure, also known as heat-low, over the northern part of the Indian region before the monsoon onset in June (Raju et al., 2005). With this system, a semi-permanent low pressure belt develops from the west to the head of the Bay of Bengal and creates a surface trough zone over the Indian monsoon region (Gadgil, 2003) (Fig. 2.2). This establishes south-westerly warm and moist airflow from the Bay of Bengal and the Arabian sea towards the Indian landmass from June to September, bringing high amounts of rainfall over the Indian sub-continent. Therefore, with the influence of the south-westerly monsoon, the countries in the Indian sub-continent (Bangladesh, Bhutan, India, Nepal, Myanmar, Sri Lanka and Pakistan) receive moderate to heavy rainfall between June to September each year. On average, the South Asian monsoon onsets over Kerala– Southwest India by June 2 with a standard deviation of 8 days, and gradually advances to cover the whole Indian region (Krishnamurthy & Shukla, 2000; Rao et al., 2005) (Fig. 2.3a). By the middle of June, the monsoon covers most of the peninsula, northeast and parts of central India, and in the first week of July, the monsoon circulation covers the whole of the Indian region (Pai et al., 2020). The monsoon flow usually continues until mid-September when the withdrawal from west Rajasthan starts and complete withdrawal occurs by the second week in October (Rao et al., 2005) (Fig. 2.3b) when reverse wind systems from the Northeast direction starts to establish over the sub-continent and winter starts to set over the region.

The South-Asian summer monsoon brings around 70-90% of the annual rainfall to the Indian subcontinent between June to September (Parthasarathy and Pant, 1985), and is the main source of flooding in this region. There is temporal and spatial variation of rainfall events during the monsoon period, and the variation is associated with oscillation of the monsoon trough, also described as the intertropical convergence zone (ITCZ) (Goswami, 2005b; Krishnamurthy and Kinter, 2003).

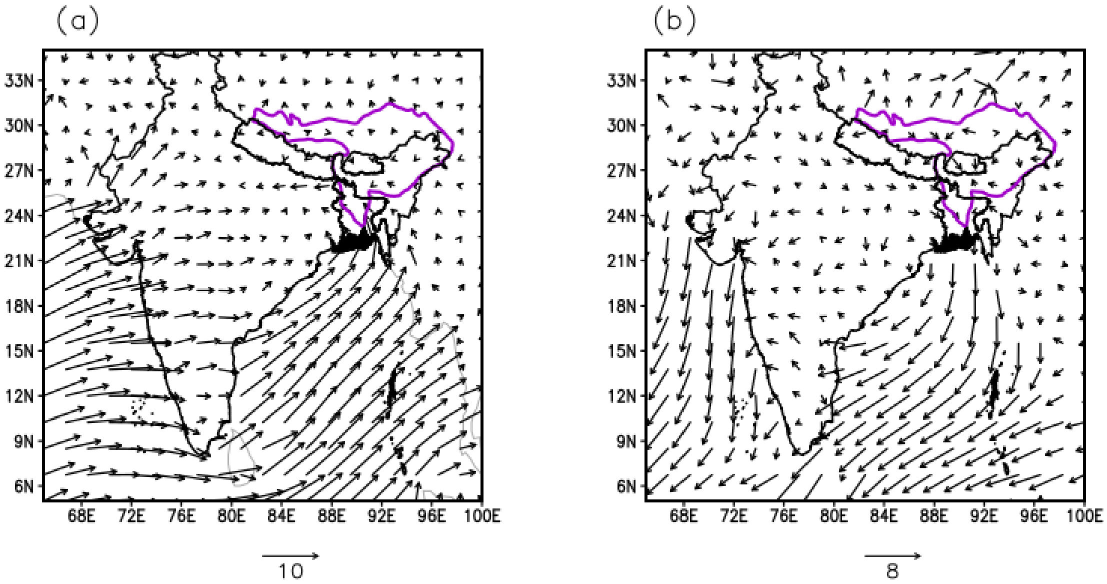

Figure 2.1. Climatology of surface wind (10 m) (a) June-July-August-September and (b) December-January-February (based on ERA5 reanalysis).

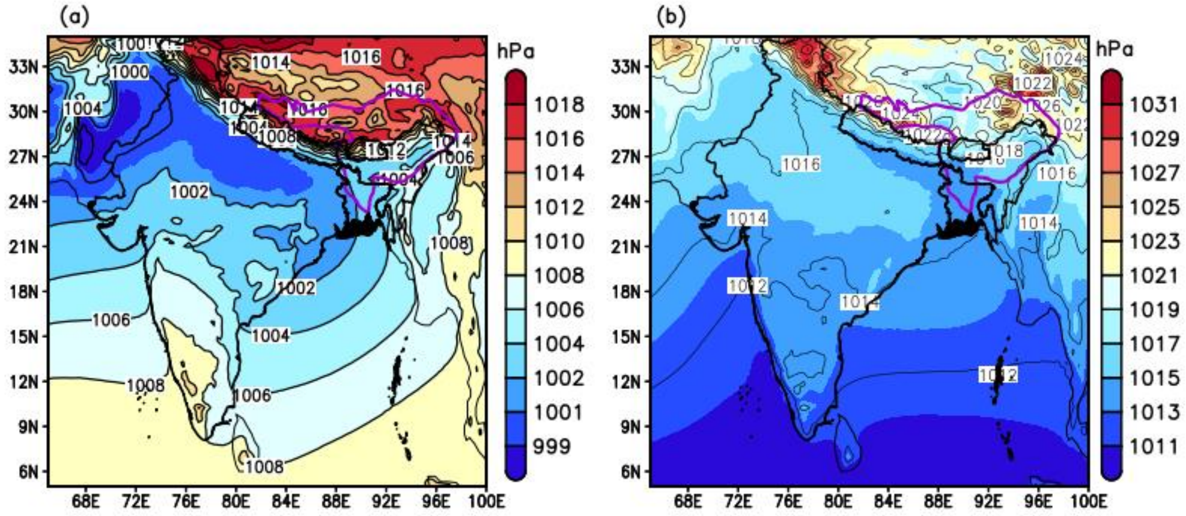

Figure 2.2. Climatology of mean sea level (MSL) pressure (a) June-July-August-September and (b) December-January-February (based on ERA5 reanalysis).

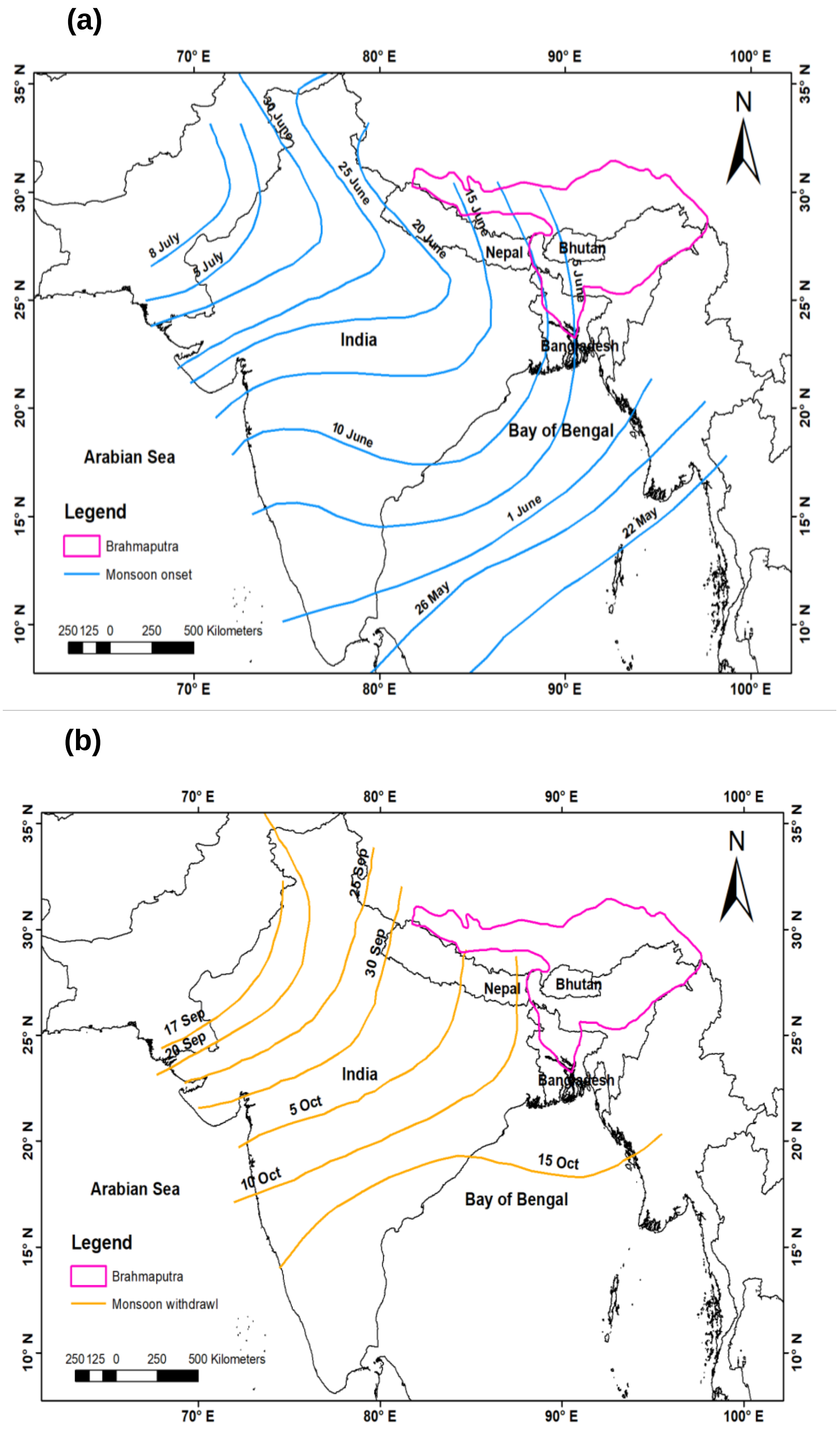

Figure 2.3. Normal dates of monsoon (a) onset/progress and (b) withdrawal over South Asian region (Pai et al., 2020). Purple colour boundary shows Brahmaputra basin boundary while blue lines and yellow lines indicate monsoon onset/progress and withdrawal, respectively.

The spatial distribution of rainfall shows that southern peninsular India, central India, northeast Indian region, Bhutan, Nepal and Bangladesh receive high monsoon rainfall between June to September, whereas winter is almost dry (Fig. 2.4). The Coefficient of Variation of rainfall during the monsoon rainfall months (June to September) varies from 13 to 22 %, whereas the Coefficient of Variation is about 10% in the interannual scale variation of the monsoon over the Indian monsoon region (Parthasarathy et al., 1994). The temporal variability of monsoon rainfall includes— synoptic (5-7 days), intraseasonal (10-20 days and 30-60 days) and interannual (Goswami & Mohan, 2001; Krishnamurthy & Shukla, 2007).

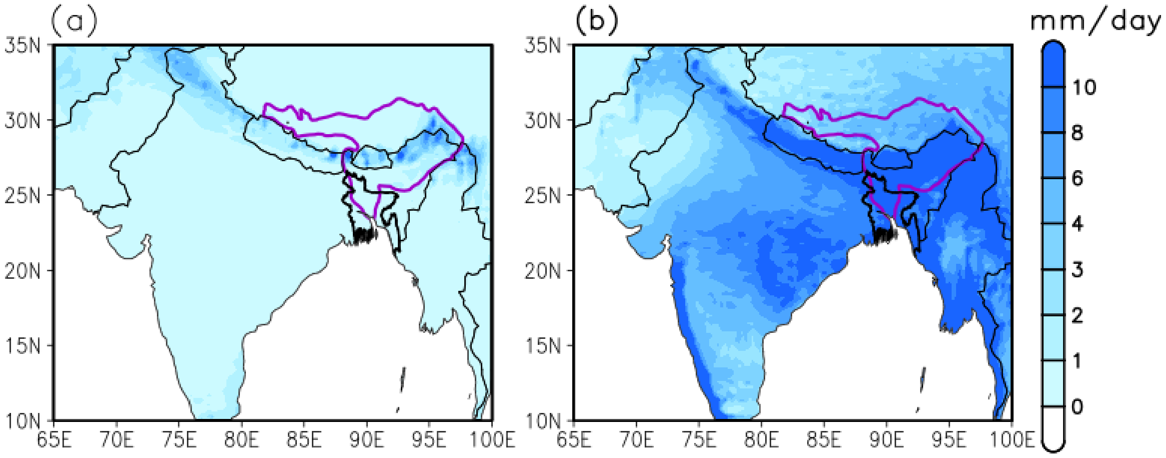

Figure 2.4. Distribution of mean daily rainfall over 1979-2017 (a) December to February and (b) June to September. The purple line indicates the basin boundary (based on ERA5 reanalysis).

The annual rainfall may be normal; however, its temporal distribution can produce devastating effects (Rao et al., 2005), including floods or prolonged dry spells leading to drought conditions. Therefore, the monsoon variation has severe implications on crop production and water availability which may affect food security (Mishra et al., 2012).

2.2 Temporal variations of monsoon rainfall

2.2.1 Synoptic scale

The key synoptic activities during the summer monsoon season consist of weather disturbances such as monsoon lows and depressions, sub-tropical cyclones, and westerly disturbances that determine the day-to-day variability of precipitation with a time scale of 5 to 7 days (Goswami, 2012; SIKKA, 2011). These synoptic systems bring most of the monsoon rainfall (Rao, 1976). Monsoon depressions are low pressure areas formed with two or three closed isobars (at 2 mb intervals) covering an area of about five degrees square, which form in the Bay of Bengal north of 18º N, move west and northwest towards the central region India (Rao, 1976; Turner & Annamalai, 2012). The systems often recurve and move north to eastward toward Bangladesh (Fig. 2.5). In the majority of cases the maximum duration of a monsoon depression is 2 to 5 days and in only 10% of cases it lasts for a week or more (Tyagi et al., 2012). Climatological data shows that about 6 monsoon depressions develop over the Indian region during the SW monsoon season (June to September) with a standard deviation of about 2.5. On average, two systems form during July and August, while one in June and September, respectively (IMD, 2017).

Monsoon lows are less intense than monsoon depressions that frequently form during the monsoon season in the Bay of Bengal, the Arabian Sea, and over land north of 22° N, i.e. Bihar, south of Uttar Pradesh and north of Madhya Pradesh (Rao, 1976). According to the criteria followed by the Indian Meteorological Department (IMD) a low pressure area is referred to as a monsoon low if the wind speed within the associated cyclonic circulation is less than 17 knots (31.48 km/hr). When the wind speed is 17 (31.48 km/hr) to 33 (61.11 km/hr) knots or more it is called a depression. More intense systems like cyclonic storms can also occur during the monsoon where higher speeds prevail (Rao, 1976; Tyagi et al., 2012). About 70.5% of the low pressure systems (LPS) have a life duration of 5 days or less, 28% have a life of 6 to 10 days, and only 1.5% survive more than 10 days (Tyagi et al., 2012).

Based on these synoptic activities, an extended period of wet or dry periods can continue for weeks, such as 2 to 3 weeks (Goswami, 2012; Singh & Ranade, 2010) and extended wet or dry periods are often linked with floods or drought, respectively. These extended periods of above normal rainfall or below normal rainfall drive intraseasonal variation in monsoon rainfall (Goswami, 2005; Raghavan, 1973; Ramamurthy, 1969).

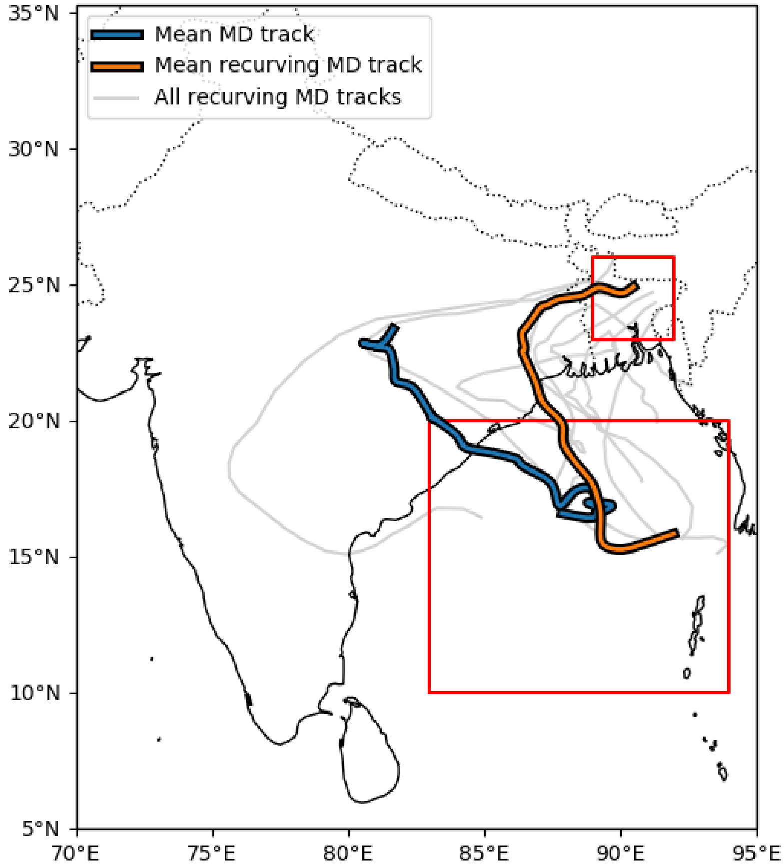

Figure 2.5. Mean monsoon depression tracks originated in the Bay of Bengal. Depression recurves towards the Bangladesh and the Brahmaputra basin (Source: Kieran Hunt, University of Reading, personal communication).

2.2.2 Intraseasonal scale

Intraseasonal scale variation is longer than synoptic variability but shorter than a season usually with periods between 10 to 90 days, with two dominant periodicities 10 to 20 days and 30 to 60 days (Goswami & Mohan, 2001; Krishnamurthy & Kinter, 2003; Kulkarni et al., 2009). These two time scales are related to alternate dry and wet spells of the monsoon, also known as ‘active’ and ‘break’ conditions (Dunning et al., 2015; Goswami, 2012). These two conditions are used to describe wet and dry spells of the summer monsoon with respect to central India region, as shown in Figure 2.6. During the active phase, rainfall is above normal over central India and below normal over northern India (foothills of the Himalayas) (Fig. 2.6a), with a life span of around two weeks (Krishnamurthy & Shukla, 2000, 2007). This situation is reversed during the break phase condition of the monsoon (2.6b). Changes in position of the monsoon trough during the active and break monsoon conditions are presented in Figure 2.6c and d, respectively. Two convective systems are associated with these two dominant modes of intraseasonal oscillations.

The 10 – 20 day variations are associated with the westward moving convective systems from the South China Sea/Bay of Bengal, propagating towards the Indian land mass and contributing substantial rainfall (Goswami, 2005; Kulkarni et al., 2009). While the 30 – 60 day variations are linked with eastward moving systems along the equatorial regions, also known as Madden–Julian oscillations (MJO) (Madden & Julian, 1971). However, the MJO is considered weaker during boreal summer and strong in winter, instead, the Boreal Summer Intraseasonal Oscillations (BSISO), which features northward propagating bands of convection at South Asian longitudes together with eastward propagation at the equator can contribute to rainfall (Annamalai & Sperber, 2005; Kikuchi et al., 2012; Lee et al., 2013). Both MJO and BSISO modes are represented in a diagram of eight phase spaces to capture the location and strength of convection propagation (Fig. 2.7). The corresponding rainfall anomalies in 8 different phases of MJO and BSISO are presented in figures 2.8 and 2.9, respectively.

In MJO, a convective anomaly starts to appear over the Africa-western Indian Ocean at phase 1 and moves eastward to the Indian Ocean through phases 2 to 4 (Fig. 2.7a) (Kikuchi et al., 2012). The formation of MJO Phases 1 and 2 is associated with a positive convective anomaly over the Western Indian Ocean (Wheeler & Hendon, 2004), which causes a break monsoon condition over the central Indian region (Fig. 2.8) (Pai et al., 2011). Due to a dipole style action between active and break monsoon conditions, positive rainfall anomalies in the north and northeast Indian region, Bangladesh (Brahmaputra basin) occurs in these two phases (Phase1 and 2) of MJO. On the other hand, the monsoon core zone (central India) receives positive monsoon rainfall anomalies in phase 5 and 6 (Fig. 2.8). A convective anomaly associated with the BSISO mode starts to appear in the equatorial central Indian Ocean at phase 1 (Kikuchi et al., 2012) (Fig. 2.7b). Then northward propagation of the convection is pronounced in the BSISO through phases 2 to 3 compared to MJO. The monsoon core zone (central

India) receives less rainfall in these two phases, while it influences the Brahmaputra rainfall during phases 2 and 3 when convection is in the Bay of Bengal (Fig.2.9).

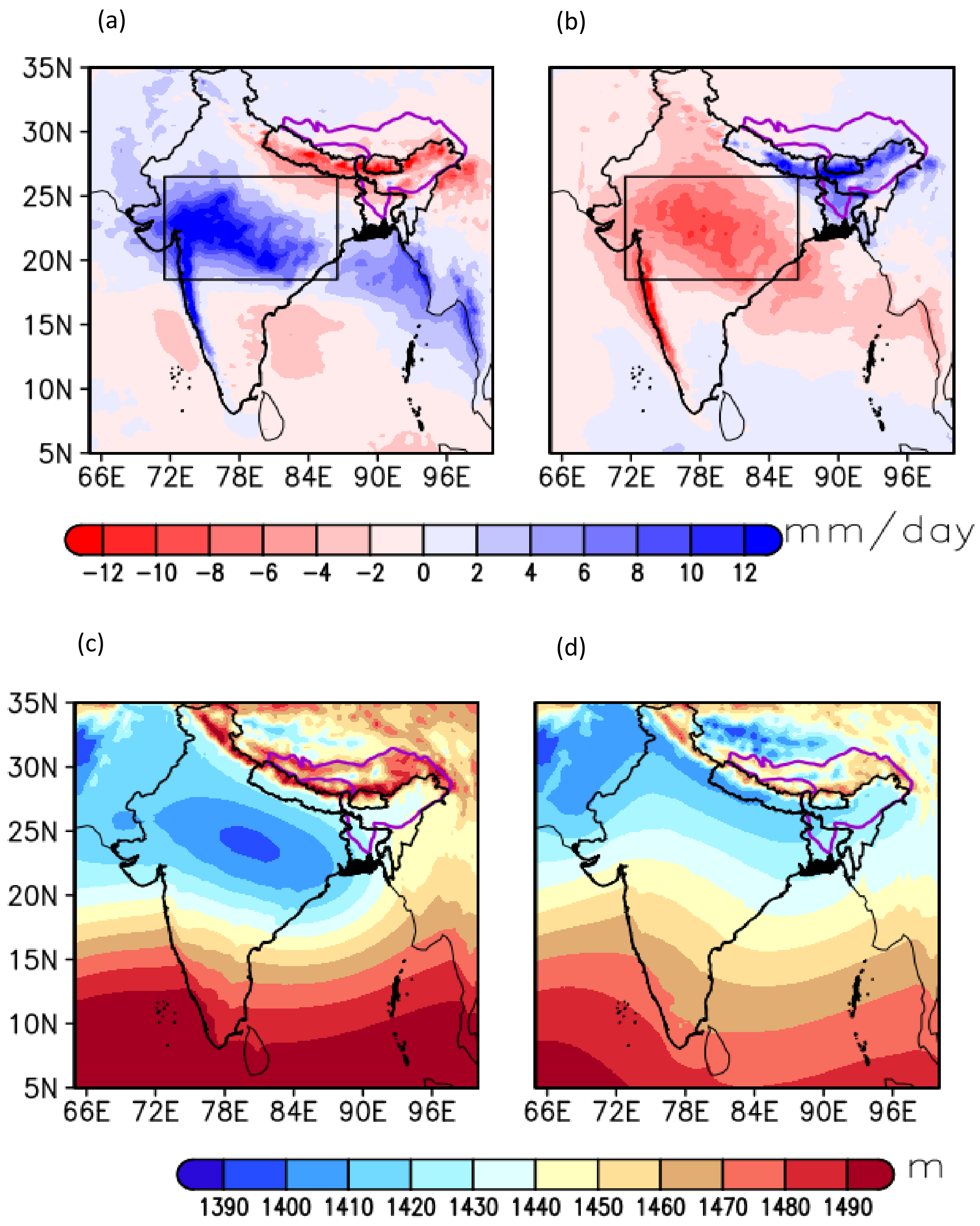

Figure 2.6. Rainfall anomaly during (a) active and (b) break phases; composite of 850 hPa geopotential height during (c) active and (d) break events. The rectangular box represents the Indian monsoon core zone (71.5–86.5° E, 18.5-26.5° N) (Dunning et al., 2015). The purple line indicates the basin boundary of the Brahmaputra river. Data used: ERA5 reanalysis 0.25° x 0.25° gridded data over the period 1987-2016 (July and August).

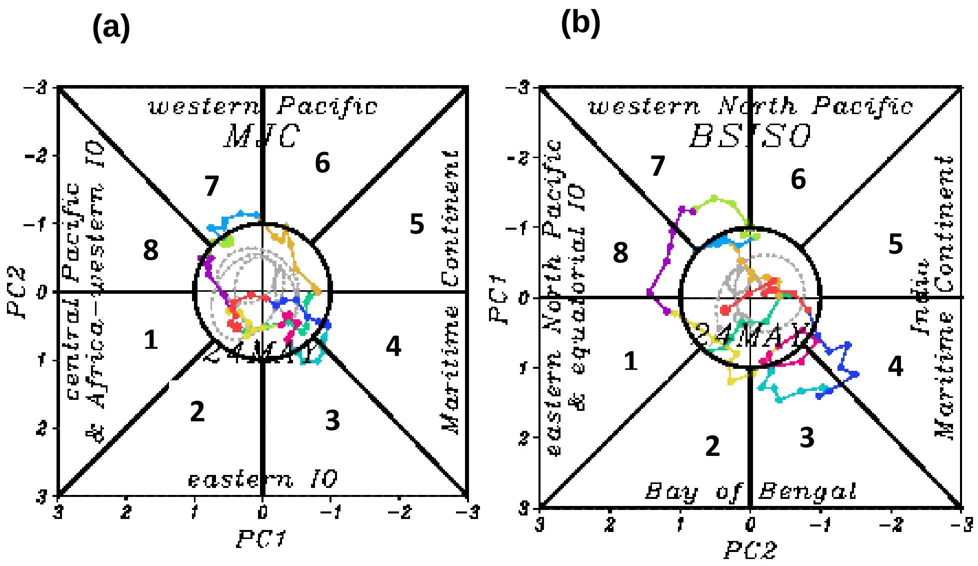

Figure 2.7. Phase space representation (a) MJO and (b) BSISO (24 May, 2022) (Bimodal ISO index), http://iprc.soest.hawaii.edu/users/kazuyosh/Bimodal_ISO.html (IPRC/SOEST, 2020).

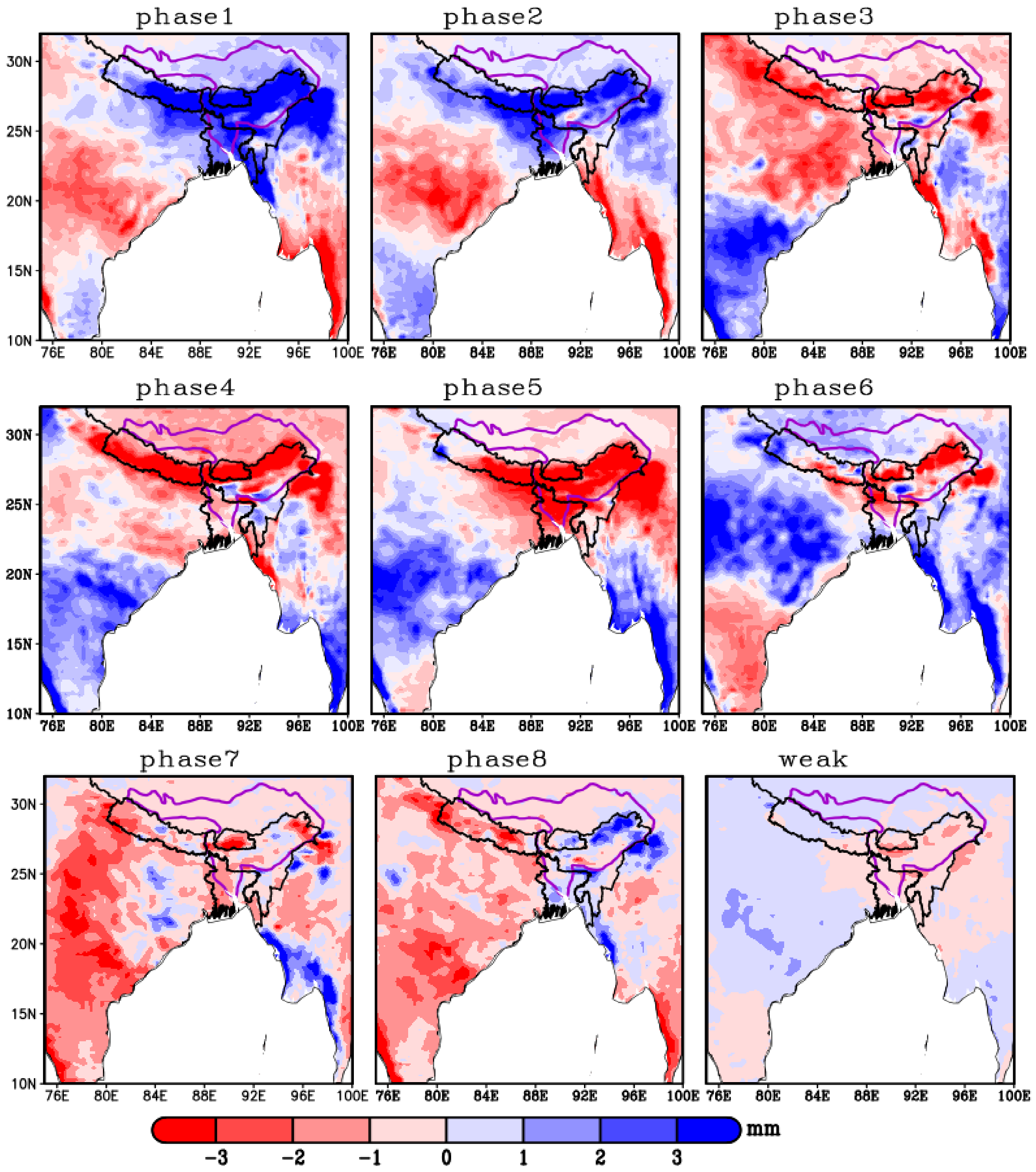

Figure 2.8. Rainfall anomaly in eight strong and weak phases of MJO events for the period 1987-2019 between June to September (based on ERA5 reanalysis). MJO events are identified at a particular time during the monsoon if the amplitude ($amplitude = \sqrt{PC_1^2 + PC_2^2}$) is greater than (or equal) to 1, also referred as strong, whereas amplitude less than 1 is considered as weak condition (Pai et al., 2011).

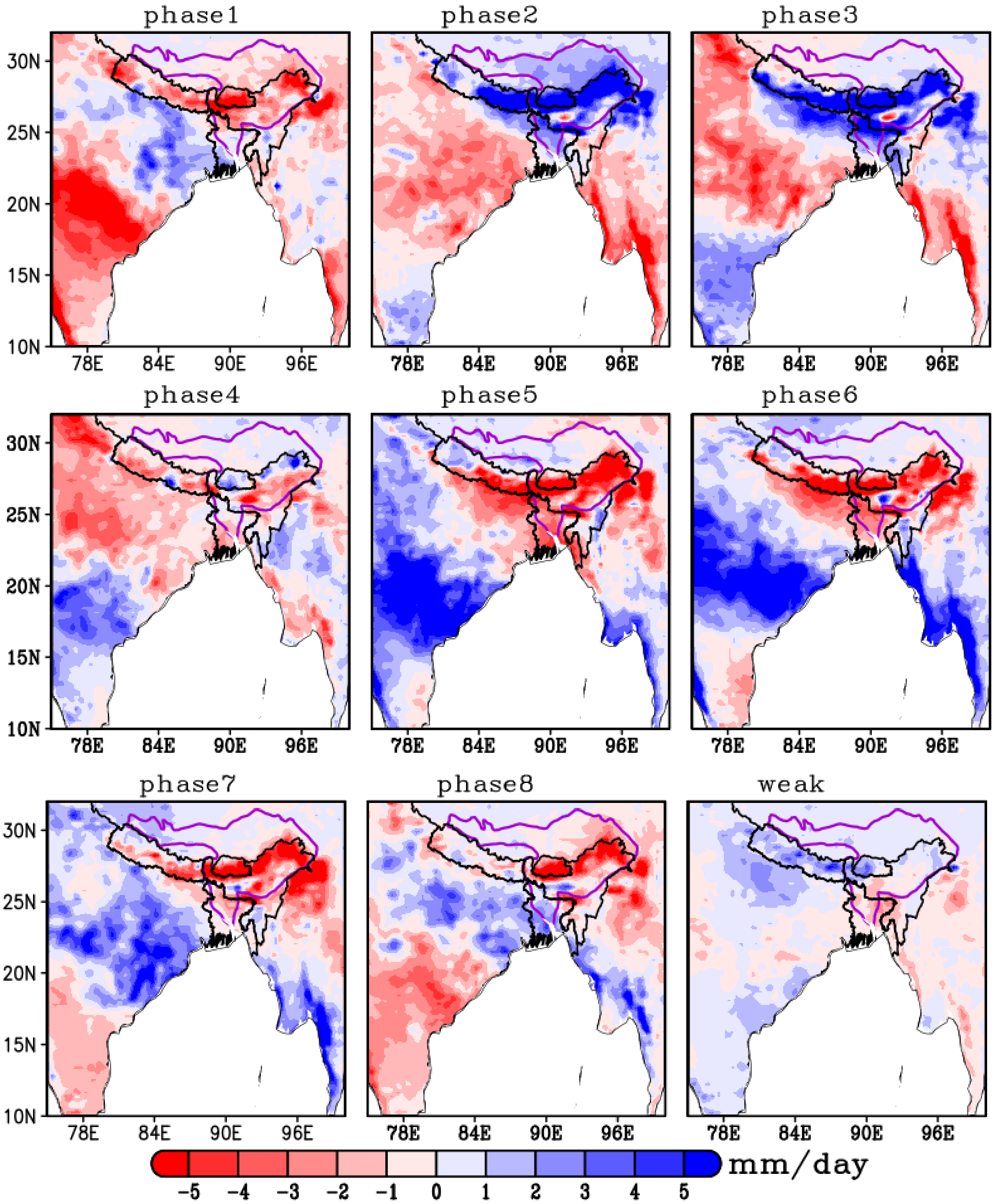

Figure 2.9. Rainfall anomaly in eight strong and weak phases of BSISO events for the period 1987-2019 between June to September (based on ERA5 reanalysis). BSISO events are identified at a particular time during the monsoon if the amplitude ($amplitude = \sqrt{PC_1^2 + PC_2^2}$) is greater than (or equal to) 1, also referred as strong, whereas amplitude less than 1 is considered as weak condition (Kikuchi et al., 2012).

2.2.3 Interannual scale

The seasonal (June to September) mean rainfall shows year to year variation. Monsoon rainfall can be well below normal in some years i.e., 2005 (21% less)[1], 2006 (24% less)[1] leads to drought like situation in Bangladesh. The interannual variability of the monsoon can be attributed to the slowly varying forcings such as sea surface temperature (SST), soil moisture, sea ice and snow at the surface (Charney & Shukla, 1981). At interannual time scales, the El Niño Southern Oscillation (ENSO) is the most well-known mode of global circulation understood as a driver of the variability of monsoon rainfall (Goswami et al., 1999; Krishnamurthy and Kinter, 2003). El Niño is characterized by a large scale weakening of the trade winds and warming of the surface layers in the eastern and central equatorial Pacific Ocean, whereas La Niña is associated with stronger than normal trade winds and the cold phase of the eastern Pacific Ocean. Therefore, the La Niña phase strengthens the easterly wind from the Pacific Ocean, bringing more moisture to the Indian landmass and contributing more rainfall (Choudhury, 1998). There are several indices used to monitor the ESNO conditions based on monthly sea surface temperature (SST) anomalies indices in the equatorial tropical Pacific averaged across certain regions which include Niño 1+2 (0-10S, 90W-80W), Niño 3 (4°N to 4°S, 150°W to 90°W), Niño 3.4 (5°N to 5°S, 170°W to 120°W), Niño 4 (5N-5S, 160E-150W) (Kousky & Higgins, 2007) (Fig. 2.10). The Niño 3.4 region is located at the centre between Niño 3 and 4 and commonly used for representation of ENSO phenomenon (Bamston et al., 1997). There is a general tendency for El Niño and La Niña to correspond to dry and wet conditions (respectively) over the Indian monsoon region. For instance, above normal rainfall and severe flooding in the Brahmaputra basin can be associated with strong La Niña years i.e., 1988, 1998 (Fig. 2.11). However, the relationship is more complex, and some droughts and flood events are found not to occur during El Niño and La Niña years (Emerton et al., 2017; Goswami, 2005a).

Several authors investigated the influence of the ENSO on the south Asian monsoon (Rasmusson & Carpenter, 1983; Shukla, 1987; Sikka, 1980). During the La Niña (El Niño) development, the Indian summer (ISM) monsoon strengthens (weakens) compared to ENSO neutral years (Samanta et al., 2020; Webster et al., 1998). However, the influence of La Nina is proposed to be diminishing in recent years due to weaker La Nina events and the impact of warmer Indian Ocean temperatures associated

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[1] Based on ERA5 data

with climate change (McPhaden et al., 2020; Samanta et al., 2020). Therefore, the influence of ENSO on monsoon rainfall makes it necessary to follow the forecast of ENSO evolution in a particular year and carefully monitor how it interacts with the monsoon.

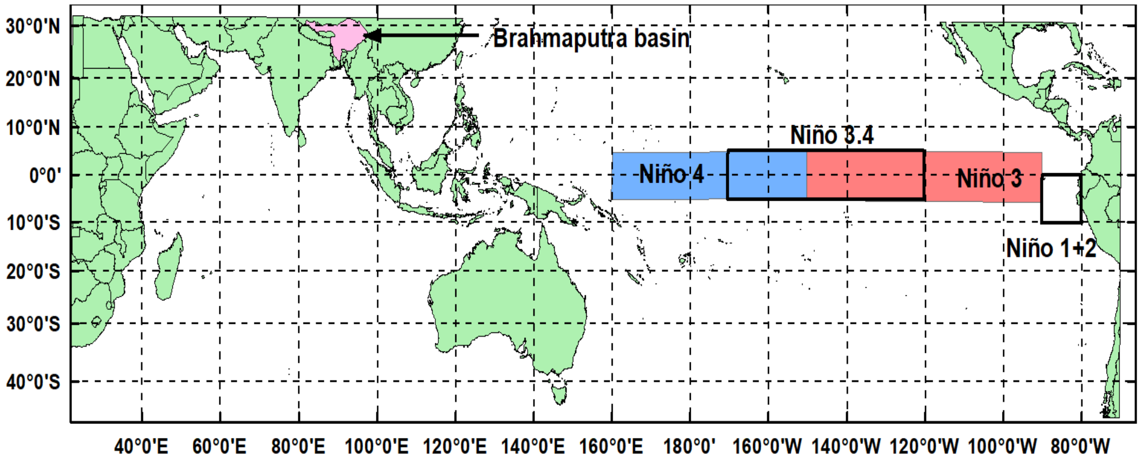


Figure 2.10. Geographical location of Niño regions in the equatorial Pacific Ocean. The Niño 3.4 region is highlighted as a box in the middle. The Brahmaputra basin is shown in pink colour area in the figure.

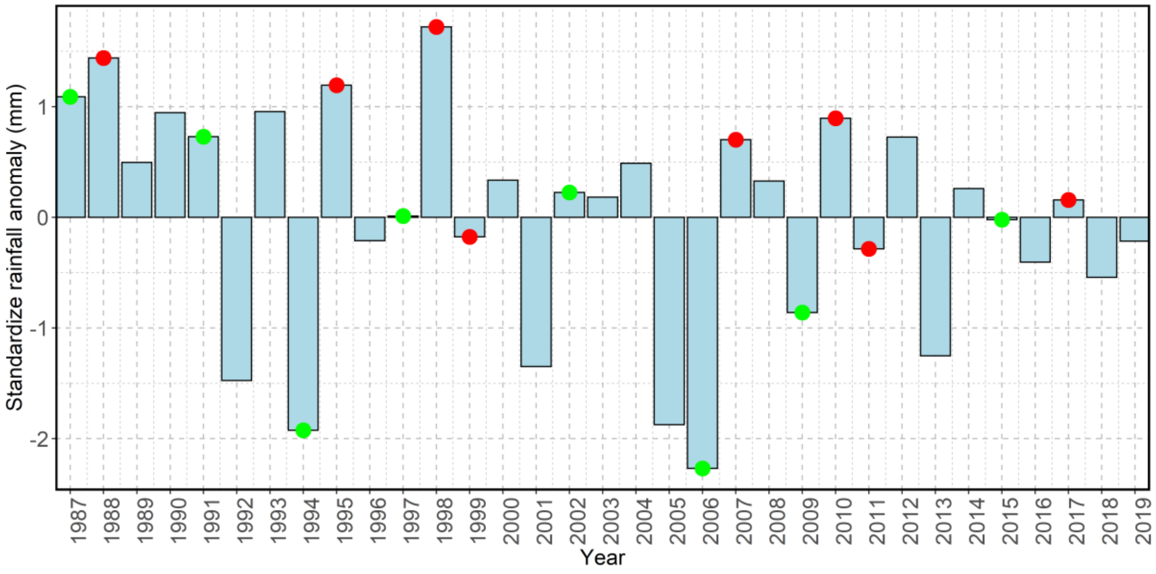


Figure 2.11. Interannual variability of summer monsoon (JJAS) mean rainfall (normalized by standard deviation) over the Brahmaputra basin (based on ERA5 reanalysis). Red dots show La Niña years whereas green dots are for El Niño years.

2.3 Flood hydrology

Floods are the result of meteorological anomalies (Garner et al., 2015), that are created by an extreme rainfall event, series of rainfall events, rapid snowmelt, or a combination of both rainfall and snowmelt (Merz & Blöschl, 2003). However, the river flow is viewed as the integrated process of catchment hydroclimatological response (Hannah et al., 2005; Hannah et al., 2000) as all meteorological anomalies do not always create floods. The characteristics of meteorological anomalies which create floods or drought can vary on both spatial and temporal scales and interact with the catchment characteristics such as land use, soil, and geology (Van Loon et al., 2012; Van Loon & Van Lanen, 2012). These characteristics influence water storage and catchment responses to river flow (Van Loon & Laaha, 2015). The flooding is a dynamic process which can be represented by the hydrological cycle where different processes are interconnected (Fig. 2.12a). For a larger catchment approach, the hydrological cycle starts with the evaporation of water from the ocean and follow complete circulation within atmosphere and earth surface before flow return to the ocean again (Dingman, 2002). Flood-generation mechanisms involve various rainfall runoff processes including surface, subsurface and groundwater pathways and processes such as saturation excess overland flow, infiltration excess overland flow and throughflow/interflow, preferential subsurface flow and groundwater contributions (Pilgrim & Cordey, 1992) (Fig. 2.12b). Hydrologists usually take a ‘catchment perspective’ for floods and however, to understand whole processes, both catchment hydrology and meteorological processes should consider that lead to floods (Merz & Blöschl, 2003). For a large scale floods, multiple mechanisms are involved in driving flood events such as catchment high antecedent condition, temporal and spatial distribution of rain with the superposition of flood waves across the river networks (Berghuijs et al., 2019; Hundecha et al., 2020; Wyżga et al., 2016). Therefore, flood events consist of a wide range of processes which determine flood timing, duration, magnitude, and extent (Tarasova et al., 2019).

The Brahmaputra is a large basin with a diverse landscape and spatial and temporal variability of meteorological anomalies, which cause variation of river flow across the basin, frequently associated with floods. Here, a short review on flood hydrology, such as monsoon rainfall, hydrological characteristics with other relevant aspects of catchment hydrology have been discussed to understand flood dynamics of the Brahmaputra basin.

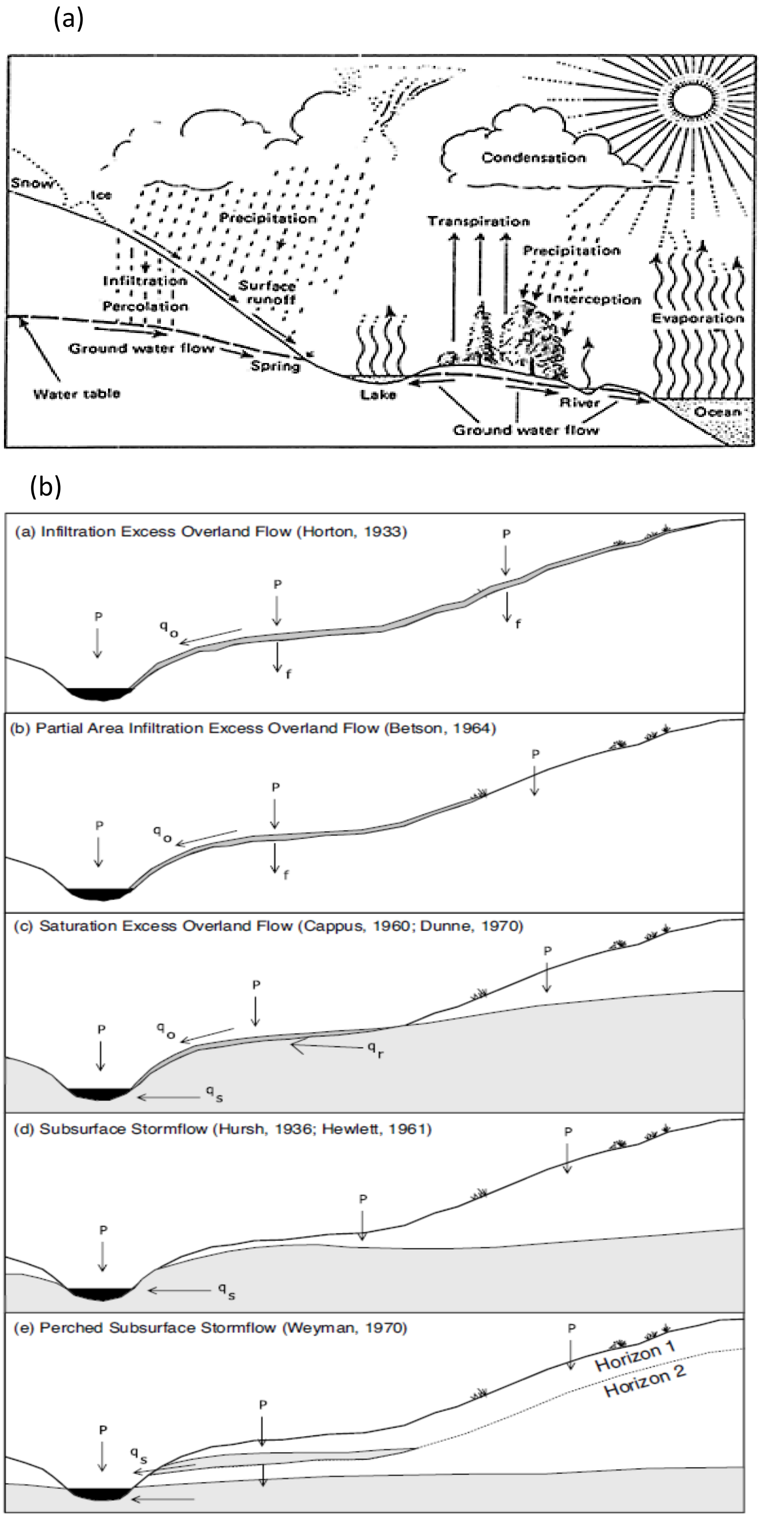


Figure 2.12. (a) The hydrological cycle (Shaw, 2005) and (b) a classification of process mechanisms in the response of hillslopes to rainfalls: (a) infiltration excess overland flow, (b) partial area infiltration excess overland flow, (c) saturation excess overland flow, (d) subsurface stormflow, and (e) perched saturation and throughflow (Beven, 2011).

2.3.1 Monsoon rainfall in the Brahmaputra basin

The Brahmaputra basin receives between 60–70% of its annual rainfall from June–September, with 20–25 % falling during the pre-monsoon of April and May (Dhar and Nandargi, 2000; Purkait, 2004; Nepal and Shrestha, 2015). The spatial distribution of rainfall in the pre-monsoon and monsoon seasons shows two distinct rainfall regimes: upper high altitude Himalayan mountainous ranges and low and medium mountainous ranges, including Assam valley and flood plain (Fig. 2.13a&b). The rainfall in the later part is up to 10 times higher than in the high mountainous part. The annual variability of monsoon rainfall is 15 to 20% of the mean, whereas this variability is about 30% for pre-monsoon except in high mountainous regions (Tibetan part) (Datta & Singh, 2004).

The pre-monsoon rainfall is primarily caused by thunderstorm activity and the movement of depressions from the west towards the basin (Khatun et al., 2016; Purkait, 2004). The onset of the monsoon precipitation usually takes place by June 10 in the basin (Fig. 2.3a), and after then rainfall follows in a sequence of wet and dry spells. The annual mean rainfall in the Arunachal Pradesh, Assam and sub-Himalayan regions is about 2,300 mm, with some places in the foothill regions receiving as much as 5,000 mm (Dhar and Nandargi, 2000; Singh et al., 2013). The high-altitude Tibet region of the Brahmaputra has an annual mean rainfall of ~730 mm (Immerzeel, 2008). The daily evapotranspiration (ET) is 3–4 mm per day, and monthly ET is comparable to (or slightly exceeds) the rainfall in pre-monsoon months when the temperature is high (Fig. 2.13c). During the monsoon, rainfall always exceeds ET, leading to a rise of river water level. Heavy monsoon rainfall in the Brahmaputra basin is associated with the movement of the eastern end of the monsoon trough to the Assam region, producing break monsoon conditions over central India and active conditions around the Himalayan foothills, often with a monsoon depression originating from the Bay of Bengal, which recurves northwards over the Brahmaputra basin i.e. Bangladesh and Assam (Dhar and Nandargi, 2003; Dhar and Nandargi, 2000; Nandargi and Dhar, 2011). Figure 2.6c&d show the typical locations of the monsoon trough during active and break monsoon rainfall events (Section 2.2.2). The extreme rainfall event can extend from a few days to a week which links to severe flooding in the tributaries as well as the main course of the river (Datta & Singh, 2004).

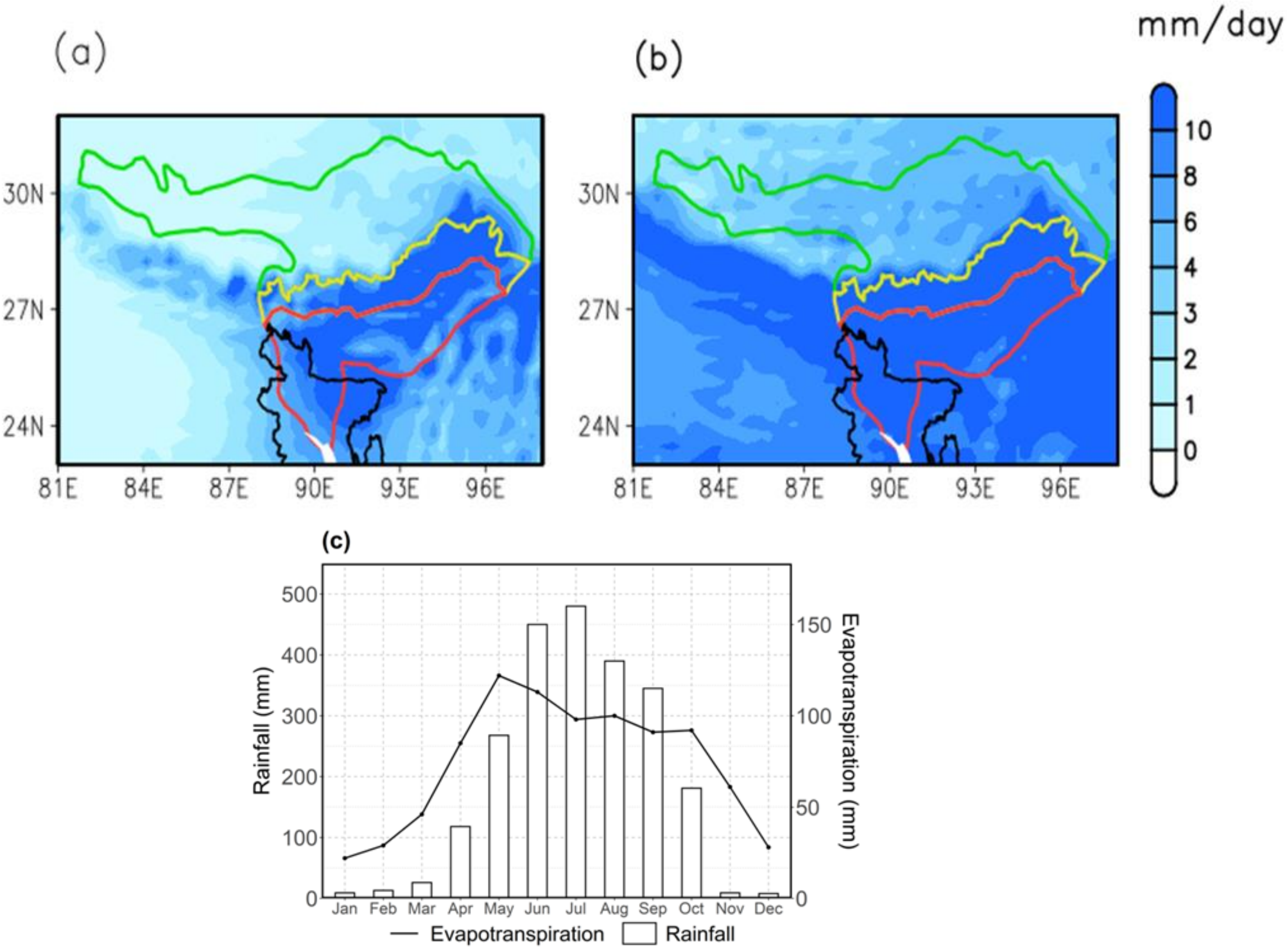


Figure 2.13. Climatology of mean rainfall (mm day^{-1}) in (a) pre-monsoon months, April-May and (b) monsoon season, June-September, based on ERA5 reanalysis (period:1987–2016). Green line shows basin boundary in the upper high mountainous region, yellow line shows basin boundary in the medium high mountainous region and red line is for Assam valley and flood plain delta in Bangladesh. (c) Monthly rainfall (mm) and evapotranspiration, ET, (mm) (average monthly rainfall and evapotranspiration over the basin located in Bangladesh) (source: Bangladesh Meteorological Department (BMD)).

2.4 Hydrological characteristics

There is a large spatial variability of flows between upstream and downstream sections of the river. The maximum daily river flows recorded at Tsela Dzong in the Tibetan plateau was approximately 10,200 m^3 s^{-1}, which is only about 14% of the maximum daily flow recorded at Guwahati in Assam and 10% of the maximum daily flow recorded at Bahadurabad in the river delta in Bangladesh (Datta and Singh, 2004). Rainfall over the Tibetan plateau makes up a very small component of the total flow downstream and thus there is spatial influence of rainfall on flow characteristics of the river. The basin area is approximately 50.5% of the total area in the high altitude Tibetan plateau at Tsela Dzong, whereas the river drains about 73% of the basin area at Guwahati in Assam valley (maximum flow 72,794 $m^3\ s^{-1}$) (Sarma, 2004). The Brahmaputra is a perennial river, part of which is fed by upstream glacial snowmelt (Immerzeel, 2008; Masood and Takeuchi, 2015; Paura, 2004), which contributes to the river baseflow. The flow starts to recede at the end of September, and the lowest flow is reached in the dry period from December to March. The recorded minimum flow at Bahadurabad gauge station in Bangladesh during the dry period is 3178 $m^3\ s^{-1}$. Both river stage and groundwater levels start to rise in April with pre-monsoon rainfall, and peak between July and August (Fig. 2.14 and 2.15) in response to the monsoon rainfall. The monsoon precipitation also recharges the groundwater annually, which contributes significantly to baseflow particularly during dry period. The average monsoon river flow (June–September) is 40,000 $m^3\ s^{-1}$ which is double the average annual flow (Table 2.1). The Key hydrological features of the basin are also presented in Table 2.1.

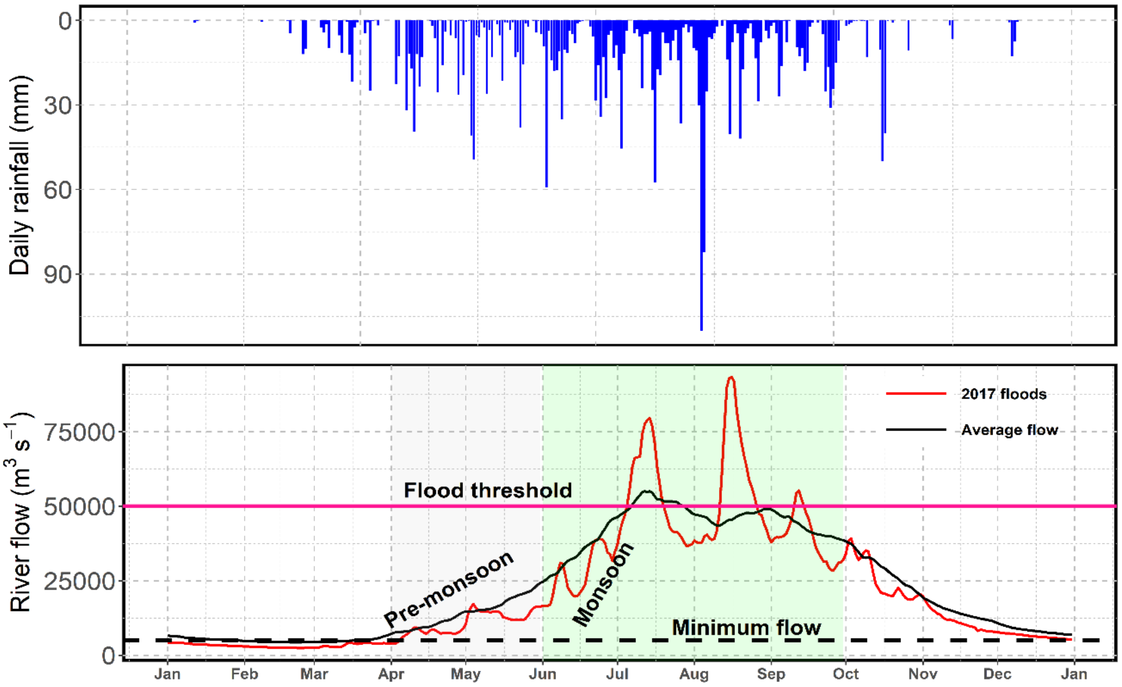


Figure 2.14. Basin average daily rainfall for 2017 monsoon (top) and flood hydrograph (below) of the Brahmaputra at Bahadurabad stream gauging station (BWDB, 2017b). Red line is for 2017 floods hydrograph and black line is for average flow (1987-2017). Grey shaded pre-monsoon whereas greenish shaded monsoon period. Horizontal dashed black line and pink solid line show minimum flow and flood threshold, respectively. Figure 1 shows map of the region including Bahadurabad stream gauging station.

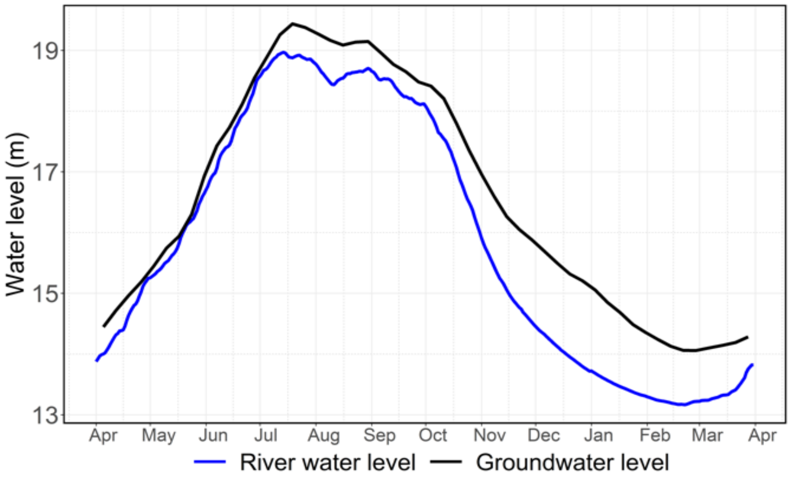


Figure 2.15. Average ground water and river stage hydrograph of the Brahmaputra at Bahadurabad gauging stations (ground water and river gauge) (BWDB, 2017a).

Table 2.1. Major hydrological characteristics of the Brahmaputra basin

Parameter	Location	Magnitude	Source
River gradient	Tibet	4.3 to 16.8 m/km	(Bora, 2004)
	Arunachal Pradesh	0.27 m/km	
	Assam	0.10-0.17 m/km	
	Bangladesh	0.079 m/km	
Drainage density	Overall basin	0.029 km/km^2	Estimated using SRTM DEM
Runoff coefficient (June to September)	Arunachal Pradesh Assam Bangladesh	0.35 to 0.65	(Hofer and Messerli, 2006)
Mean annual flow	Bahadurabad, Bangladesh	20,000 m^3/s	BWDB hydrological data
Mean flow in July to September	Bahadurabad, Bangladesh	40,000 m^3/s	
Maximum flow	Bahadurabad, Bangladesh	103,128 m^3/s	
Annual sediment load	Bahadurabad, Bangladesh	607 Mt/yr	(Islam et al., 1999)
		540 Mt/yr	(Coleman, 1969)
		721 Mt/yr	(Milliman & Syvitski, 1992)
Land use (% area)	Overall basin		(Mahanta et al., 2014)
Grass		44%	
Agriculture		14%	
Forest		14%	
snow and ice		11%	
Soil	Tibet	Lithosols (rocky)	(Driessen et al., 2000),(Goswami, 1985)
	Assam and Bangladesh flood plain	Alluvium	
Underlying geology	Assam valley, flood plain delta in Bangladesh	Alluvium deposits consists of clay , silt, sand, pebbles (200-300 m thick),	Goswami, 1985
	At elevation1000 m	Tertiary Sandstones	
	At elevation 4000 m	shales, slates, basalt	

2.5 Other controls of floods in the Brahmaputra basin

2.5.1 Groundwater

Groundwater table is very high in the Assam valley and floodplain delta of the Brahmaputra basin (Purkait, 2004; Zahid & Ahmed, 2006). The Groundwater recharge starts with the pre-monsoon rain and peak reaches during the monsoon. Low lying areas in the basin remain saturated due frequent rain events during the monsoon and underlying aquifers are recharged from rainfall infiltration into soil as well as seepage from the surface water bodies (Zahid & Ahmed, 2006). When aquifer is fully recharged in the monsoon, further rain events contribute more runoff which has a linkage with surface flooding (Shamsudduha et al., 2011). The annual recharge makes the basin high groundwater potential which varies with the geologic formation. The most ground confined to piedmont regions with an annual yield of 10.7 km^3 in the Indian part of Assam and Arunachal Pradesh (FAO, 2012). Similarly, the Tibet region of the basin has the potential to provide a sustainable yield of groundwater for human use (Ray et al., 2015). In Bangladesh, groundwater is used extensively for irrigation and 79% of agricultural land is irrigated by using groundwater (Qureshi et al., 2014) and also main source of drinking water.

2.5.2 Sedimentation and morphological aspects

The Brahmaputra is one of the highest sediment carrying rivers in the world, with approximately an annual sediment load 1128 metric tons per sq. km (Goswami, 1998) and the annual total sediment load is estimated to be approximately between 540 to 721Mt (Coleman, 1969; Islam et al., 1999; Milliman & Syvitski, 1992) (Table 2.1). A recent study shows a declining trend of sediment in the Brahmaputra River (Rahman et al., 2018). As Bangladesh is located at the downstream of the basin, a vast amount of sediment deposits here and develops sandbars (locally known as Charland), which cause morphological changes and contributes to decrease river capacity. Charlands are formed from sandbars that develop as island within main course of river or connected to riverbanks (Ashworth et al., 2000). The morphological changes of riverbed due to sedimentation may influence the recent positive trend in flood risk. The Brahmaputra is classified as a braided river with numerous channels and sandbars. The river width varies from 9 km to 16 km in Bangladesh (BWDB, 2011) (Fig. 2.16). These Charland are highly erosion prone, and complete disappearance of the old Charland and development of a new Charland somewhere else in the river is very common. The shifting channel or bed of the river due to erosion and deposition of sediment can increase flood risk. Though, low hydraulic gradient of the river and decreasing river carrying capacity due to sedimentation on the riverbed can aggravate the flood situation (FFWC, 2016); however, the current research is focused primarily on the hydrometeorological aspects of floods in the basin.

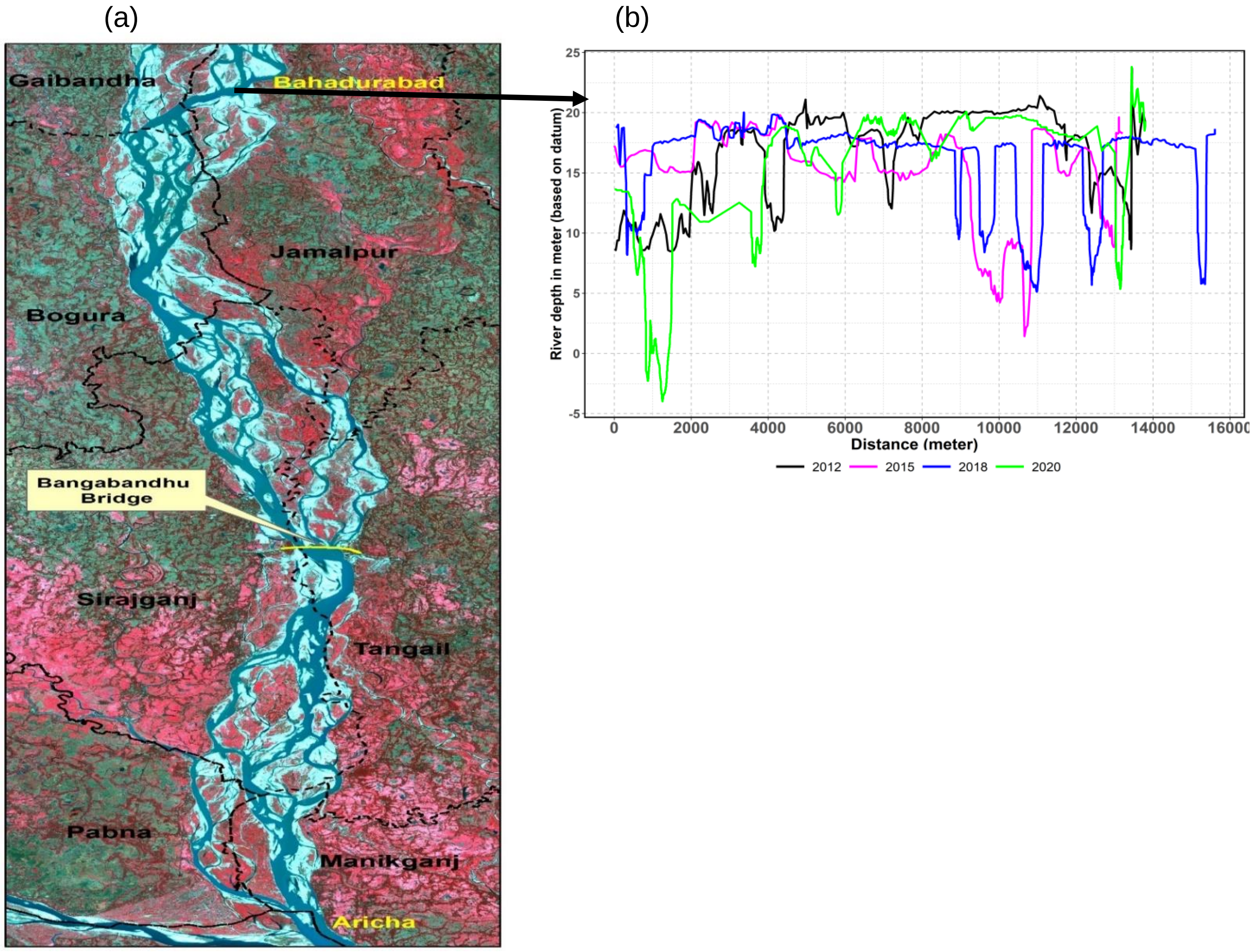


Figure 2.16. (a) Satellite image of the Brahmaputra River (2021) in Bangladesh showing river is a highly braided (Source: CEGIS, Bangladesh, personal communication) and (b) River cross section of the Brahmaputra River in 2012, 2015, 2018 and 2020 (location at Bahadurabad stream gauging station) (BWDB, 2020).

2.5.3 Orographic control

Orography plays a key role in the spatial variability of monsoon rainfall in the Himalayan region. It provides orographic lifting of southwest monsoon flow along the southern slope (windward side) which results in rapid moist adiabatic cooling which accelerates condensation and subsequent rainfall (Bookhagen & Burbank, 2010; Datta & Singh, 2004). As a result, the annual maximum rainfall in the basin occurs in the foothills and southern slopes of the Himalayas (Datta & Singh, 2004; Dhar et al., 1984; Patel et al., 2021; Singh & Kumar, 1997). However, the rainfall variability on the windward side is not uniform, rather having several maximum rainfall cells and rain shadow areas in the Brahmaputra basin (Datta & Singh, 2004; Masood et al., 2015) (Fig. 2.17). Locations with high rain cells usually receive annual rainfall of more than 4,000 mm whereas rain shadow areas receive less than 1,000 to 2,000 mm (Datta & Singh, 2004). Patel et al. (2021) found a higher amount of rainfall was observed in elevations less than 1,000 m and maximum rainfall variation in the middle elevation zone between 1,000 and 4,000 m. However, most of the extreme events were experienced at an elevation between 1,000 m and 2,500 m and within the valley folds of the southern slope of the Indian Himalayas (Dimri et al., 2017; Kumar et al., 2018). The extreme rainfall in the rain cells is essentially important for flood characteristics in Bangladesh, particularly are located near Bangladesh or part of it covers the basin inside Bangladesh (Fig. 2.17).

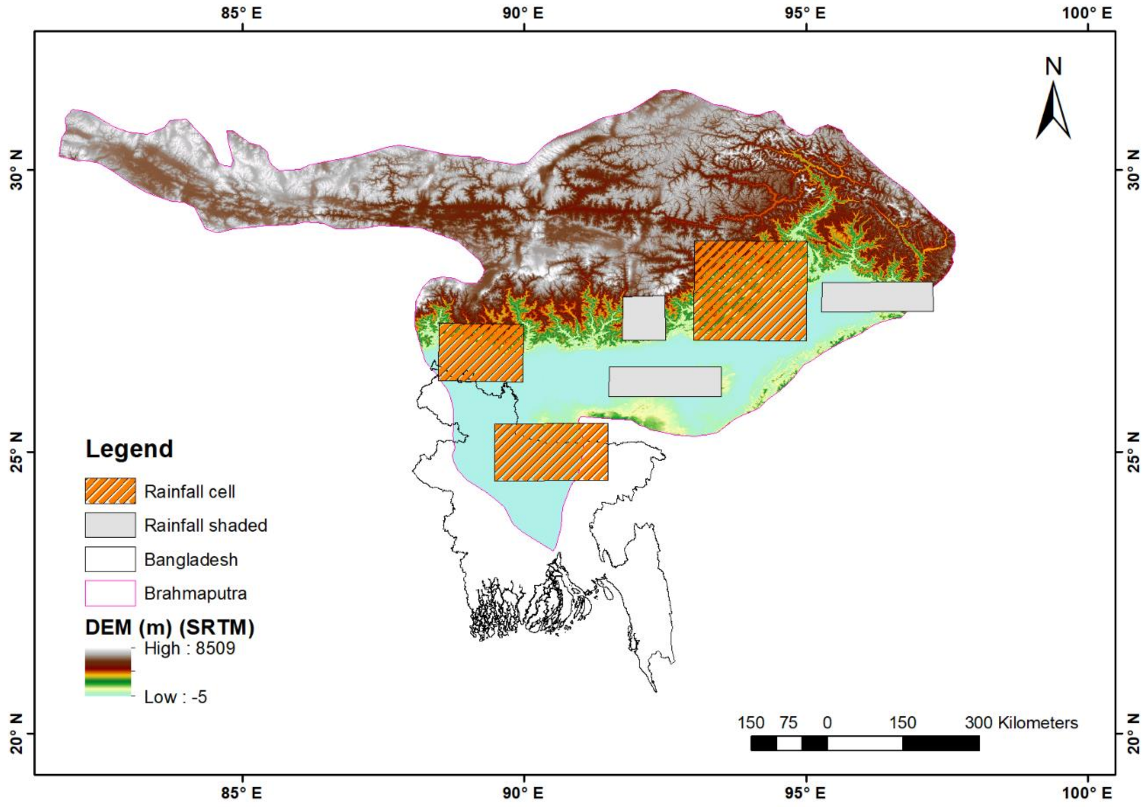


Figure 2.17. Location cells of annual maximum rainfall and rain shadow areas. Hatched areas are annual maximum rainfall and grey shaded areas are rainfall shadow area (Datta & Singh, 2004).

2.6 Flood characteristics

Flood characteristics (magnitude, timing, duration, and number of events) vary each year in response to variations in the monsoon rainfall (Fig. 2.18). The flood characteristics in terms of duration can vary from a few days or more than a month. Meteorological and hydrological factors play a key role in shaping flood variations annually. Flooding is defined by the FFWC as when the river water level exceeds the predefined threshold known as “danger level” in terms of water level with 2 year return period. This is often called ‘moderate’ or ‘normal’ flooding and at this stage floodwater starts to cause damage to property, crops or other infrastructure. A “severe flood” is defined when river water levels reach 1 meter above the danger level which is equivalent to 10 year return period (Mirza, 2002). For the Brahmaputra River, the danger level at the Bahadurabad stream gauging station is 19.5 m water level with respect to local reference datum (mPWD). The river discharge is estimated using a rating curve based on the measured water level. The stage discharge relationship shows a flood threshold of 19.5 m water level is equivalent to about 50,000 $m^3 s^{-1}$ in terms of river discharge. Over the last 33 years, 'severe flooding' has occurred during the 1988, 1998, 2012, 2016, 2017 and 2019 monsoons (FFWC, 2019).

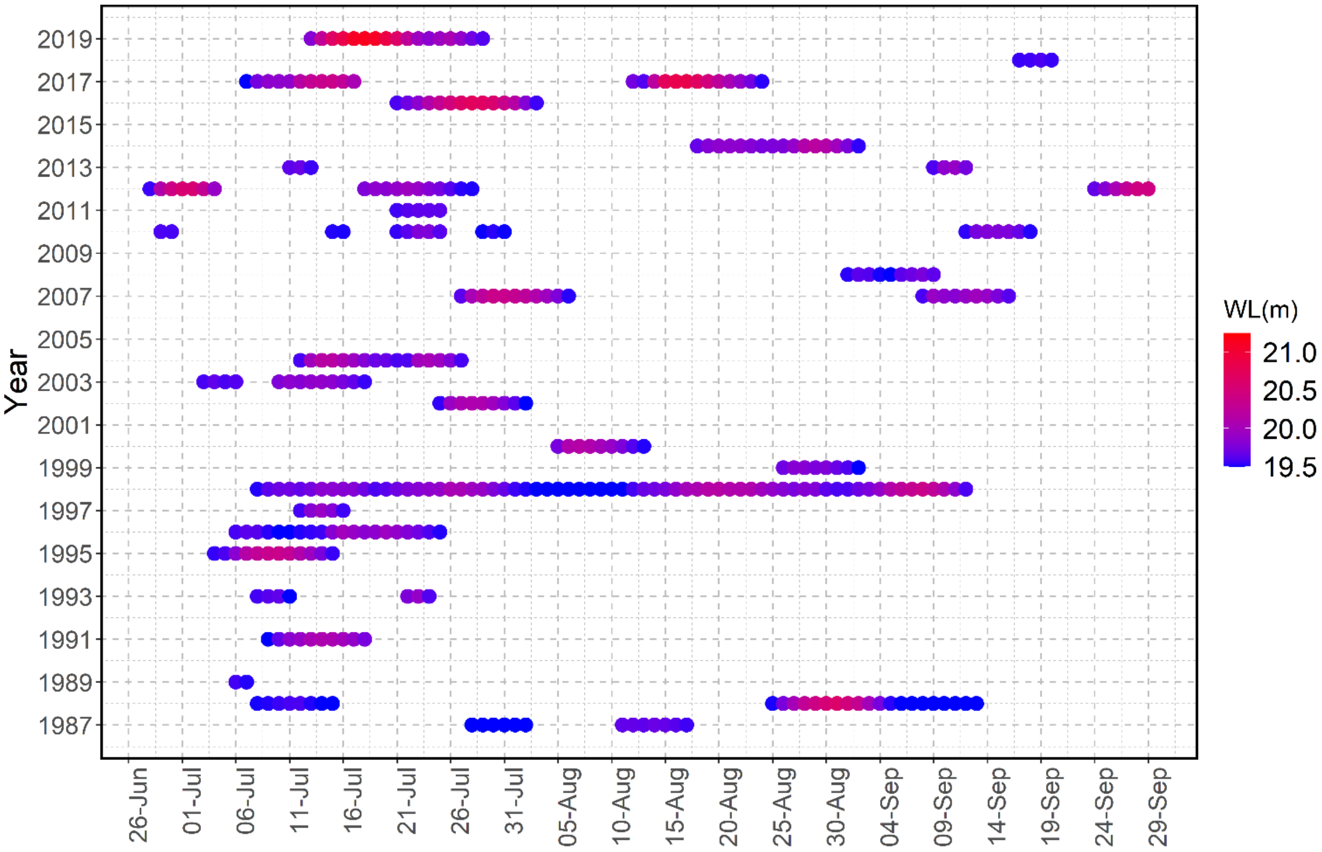


Figure 2.18. Dates indicated by coloured dots show when the water level (WL) exceeded the danger level at the Bahadurabad station on the Brahmaputra River (see Fig.1b for location of the gauge). The colour indicates the water level (from low, blue, to high, red) (Hossain et al., 2021).

2.7 Flood forecasting model and decision making perspective for the Brahmaputra basin

The objective of flood risk management (FRM) is to protect society, where it explains risk as the likelihood of an unexpected outcome and the capacity to manage that impact (Sayers et al., 2013). FRM can be viewed as a management cycle which consists of different stages such as preparedness, response, and recovery (Tucci, 2008) (Fig. 2.19). Conventional flood risk management primarily consists of structural protection measures such as dams, levees, and flood storage within the prevention phase of the FRM cycle which modify flow characteristics to reduce the flood peak and spatial extent of flooding. Although structural measures reduce flood risk, they cannot eliminate flood damage completely. In addition, these measures are not always feasible in some areas, particularly high mountainous areas where the risk of glacial lake outburst floods is very high (Tullos, 2008). On the other hand, non-structural measures of FRM often provide more cost effective solutions to reduce flood risk than structural approaches (DiFrancesco & Tullos, 2014). Flood early warning systems are one type of non-structural approach that form an important part of the FRM cycle. The objective of early warning is to alert people about the timing and location of the flood event. They act to reduce risk by taking preparatory actions in the immediate period before a flood event, for example shutting flood barriers and evacuations, and thus avoiding unwanted consequences of floods (Verkade & Werner, 2011; Wendleder et al., 2015). Advances in the development of flood forecasting and warning systems and their proven effectiveness in saving lives and protecting livelihoods has meant that there has been substantial global interest in implementing such systems in recent years (Mehring et al., 2018; Pappenberger et al., 2015).

Flood risk and disaster management are often treated differently. Disaster management can be regarded as the reaction to an event, which is indicated by the response and recovery phase in the cycle (Lumbroso, 2007) (Figure 2.19). Flood risk management applies to a whole range of events, whereas flood disaster response tries to minimize the effects of just one specific flood disaster. Therefore, flood forecasting occurs in both phases of the flood risk management cycle: during planning, the forecast model is designed and calibrated, and during operation its successful application is a prerequisite for any effective early warnings (Plate, 2009). The preparation phase consists of measures that can be taken between the forecast of a flood event and the actual event (Marjolein, 2008). The major activities in the preparing stage consist of evacuation, recuse plan and emergency services such as food storage, medicine etc.

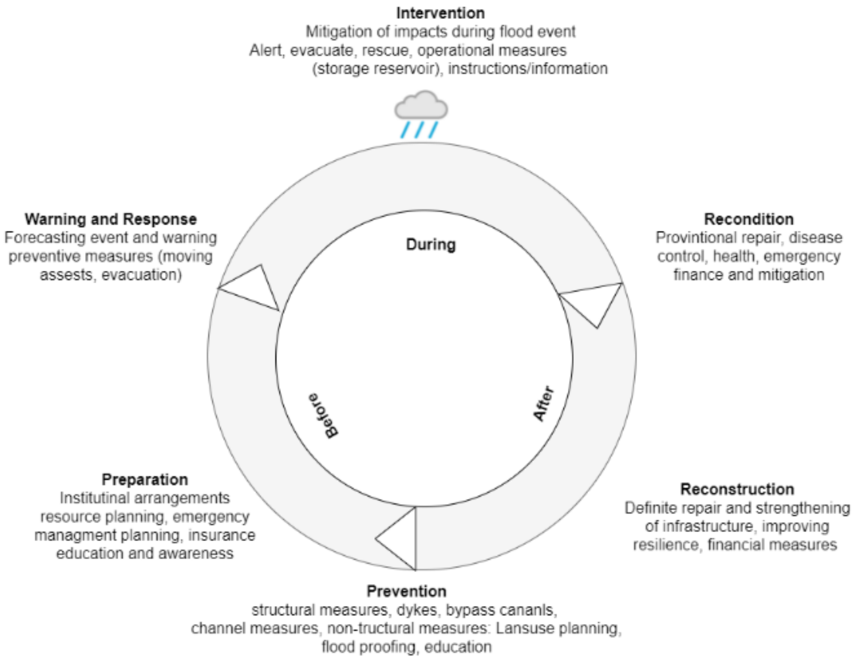


Figure 2.19. Flood risk management cycle (Tucci, 2008)

Early warning system consists of several components which are essential to build the system effective and efficient. The key components include hydrological and meteorological data collection and transmission, forecast generation and dissemination of early warning message to different users, including disaster managers, humanitarian agencies, and communities (Fig. 2.20). These components can be grouped into four inter-connected components including users knowledge about potential risk and response to early action– (1) risk knowledge, (2) monitoring, forecasting and warning, (3) communication of an early warning, and (4) response capability (UNISDR, 2006). The following sections provide a review of flood forecasting models, evaluation and early warning to understand the historical development and users' perspectives on flood early warning in Bangladesh.

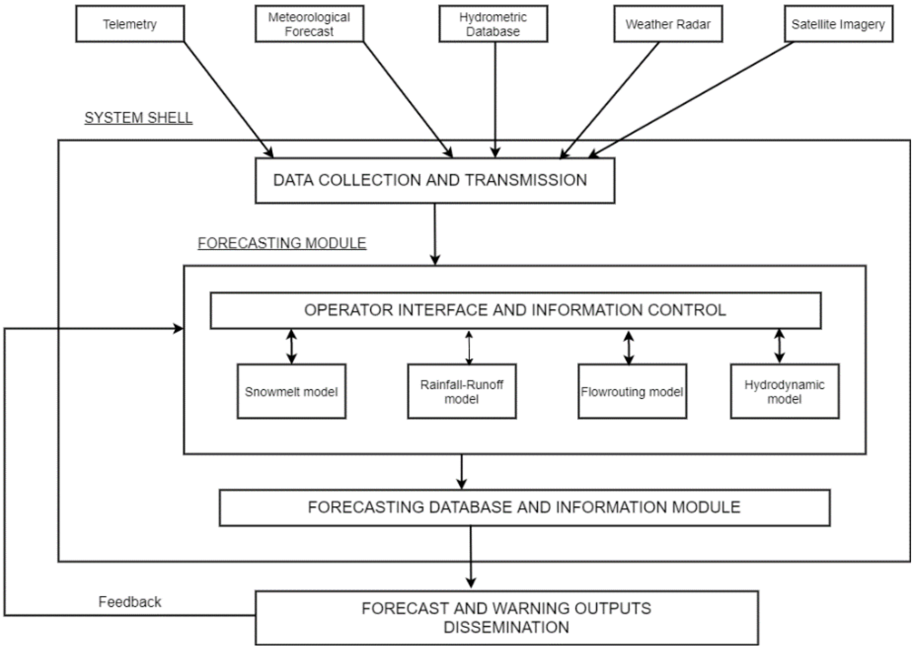


Figure 2.20. Components of flood forecasting system (WMO, 2011).

2.8 Flood forecasting model

Flood forecasting methods can vary from simple stream gauge to gauge correlation (establishing relation between upstream and downstream stream gauge based on their lag time), and travel time relationships to sophisticated models. However, extrapolation of forecasts from gauged data can provide lead time only for few hours and is not suitable to provide early warning on a longer time scale than model based forecasts (Agarwal et al., 2021; Moore et al., 2005). The development of flood forecasting models depends on several factors: catchment characteristics, data quality and availability, cost for development, technical feasibility, and user requirements in terms of accuracy and lead-time (Tilford et al., 2007). For many catchments the complexity of the hydrological controls on flood generation (Wanzala et al., 2022b) mean that a catchment hydrological model is better in developing a robust integrated early warning system combining flow routing and hydrodynamic components (Henonin et al., 2013; Lin et al., 2006; Tilford et al., 2007; WMO, 2013).

Hydrological models can be classified based on different perspectives (Fig. 2.21). Models are classified by the way in which catchment hydrological processes are presented—deterministic or stochastic or spatial representation of the catchment lumped or distributed (Bathurst & O'connell, 1992; Devia et al., 2015; Jain et al., 2018; Refsgaard & Knudsen, 1996). A deterministic model provides same result for a single data set whereas a stochastic model can generate different results from a single data set (Devia et al., 2015; Jain et al., 2018). In the lumped model, the entire river basin is taken as one unit where spatial variability is disregarded. In this modelling approach, one tries to relate the forcing data, mainly precipitation inputs to system outputs (streamflow) without considering the spatial processes, patterns and organisation of the characteristics governing the processes (Moradkhani & Sorooshian, 2009). Whereas, in a distributed model, the catchment is divided into a large number of cells or hydrologic response units which can account for spatial variations of variables and parameters; thereby explicit characterisation of the processes and patterns is made (Beven, 1985; Refsgaard & Knudsen, 1996; Smith et al., 2004). While distributed models are generally expected to reproduce the hydrological processes in spatially varied catchments more accurately presented, therefore, uncertainty in model parameters can lead to substantial errors in distributed models.

Operational flood forecasting can be provided as deterministic and probabilistic forecast based on single or ensemble forcing, respectively. For example, the European Flood Alert System (EFAS) gives flood alerts both in deterministic and probabilistic flood forecasts using an ensemble prediction system (EPS) (Smith et al., 2016).

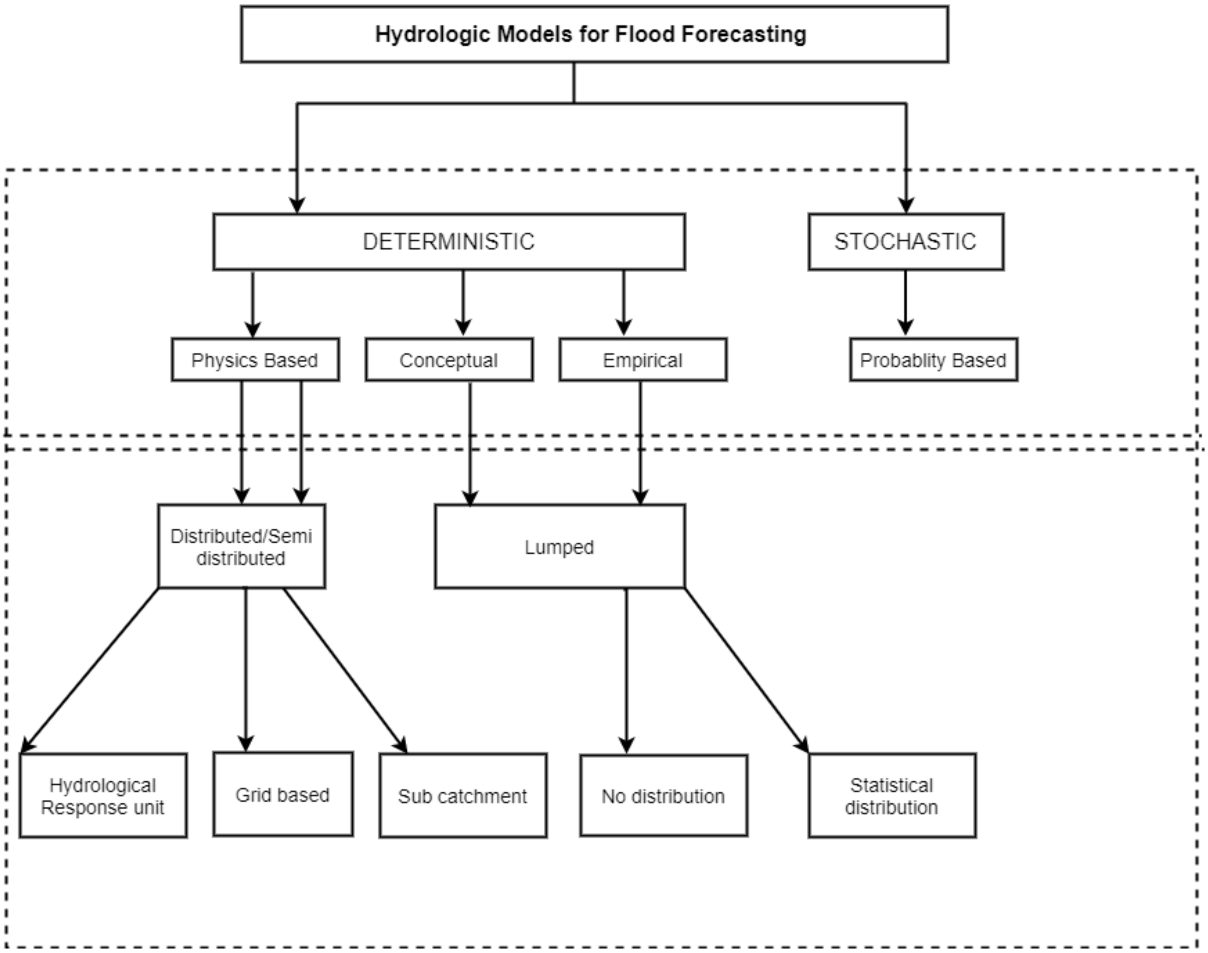


Figure 2.21. Classification of hydrological models used for flood forecasting (Jain et al., 2018).

2.8.1 Deterministic flood forecast

A deterministic model always provides the same output for a single set of input data (produces single output) by solving a set of equations of hydrological processes; therefore the model output does not say anything about uncertainty (Szöllősi-Nagy & Mekis, 1988). The hydrodynamic-based deterministic water level is produced using MIKE11 modelling tool of the Danish Hydraulic Institute (DHI) by the FFWC with initial conditions coming from hydro meteorological observations within the country (Fig. 2.22a). In the modelling simulation unit, boundary conditions for the river flow hydrodynamic modelling are estimated based on rainfall forecasts and hydrological model simulations together with upstream river gauging information from the transboundary catchments. Only a single deterministic output is produced based on the predefined model parameters. There are key challenges in only producing deterministic forecasts, for instance, rainfall forecasts are known to be uncertain, and this will not be taken into account, meaning flood forecasts will be less robust. A typical deterministic flood forecast of the FFWC shows how it predicts onset of floods with single value for each day having and no uncertainty information (Fig. 2.22b). If a decision-maker makes responses merely according to the deterministic forecasts, then some improper measures might be taken, or nothing will be done, due to the underestimation of the deterministic forecasts i.e., model systematic negative bias. Conversely, if the uncertainty is considered via probabilistic forecasts, then the decision-maker should be aware of the full range of possibilities for upcoming flooding, including the potential for greater floods, and from these appropriate countermeasures against the floods should be adopted. Deterministic forecasts may leave the user with an illusion of certainty, which can easily lead the user to limited action (Krzysztofowicz, 2001). Performance evaluation of EFAS continental scale EPS-based forecasts showed, in general, higher skill than the deterministic-based forecasts (Bartholmes et al., 2009).

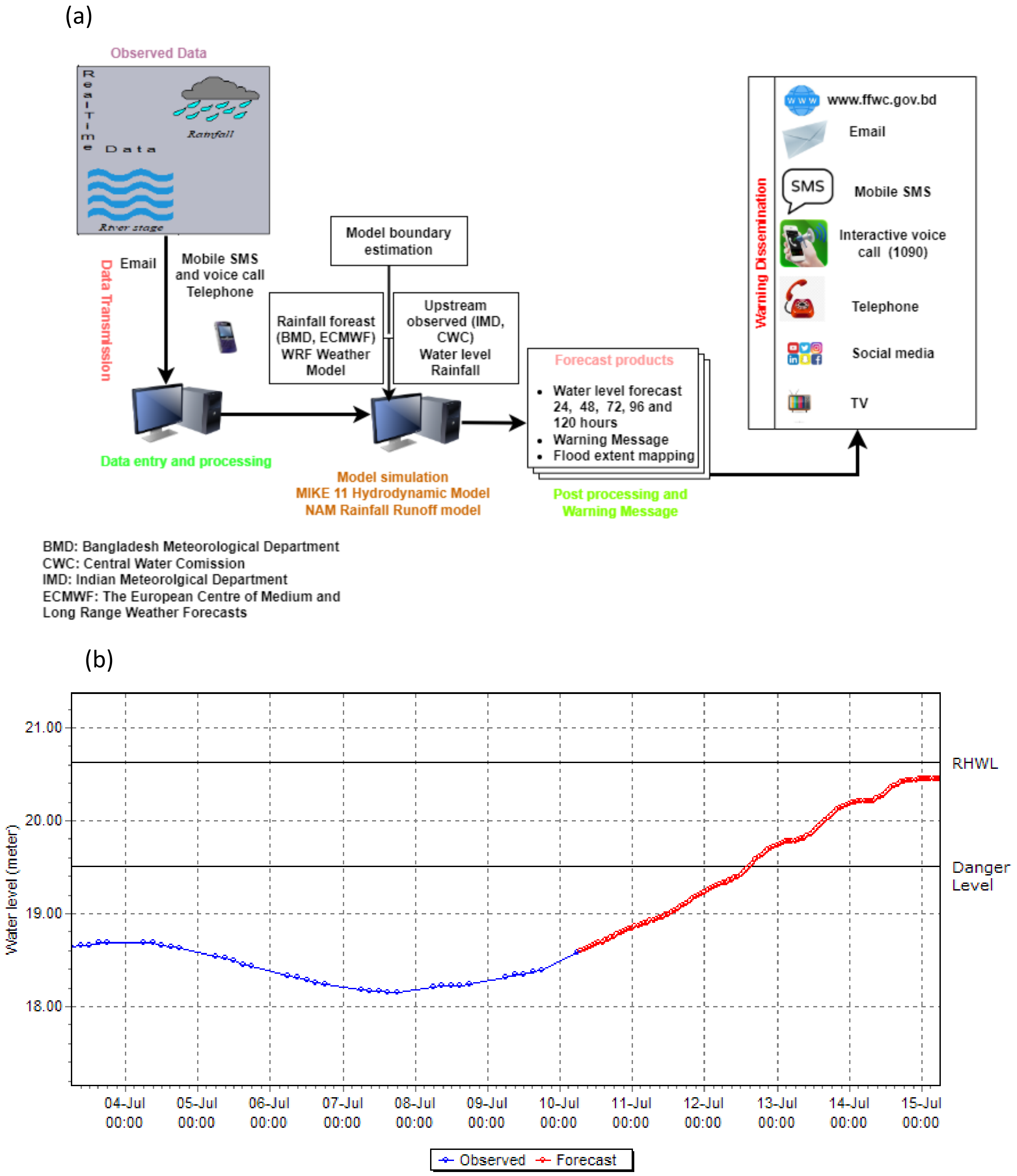


Figure 2.22. (a) Deterministic flood forecasting system operated by the FFWC in Bangladesh and (b) FFWC's 5 day deterministic forecast at Bahadurabad stream gauging station of the Brahmaputra River. Date of forecast 10 July 2019. Red and blue colours show forecasting and hindcast period, respectively. Onset of floods was forecasted 48 hours before (Source: FFWC).

2.8.2 Ensemble flood forecast

There is a limitation of deterministic forecasting due to the unpredictability of atmospheric conditions for a lead time more than two weeks (Inness & Dorling, 2012). To capture the atmospheric predictability of numerical weather prediction (NWP) models simulations are run to produce an ensemble forecast instead of a single deterministic forecast. This can be undertaken by changing initial conditions or by using multiple different models (Jain et al., 2018; WMO, 2011, 2012b). Ensemble forecast provides advantages over single deterministic forecasts by considering uncertainty, and the forecast can be provided in the form of probability. The skill of deterministic weather forecasts is typically limited to about two weeks due to chaotic of initial conditions and atmospheric model's inaccuracies (Weyn et al., 2021). Therefore, the deterministic river stage forecast skill at short lead time depends on initial conditions and model calibration whereas precipitation forecasts contribute the major skill in forecasts at longer lead times (Welles & Sorooshian, 2009). Hence, ensemble forecasts are used to provide longer lead-time forecast for decisions due to limitations of lead time in deterministic forecasts (WMO, 2012a). However, the successful application of the ensemble forecast requires proper communication of uncertainties among the decision makers (Cloke & Pappenberger, 2009b). ECMWF IFS and UK unified model are examples of operational ensemble weather forecasting system (Golding et al., 2016; Roberts et al., 2018). These ensemble weather forecasts can be used as forcing for hydrological models to generate ensemble flood forecasts. For example, GloFAS provides 30 days lead time flood forecast using the ECMWF ensemble weather forecasts as forcing to produce river flow forecast for the major river basins of the world (Alfieri et al., 2013). Figure 2.23 shows an example of a forecast hydrograph of the Brahmaputra River in Bangladesh.

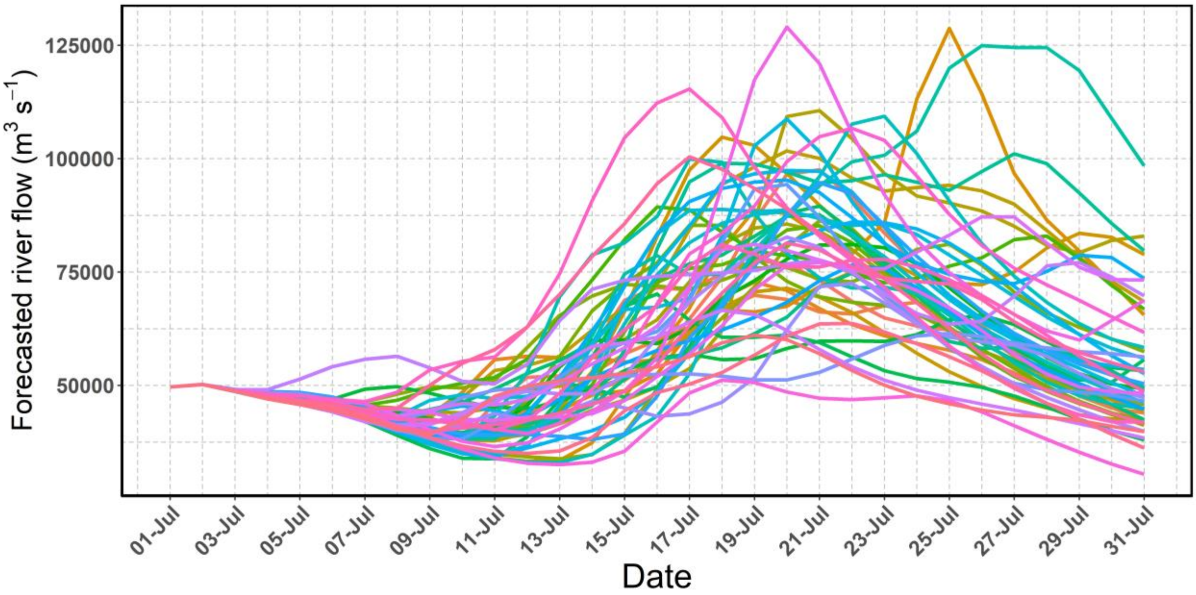


Figure 2.23. GloFAS 30 day ensemble forecast (51 member) at Bahadurabad stream gauging station of the Brahmaputra River (Source: www. https://www.globalfloods.eu); forecast date: 01 July 2020.

2.9 Historical development of flood foresting in Bangladesh

After the major floods in 1955, flood risk management was focused primarily on flood control approaches such as construction of embankments along the riverside or creating enclosed polder areas to protect agricultural land from flooding. Due to the monsoon climate and complex transboundary basins, it is not possible to have complete flood control in Bangladesh. Complete protection from floods is not always considered a viable alternative (Moore et al., 2005). Non-structural measures, particularly early warning and evacuation of vulnerable communities, can reduce flood damage and loss of lives. Incorporation of flood early warning in the flood management process was implemented in 1972 alongside structural approaches. In Bangladesh, 1 to 5 days lead-time is generally considered a short-range forecast, between 5 to 10 days is medium-range, and extended-range is when a forecast exceeds 10 days lead-time for monsoon floods (BWDB, 2004). Flood forecasting, warning, and dissemination services are provided by the Flood Forecasting and Warning Centre (FFWC) of the Bangladesh Water Development Board (BWDB) as part of the hydrological service. The main flood early warning development focus in the last four decades was to increase forecast lead-time. There was a stepwise improvement in the forecasting system in Bangladesh which started in 1972. The timeline for the development of flood early warning in Bangladesh has been divided into three phases: initial phase: 1972 to 1990, the development phase:1990 to 2010 and the strengthening phase: 2010 to the present day (Fig. 2.24).

2.9.1 Initial phase: 1972 to 1990

Flood forecasting in Bangladesh was started with only 6 stations along the main course of the Brahmaputra (4 stations) and the Ganges River (2 stations) based on co-axial correlation, gauge to gauge relation and Muskingum-Cunge Routing Model (FFWC, 1998). Using these methods, forecast lead time was limited to only 6 to 8 hours. After the devastating floods in 1987 and 1988, there was a policy shift in flood management by incorporating comprehensive flood action plan (FAP) with support from international development partners (Dempster & Brammer, 1992; Minkin et al., 1992). Under this plan, the development of a flood forecasting system using mathematical modelling (hydrological and hydrodynamic) was started in 1989 with the aim to increase lead-time from hours to days.

2.9.2 Development phase: 1990 to 2010

Initially, the flood forecasting model development was primarily focused on major river systems. In 1992, forecast lead-time was increased to 1 day at 16 stream gauging points using MIKE 11 modelling of the Danish Hydraulic Institute (DHI). The forecast network was extended to 30 stream gauging stations while the model was capable of predicting floods with acceptable accuracy for a lead time of up to 2 days for major rivers in 1994 (Chowdhury, 2000; FFWC, 1998). Based on the model capability to simulate flood behaviour, a countrywide hydrodynamic modelling network was developed to include key secondary river systems along with the major river stems between 1994 to 1998. The country faced devastating floods in 1998, with the longest duration on record, and further improvement was focused on increasing lead time and dissemination of early warnings with the recommendation of the National Water Management Strategy-2001 as part of continuous upgrades to the flood early warning in Bangladesh (Samuels et al., 2006). Based on the model performance, lead time was improved up to 3 days in 2001. Though a short-range forecast was useful for disaster response activities, a lead time of 2 to 3 days is not sufficient for flood preparedness, particularly for agricultural planning (Fakhruddin et al., 2015). Hence, further improvement of lead time was to introduce a medium-range forecast (lead-time 1 to 10 days) using ECMWF's ensemble weather forecasts from the 2007 monsoon (Hopson & Webster, 2010) and was disseminated to limited users as experimental basis. Dissemination is an important element of a flood forecasting system, and early warning messages should reach all users before flood events. Web-based early warning dissemination was introduced in 1998 to disseminate quickly along with conventional tools: radio, television, newspapers, and facsimile. The FFWC generates early warning at the river stream gauging stations, which needs to be transformed into location specific warning messages for communities living at the flood plain. There were some piloting of dissemination at the community level by installing additional gauges on the floodplain and establishing a correlation between river and flood plain gauge (CEGIS, 2010).

2.9.3 Strengthening phase: 2010 to the present day

This phase is the strengthening phase of the flood early warning system under the government's national comprehensive disaster management plan (CDMP), which focuses on "early warning generation, institutional capacity and development and operation of the dissemination mechanism" (GoB, 2010). This phase provides further improvement of lead time of previous deterministic forecast and expansion of forecasting network (Fig.2.25a), innovation in dissemination and access to global forecast to increase lead time. FFWC's challenge is to estimate model boundary conditions to the hydrodynamic model to generate the deterministic forecast. Current practice is based on correlation between transboundary inflow information and stream gauging inside Bangladesh. Using the quantitative precipitation forecast (QPF) of NWP and upstream flow information, the FFWC extended the deterministic forecast from 3 days to 5 days (Fig. 2.25b) and expanded the forecasting network from 38 stream gauging stations to 54 stream gauging locations across the country (FFWC, 2013). The FFWC made an operational 10 days ensemble water level forecast (Fig. 2.25c). These provide an additional lead time for decision makers in Bangladesh. There are also improved disseminations by introducing interactive voice response (IVR), and mobile users can get an early warning by calling a toll-free number and SMS alert service at the community level. In addition, the FFWC's capacity increases due to collaboration with regional and international organizations such as the International Centre for Integrated Mountain Development (ICIMOD), the Regional Integrated Multi-Hazard Early Warning System (RIMES), and the ECMWF, which provide support for developing early warning at the basin scale. Currently, RIMES, a regional initiative, supports by providing 15 days discharge ensemble forecast based on ECMWF's weather forecasting. A longer horizon is essential to anticipate probable flood duration and timing. Global scale forecast (GloFAS flood forecast) provides longer range lead time forecast which can play an important role in improving flood early warning for the river basin in Bangladesh.

Floods in Bangladesh are a transboundary risk. Therefore, it is essential to develop a regional scale flood forecasting system by incorporating all the co-riparian, much like the European Flood Alert System (EFAS) (Thielen et al., 2009). Though upper riparian countries exchange hydrological information with the Flood Forecasting and Warning Centre in Bangladesh during the monsoon, there is a lack of formal initiative from the associated countries to build a basin-wide integrated forecasting system in South Asia. However, several research initiatives have developed basin scale flood forecasting models for the Ganges-Brahmaputra and Meghna basins for short to medium-range lead-times (Hopson & Webster, 2010; Palash et al., 2018; Shrestha et al., 2015). These initiatives help to increase flood forecast lead time in Bangladesh.

The access of global scale forecasts can be useful in improving flood early warning and capacity building of national hydromet institutes. For example, Global Flood Awareness System (GloFAS) forecast is run by ECMWF as part of the Copernicus Emergency Management Service (CEMS) and provides 30 days flood forecast for the major river basins in the world and is freely available at http://www.globalfloods.eu/ (Alfieri et al., 2013). This extended range forecast is also available for the Ganges, the Brahmaputra and the Meghna River basins in Bangladesh. Since 2016, humanitarian agencies in Bangladesh have been using GloFAS forecast for the pre-activation of humanitarian activities due to its extended lead-time. Similarly, the FFWC has been using the GloFAS forecasts along with its short and medium range forecasts to anticipate the flood events during the monsoon in Bangladesh since 2016. In addition, short-range e.g., 3 days and medium-range e.g., 10 days forecasts cannot predict the potential flood duration which is essential for flood preparedness activities. Therefore, extended lead times are necessary to support better flood preparedness decisions to reduce potential flood damage. For example, agricultural decisions such as transplanting or harvesting of crops, need longer lead-times, and humanitarian agencies require enough time for resources planning and mobilization before floods occur.

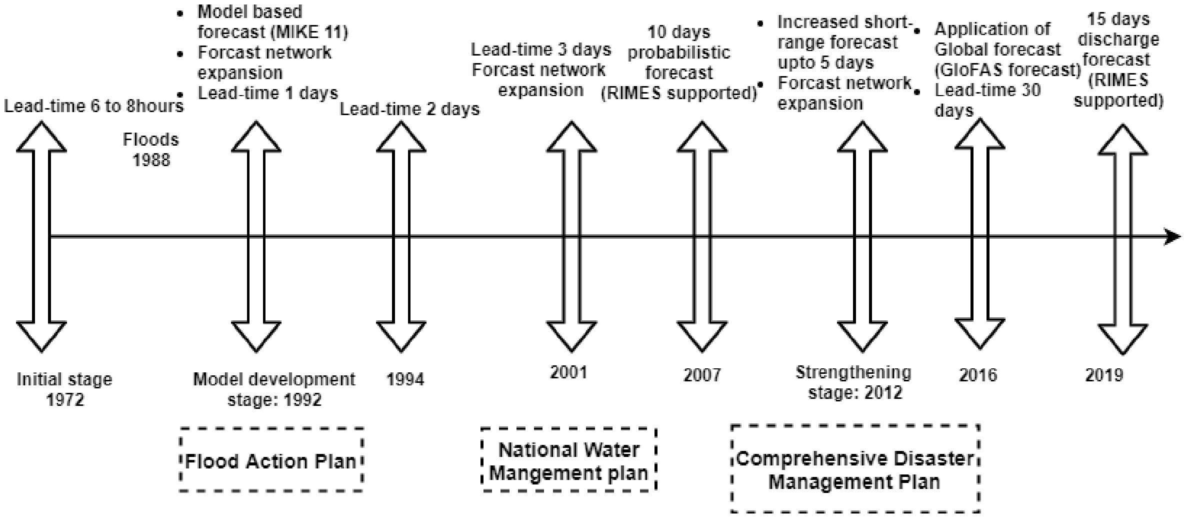


Figure 2.24. Timeline for development of flood early warning in Bangladesh (Source: FFWC).

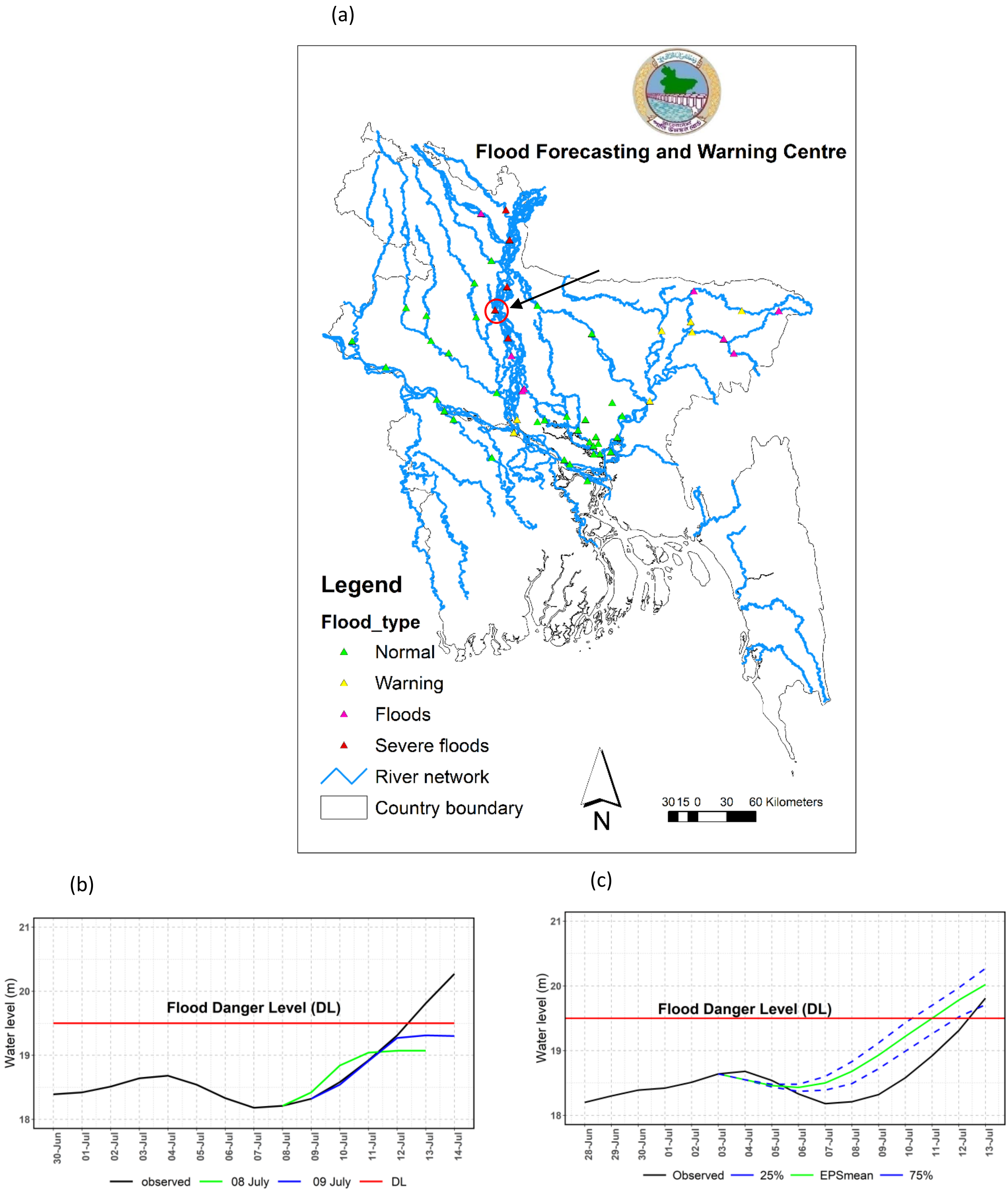


Figure 2.25. (a) Flood forecasting network. Red circle shows Bahadurabad stream gauging station on the Brahmaputra River, (b) 5 day deterministic forecast and (c) 10 days ensemble forecast at the Bahadurabad stream gauging station is located on the Brahmaputra River in Bangladesh (Source: FFWC).

2.10 Stakeholders’ perspectives flood early warning

For flood risk management, stakeholders are essential in engaging in risk management activities (Thaler & Levin-Keitel, 2016) and can contribute to various levels of the risk management lifecycle (Atkinson et al., 2006). Key stakeholders include communities, local government, national government, sub-national, Non-government Organisations (NGOs), development partners, and humanitarian agencies. National level users who are primarily involved in policy making and coordination of national disaster management activities. They coordinate to regional and international organizations for strengthening and capacity development of early warning and ensure that warning can reach community people for early actions before disaster. The community people are the vulnerable group and key for “people-centred” early warning systems both from operation and implementation (UNISDR, 2006). There are different aspects of early warning from users’ perspectives. For example, the general trend is to give more emphasis on improvement of observation capacity and the efficiency of a forecast, rather than the proper dissemination and reception of the information by the different users during floods (Erlich, 2007). Early warning messages should contain simple and understandable information for users to respond to save lives and livelihoods (UNISDR, 2006).

When developing an early warning, forecast information needs to focus on user decision requirements, such as lead-time for potential users, whether they are farmers or humanitarian workers (Erlich, 2007). In the following sections, a short discussion on users’ perspectives such as users engagement, users specific forecast and uncertainty communication of flood early warning with respect to Bangladesh is provided.

2.10.1 Engaging stakeholder and flood early warning

In flood risk management, stakeholder engagement includes management processes such as planning and decision-making (Edelenbos et al., 2017; Mehring et al., 2018; Thaler & Levin-Keitel, 2016). There are challenges in engaging stakeholder which includes resources, institutional support, communication, and motivation (Kuhlicke et al., 2011; Thaler & Priest, 2014). A flood early warning system is built on both technical and policy level tools. However, early actions depend on the social system of the river basin (WMO, 2011).

Community based cyclone early warning has been implemented successfully in the coastal area of Bangladesh to reduce death and casualties from tropical cyclones and storm surges (Ahamed, 2013; Singh, 2010). In this system warnings are effectively disseminated to and by communities who are then able to take effective actions such as evacuation before a cyclone hits. While some piloting has been carried out for the river flood, this has not been implemented yet at full scale (CEGIS, 2010). Flood forecasting in Bangladesh is based on river stage-based forecasting, and not explicit modelling of flood inundation. Instead, inundation forecasts are made by linking the water level to a static flood inundation map for the danger and severe flood thresholds. This information is often not precise or localised enough for people in specific communities to take early action, e.g., communities living on low-lying char islands. In the current forecasting system (gauged based forecast), river forecasts therefore need to be translated into a community level forecast. So, community engagement is essential to translate into a warning message for community response. Community stakeholders can play a crucial role in collecting hydrometeorological data, sending to forecast centres, and receiving forecast information (Fig. 2.26). Two-way communication can be set between community and forecaster. Some community based piloting were carried out in the Brahmaputra basin at fewer locations, which led to develop of impact-based forecasting (Sai et al., 2018). The major setbacks towards sustainability in these community-based initiatives area lack of funds, and local capacity, as most of the initiatives are implemented as experimental basis. Successful engagement communities takes time, effort and the establishment of trust and utilisation of social learning and pooling of knowledge to create a better understanding of flooding, which can lead to increasing societal connectivity to flooding and its impacts (Mehring et al., 2018).

Figure 2.26. Local level gauge reader collecting and sending river stage information (Source: FFWC).

2.10.2 Users specific flood early actions

Flood early warning information varies depending on type of early action and users—farmers, humanitarian agencies, disaster managers. During the monsoon, floods can affect crops at different growth stages as crop seasons are linked with the annual hydrological cycle (Fig.2.27). For example, floods in June can affect Boro harvesting, whereas transplanted Aman rice planning can be affected by flood timing i.e., delay plantation or early plantation. Floods in the Brahmaputra basin vary on intraseasonal time scales with the monsoon rainfall (Section 2.6) (Hossain et al., 2021). Therefore, farmers need information on the timing of floods for their crop planning, either harvest or plantation. For anticipated long duration floods like in 1998, farmers can stop plantation, which can save their investment for cultivation. A number of other factors such as land type, the capacity of the local community, early warning information, and knowledge can affect users' decisions to response to floods in Bangladesh (Paul, 1984; Shah et al., 2012). An earlier study reported 2 to 3 months lead time forecast information can help to select alternative options in crop planning (Fakhruddin et al., 2015), However, this could be difficult to convince farmers as flood signal has a strong annual cycle and intraseasonal scale variation within the season.

Humanitarian anticipatory action based on a flood forecast could help better flood preparedness. Anticipatory action is supported by forecast-based financing (FbF) before the flood strikes, in contrast to financing for conventional humanitarian response (Thalheimer et al., 2022; Weingärtner & Wilkinson, 2019). Anticipatory actions aim to reduce or mitigate the impact of disasters and enhance post-disaster response, using forecasts or early warnings of imminent shock or stress (Weingärtner & Wilkinson, 2019). For example, earlier responses to floods (2017 flood events) in Bangladesh, the Bangladesh Red Crescent Society (BDRCS) provided cash for the wellbeing of the vulnerable communities during and after floods compared to post disaster response (Gros et al., 2019).

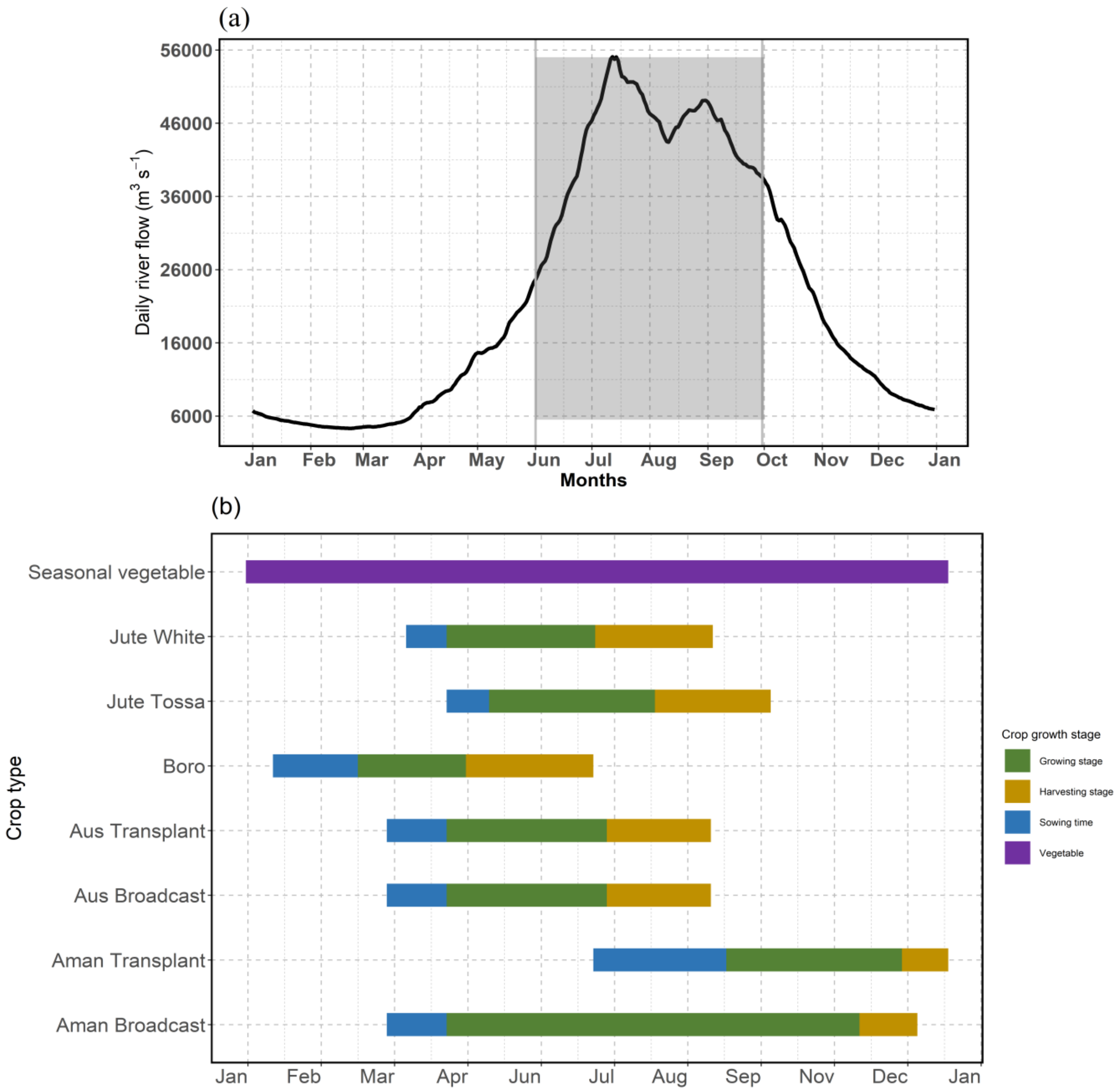
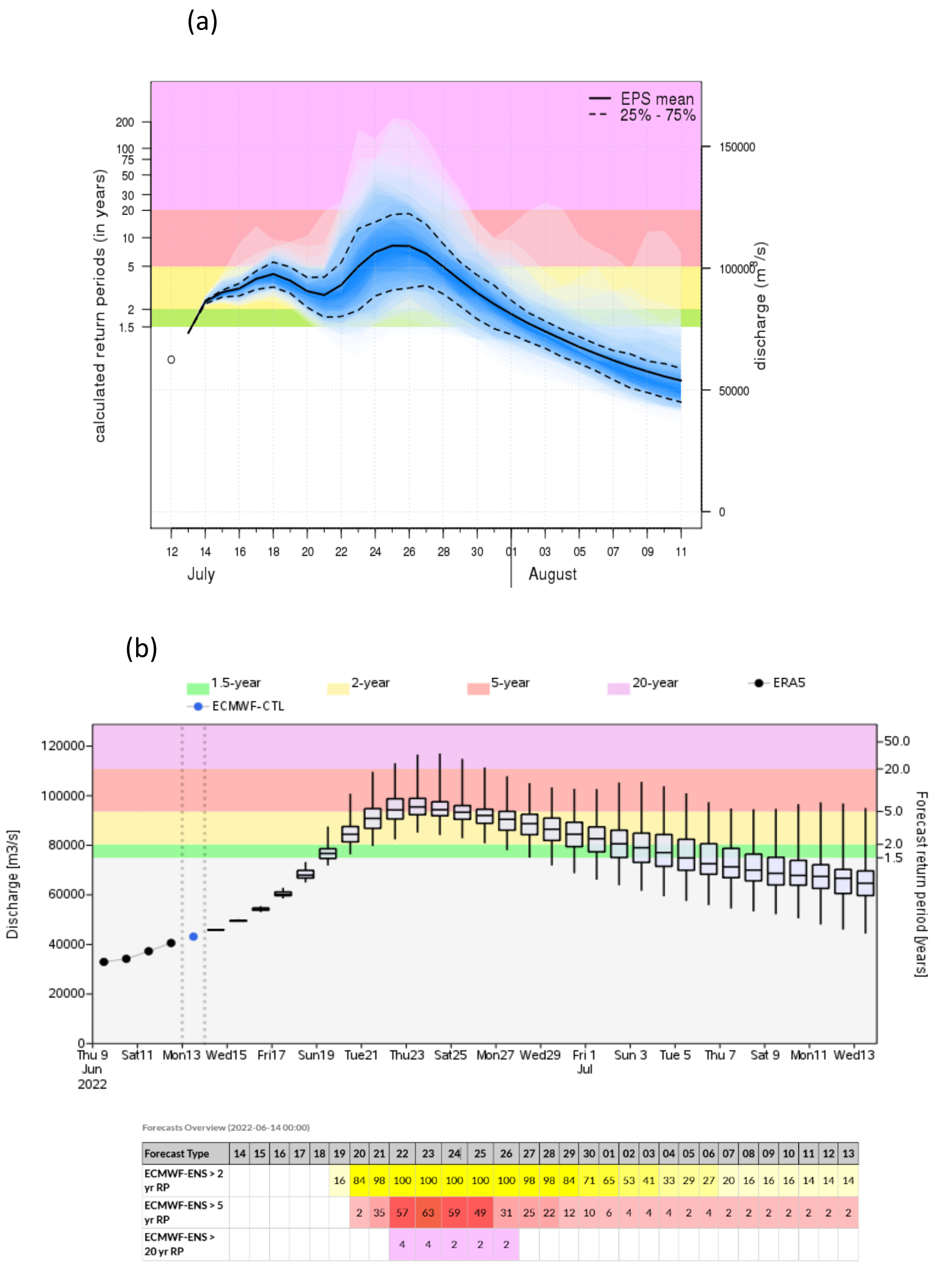


Figure 2.27. (a) Annual hydrological cycle (shaded area indicates monsoon period) (BWDB, 2017b) and (b) crop calendar in the Brahmaputra basin (BBS, 2017) .

2.10.3 Uncertainty communication of flood forecast

An ensemble forecast produces multiple outputs compared to a single value of deterministic forecast (Inness & Dorling, 2012). Hence, forecasts need to be presented in an understandable way for users. Though many operational centres present ensemble forecasts, there is no universally adopted system for communicating them (Lumbroso, 2009). There are various ways of presenting ensemble flood forecasts for a specific location: the evolution of uncertainty of river flow forecast can be plotted by spaghetti plot, which represents every ensemble member of the forecast (Figure 2.28a). The spaghetti plot can be replaced with 'box-and-whisker' to present the spread of the ensemble (Fig.2.28b). The probability to exceed a pre-defined threshold can be provided in a table for each day to support decision makers for early action. Similarly, precipitation forecasts are also provided in the form of a probability forecast to predict a rain event (Figure 2.29), and higher probability will give more confidence to users for taking early action decisions.

Demeritt et al. (2010) suggested that operational flood forecasters and EPS system designers can help to ensure the uncertainty represented by ensemble forecasts is represented in ways that are most appropriate and meaningful for their potential users. In Bangladesh, the FFWC is providing medium-range ensemble water level (10 days lead time) forecast in the form of maximum, mean and minimum value (medium range forecast available at the www.ffwc.gov.bd). This type of forecast information is understandable for expert level users such as national level policy makers, whereas understanding of ensemble forecast to "non-expert" level users is very limited (Fakhruddin et al., 2015).



Forecasts Overview (2022-06-14 00:00)

Forecast Type	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	01	02	03	04	05	06	07	08	09	10	11	12	13
ECMWF-ENS > 2 yr RP						16	84	98	100	100	100	100	100	98	98	84	71	65	53	41	33	29	27	20	16	16	16	14	14	14
ECMWF-ENS > 5 yr RP							2	35	57	63	59	49	31	25	22	12	10	6	4	4	4	2	4	2	2	2	2	2	2	2
ECMWF-ENS > 20 yr RP									4	4	2	2	2																	

Figure 2.28. Presentation of GloFAS 30 days ensemble river discharge forecast for the Brahmaputra River at Bahadurabad stream gauging station (a) spaghetti plot and (b) 'box-and-whisker' (Source: www. https://www.globalfloods.eu); forecast date: (a) 14 July 2020 and (b) 14 June 2022.

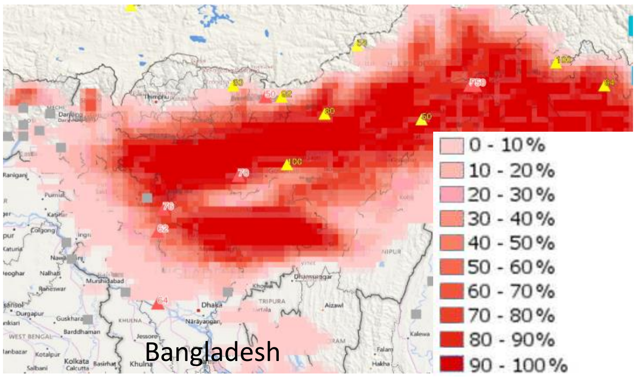


Figure 2.29. Probability (%) of exceeding 300 mm of accumulated rainfall over the forecast range of 10 days for the ensemble ECMWF forecast (Source: www. https://www.globalfloods.eu); forecast date: 14 July 2020.

2.11 Conclusions

The first part of the literature review provides a comprehensive overview of the Brahmaputra basin's monsoon and flood hydrology, while the second part includes the flood early warning perspective. The monsoon precipitation, which varies on temporal and spatial scales, is the major cause of flooding in Bangladesh. Various meteorological factors are associated with these variations. The annual monsoon's strength depends on internal dynamics, i.e., synoptic scale disturbances and external boundary forcings, i.e., SST (Krishnamurthy & Kinter, 2003; Kulkarni et al., 2009). The synoptic, intraseasonal or seasonal scales of the monsoon (Gadgil, 2003; Goswami & Mohan, 2001; Krishnamurthy & Shukla, 2007) have different effects on floods that links to flood behaviour during the monsoon period. Large scale drivers such as ENSO influence seasonal monsoon rainfall, whereas intraseasonal scale oscillations, including the synoptic situation, are important for sub-seasonal variation. Within the south Asian monsoon domain, rainfall events follow “active” and “break” patterns, which are related to spatial scale variation over the large domain. These weather and climatic factors affect flood characteristics in Bangladesh. Therefore, the annual evolution of the monsoon on the temporal scale is important to understand the flood characteristics in a particular year. Floods are annual hazard in the Brahmaputra basin, but with varying characteristics such as timing, duration, and magnitude. The assessment of flood characteristics (flood duration, high water levels or rapid rise of water levels) with respect to key drivers has not been undertaken comprehensively in the basin. For example, previous studies addressing monthly or seasonal rainfall totals are unable to examine the nature of high frequency rainfall events which trigger flooding but are only captured by daily data. Therefore, this thesis investigates three key flood types – long duration, high water levels and rapid rise water levels to understand how major hydrological and meteorological drivers cause annual variation in flood characteristics in the Brahmaputra basin (Objective 1, Chapter 3). These are required to anticipate flood characteristics during the monsoon and improve flood early warning.

Operational flood early warning is key to warning people before floods, helping in preparedness to save lives and livelihood of vulnerable communities (Carsell et al., 2004; Gautam & Phaiju, 2013; Zschau & Küppers, 2013). Due to the improved weather forecasting system, operational hydrometeorological forecasts are now available at much longer lead times and regional to global scale (Alfieri et al., 2013; Emerton et al., 2016). GloFAS is an operational forecasting system at global scale and provides a forecast out to 30 days lead time for the major river basins of the world (Bischiniotis et al., 2019; Coughlan de Perez et al., 2016) giving potential to anticipate flood events with a longer lead time. Several model versions have been implemented in the GloFAS flood forecasting system since it became pre-operational in 2011; the initial version 1 was upgraded to version 2 in 2018 and version 2.1 in 2019 (Harrigan et al., 2020a). Recently, it has been upgraded to version 3.1 from its previous versions by changing modelling approaches; GloFAS 3.1 is based on the LISFLOOD hydrological model (Alfieri et al., 2013; Thielen et al., 2012), while 2.1 was coupled with the land surface model H-TESSEL and channel routing from LISFLOOD (Wiki, 2021). Global scale evaluations of the model show GloFAS skilfulness in simulating floods for the majority of large river basins in the world (Alfieri et al., 2013; Harrigan et al., 2020a). At regional level, a few studies showed that GloFAS skill is relatively good for predicting flood events for large rivers with high discharge at lead time from 1 to 15 days (Bischiniotis et al., 2019).

Users are one of the key elements of an effective early warning system in both the developing and operation phases of early warning (UNISDR, 2006). A flood early warning system is either deterministic or probabilistic (Mylne, 2002). Deterministic forecasts provide limited usable lead time and do not have any information about forecast uncertainty. On the other hand, probability forecasts provide benefit over deterministic forecasts by providing forecast uncertainty, which allows for increased lead time and risk based decisions (Krzysztofowicz, 2001; Michaels, 2015). Therefore, decision makers need to be provided with forecast uncertainty for better decision making, and this should be undertaken by considering the users' perspectives.

The chronological development of flood early warning reflects national policies and guidelines for flood management in Bangladesh. There have been initiatives to increase lead time from short to medium range forecasts to improve early warning (Hopson & Webster, 2010; Paudyal, 2002). Different stakeholders are involved in flood risk management from national to community levels (Thaler & Levin-Keitel, 2016) and users decisions vary depending on forecast information; for example, forecast information for farmers is different from humanitarian actions. They have separate roles in developing early warning systems and responding to flood events based on forecast information. For example, national level involves high level policies and support to community people, whereas community people are the vulnerable group and need to take early actions to minimise loss (UNISDR, 2006). Therefore, it is essential to study the users' perspectives about existing flood early warnings such as their perception and their requirements for better preparedness. While there are a few studies which address this, these are limited to community level flood response, and therefore exclude key users at national and sub-national levels (Fakhruddin & Ballio, 2013; Fakhruddin et al., 2015; Shah et al., 2012). Therefore, this research focuses on users of flood early warning information (e.g., lead-time, mode of dissemination warning message, probability forecast) from national to community levels for flood preparedness decisions (Objective 2, Chapter 4).

There is no comprehensive evaluation of GloFAS forecast skill from decision making perspectives for the river basins in Bangladesh. Humanitarian organizations use GloFAS forecast for early action decisions in Bangladesh, and they require a longer lead time for humanitarian actions before flood events. GloFAS extended range forecast information provides additional lead time for both decision makers and forecasters to anticipate flood events. Decision makers are unaware of the model performance of the new versions. Therefore, it is necessary to evaluate the forecast skill for different early action decisions due to changes in model versions. Here, the thesis aims to evaluate the changes in forecast skill in the GloFAS two versions (version 2.1 and 3.1) considering the criteria for different early action decisions such as lead time, flood thresholds, probability and acceptable margin of error.

Additionally, Kling-Gupta Efficiency (KGE) has been calculated to study model performance to simulate the annual flood behaviour of the Brahmaputra River in Bangladesh (Objective 3, Chapter 5).

Chapter 3 Assessment of the hydroclimatological characteristics of flooding in the Brahmaputra basin

3.1 Introduction

The Brahmaputra is one of the most flood-prone basins in Bangladesh where flooding occurs annually during the South Asian summer monsoon season between June to September. Floods in this basin are characterised as large magnitude, higher frequency and destructive in nature (Bhattachaiyya & Bora, 1997). There is significant interannual variation of the flooding in terms of timing (time of occurrence, and duration) and magnitude. Some of the most extreme flood events in the recent decades showed clear differences in flood characteristics. For example, while in the 1998 monsoon floods had very high impact and long duration (Siddique & Chowdhury, 2000), recent floods in 2017 and 2019 had shorter durations. However, there are also newly emerging characteristics of floods in the Brahmaputra basin, such as rapid rise in water levels, exceeding previous recorded maximum water levels in 2017 and 2019 floods (FFWC, 2019), compared to other impactful floods years such as 1988 and 1998 (Fig. 3.1). Understanding the relevant drivers of floods causing flood variations in flood characteristics is important for flood forecasting and early warning (Stephens et al., 2015a) due to increased vulnerability from transboundary floods (Bakker, 2009). The flood characteristics such as timing (onset of floods in a monsoon) and duration in a particular monsoon is essential for agricultural planning such seeding and harvesting time, as well as for national and community level flood preparedness activities (Brammer, 1999).

Understanding the major drivers of these floods is key to informing the development of reliable early warning systems (Blöschl et al., 2013; WMO, 2013) and accurate predictions of future flood hazard in a changing climate (Merz et al., 2012). For example, increase in mean summer monsoon rainfall or changes in rainfall extremes at sub-seasonal scales due to climate change (Katzenberger et al., 2021; Menon et al., 2013; Turner & Slingo, 2009a, b) can be used to estimate changes in associated flood risk. There is currently a lack of understanding of how interannual and intraseasonal monsoon variability affects the flood characteristics which drive risk in the Brahmaputra, despite indications that this variability has important controls on the river discharge (Jian et al., 2009). During a developing La Niña event, an enhanced Walker circulation over the maritime continent drives intensified precipitation during the Indian summer monsoon (Shi & Wang, 2019). However, the influence of La Niña has been proposed to be diminishing in recent years due to weaker La Niña events and the impact of warmer Indian Ocean temperature (Samanta et al., 2020). Analysis of the floods at seasonal or monthly scales (Islam & Chowdhury, 2002; Islam et al., 2010; Mirza, 2003) is inadequate for the investigation of the drivers of flood events (Gaál et al., 2012), especially for floods which have a rapid rise in water level (e.g. 2017 floods); events for which the Bangladesh Flood Forecasting and Warning Centre (FFWC) is also keen to improve their early warnings. Therefore, the aim of the chapter is to provide assessment of flood characteristics by analysing key meteorological and hydrological drivers that responsible for annual variation of flood characteristics in the Brahmaputra basin in Bangladesh. Three most severe examples of flood events with different characteristics: (i) long duration flooding in 1998, (ii) flooding with a rapid rise in water levels in 2017 and (iii) flooding with high water levels in 2019, but low damages (Fig. 3.1) have been selected in this study.

The key meteorological drivers: large-scale drivers i.e., El Niño and La Niña (Goswami, 2005; Krishnamurthy & Shukla, 2000; Webster et al., 1998), intraseasonal oscillations (Kikuchi et al., 2012; Lee et al., 2013) that cause variation of the monsoon rainfall from annual to short-range time scale. From hydrological perspectives, antecedent river condition (Carter & Steinschneider, 2018), annual cycle and extreme statistics of rainfall and river flow (Schröter et al., 2015) have been analysed to understand meteorological influences on flood characteristics.

Note[2]

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[2] Two discussion papers on this chapter is available https://hess.copernicus.org/preprints/hess-2019-286/ and https://hess.copernicus.org/preprints/hess-2021-97/. Abstracts are added in appendix 1.

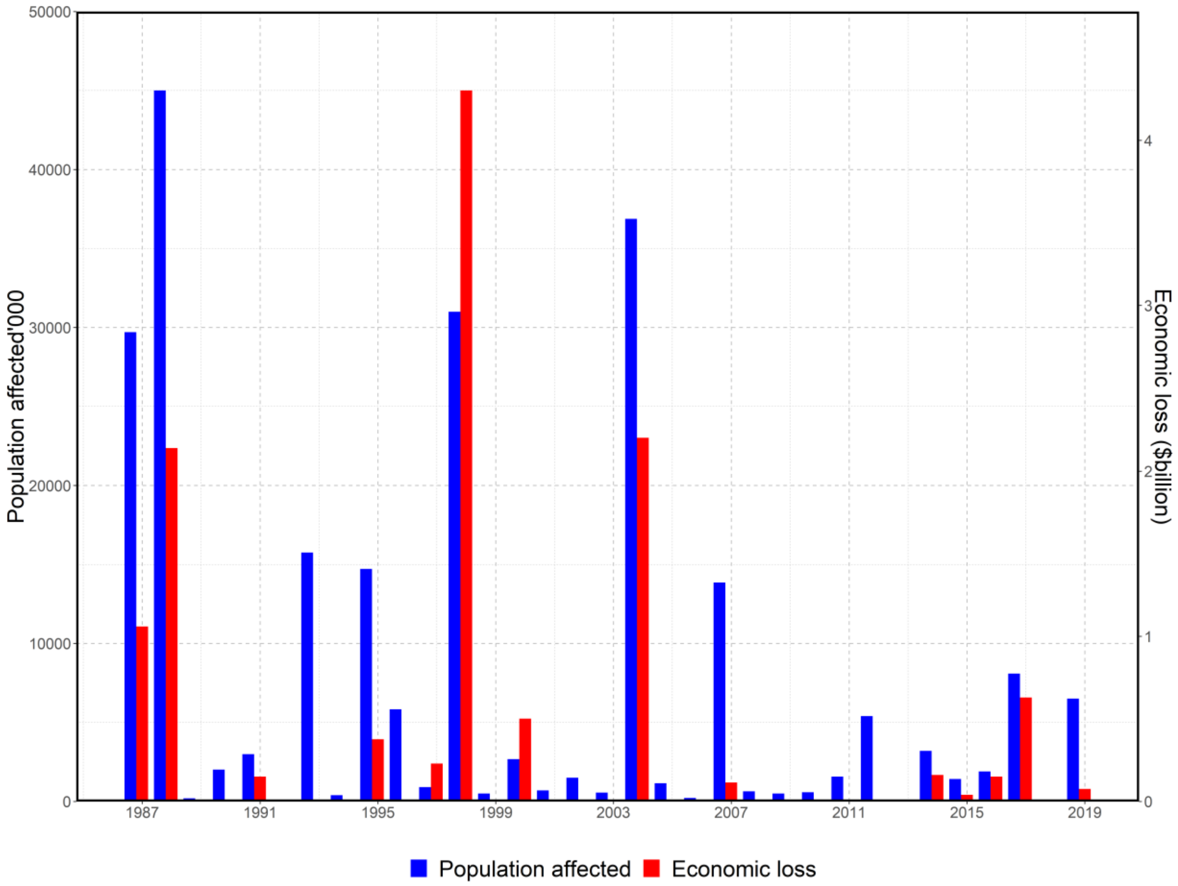


Figure 3.1. Population affected and economic loss caused by monsoon floods in Bangladesh from 1987 to 2019 (Source: EM-DAT, https://www.emdat.be/).

3.2 Data

3.2.1 Observed rainfall

Observed daily water level and river flow data were provided by the hydrological division of the Bangladesh Water Development Board (BWDB) for the 33-year period from 1987 to 2019. Four key flood monitoring river gauges had been used in this study: Bahadurabad (Brahmaputra), Dalia (Teesta), Kurigram (Dharla) and Pateswari (Dudkukmar). In addition, water level data from the Ganges and the Meghna were used to demonstrate the flood synchronization of these two large rivers with the Brahmaputra. Water level data is collected using a manual water level staff gauge at 3-hour intervals five times per day between 6:00 AM and 6:00 PM local time, with no data at night. The river flow is measured using a current meter (or Acoustic Doppler Current profiler) approximately twice a month to compare with water level, and a continuous time series of daily river flow is estimated based on the stage-discharge relationship for the same length of record as the water level data. Observed rainfall data from the Bangladesh Meteorological Department (BMD) were used to study the rainfall events over the same period as hydrological data. There are six rain gauge stations located inside the Brahmaputra basin in Bangladesh.

3.2.2 Reanalysis data

High resolution daily gridded precipitation and soil moisture data of ERA5 reanalysis (Hersbach et al., 2020) were used in order to study the large-scale rainfall situation and soil saturation. ERA5 is the most recent global atmospheric reanalysis data from the ECMWF which covers a long record from 1950 which is based on the Integrated Forecasting System (IFS) Cy41r2 (Hersbach et al., 2020). It incorporates assimilation by using conventional observation as well as satellite Data. Therefore, the variability of ERA5 precipitation from month to month matches well with observations for all continents across the globe, with correlations above 90% for most of Europe and above 70% for North America, Asia and Australia (Bell et al., 2021). Recent study shows that ERA5 perform well for hydrological studies compared to other reanalysis products in a poorly gauged catchment (Wanzala et al., 2022a). The Brahmaputra is a transboundary basin where complete records of upstream observed data is not available. Moreover, due to high mountainous terrain observation data is inadequate as major part of the basin is ungauged. The ERA5 reanalysis has been determined to the most suitable reanalysis for hydrological applications in the Indian monsoon region (Mahto & Mishra, 2019). Data was retrieved from the Climate Data Store (CDS) of the Copernicus Climate Change Service for the period 1987–2019. The output resolution of ERA5 is 0.25 degree with global coverage and hourly time samples.

3.2.3 Climate indices data

Large-scale climate indices were used to study ENSO and tropical intra-seasonal oscillations (ISOs), namely the boreal summer intra-seasonal oscillation (BSISO) for different flooding years. Ninõ (La Ninã) years were classified based on anomaly of monthly Extended Reconstructed Sea Surface Temperature (Huang et al., 2017) for the Niño 3.4 region (5° N to 5° S, 170° W to 120° W) available from NOAA (2020) for the period 1987–2019.

The ISO indices of Kikuchi et al. (2012) were used to represent the phase and amplitude (location and strength) of the BSISO that are available from IPRC/SOEST (2020) for the same period as ENSO. The

ISO indices are derived based on the first two principle components (PC1 and PC2) of extended empirical orthogonal functions (EEOFs) of outgoing longwave radiation (OLR) with a 25–90 days filtered time series over the tropics between 30° S to 30° N (Kikuchi et al., 2012). The first two PCs (PC1 and PC2) for each mode are used to determine the strength and phase of the BSISO (Kikuchi et al., 2012).

3.3 Methods

3.3.1 Meteorological drivers

3.3.1.1 Large-scale atmospheric drivers

The ENSO state is known to influence the interannual variability of monsoon rainfall (Krishnamurthy and Kinter, 2003; Nanjundiah et al., 2013). During a developing La Niña (El Niño), the monsoon strengthens (weakens) compared to ENSO neutral years (Samanta et al., 2020; Webster et al., 1998). ENSO begins in boreal spring (March–April), and usually peaks at the end of the year, decaying during the following spring. Classification of ENSO was done using the SST anomaly for the Niño 3.4 region averaged over November–January (NDJ). ENSO years were classified based on a comparison with the standard deviation of the anomaly (>1 = strong ENSO, 0.5 –1.0 = weak ENSO,<0.5 neutral conditions) (Santoso et al., 2017). ENSO events were also classified by whether they are developing or decaying years if the event spans multiple years. Based on this classification, a composite of June–September rainfall was calculated to compare between strong developing La Niña years and other years.

The intra-seasonal variation of monsoon rainfall is marked by wet and dry spells known as active and break events, with typical lifespans of around two weeks (Krishnamurthy and Shukla, 2007). There are two dominant modes of tropical ISOs linked to the intra-seasonal variability of the monsoon (Lee et al., 2013): the Madden-Julian Oscillation MJO is dominant during boreal winter with eastward propagation along the equator (Kikuchi et al., 2012; Lee et al., 2013), whereas active and break events form part of the 30-50 day intra-seasonal variation as part of the BSISO, featuring northward-propagating bands of convection at South Asian longitudes together with eastward propagation along the equator, akin to the MJO (Annamalai and Sperber, 2005). The MJO mode dominates from December to April (Kikuchi et al., 2012) so, is not considered as an important driver for the Brahmaputra floods, which occur between June and September.

BSISO events are identified at a particular time during the monsoon if the amplitude ($amplitude = \sqrt{pc_1^2 + pc_2^2}$) is greater than (or equal to) 1, whereas amplitudes less than 1 are considered as weak conditions (Kikuchi et al., 2012). The phase space diagram (8 phases, a variant of that used to classify the MJO as in (Wheeler and Hendon, 2004)) shows the advancement of BSISO, which originates in the equatorial Indian Ocean and propagates in a northwards direction (Kikuchi et al., 2012). The rainfall anomalies were calculated for 8 phases of BSISO events (amplitude >1) including weak phase when amplitude <1 irrespective of BSIOS phases. The phase-space diagram of BSISO events was drawn for the 1998, 2017 and 2019 monsoons to study the position of events within the diagram.

3.3.1.2 Rainfall characteristics

The spatial and temporal variation of monsoon rainfall was analysed based on the magnitude, intensity, duration and spatial distribution of rainfall events, as well as monthly anomalies and accumulations over the monsoon period (June–September). Rainfall extremes were analysed by developing a depth-duration frequency curve using the Generalized Extreme Value (GEV) method.

Rainfall events were defined using the method to identify ‘wet spells’ described in Singh and Ranade (2010), which identifies continuous periods with daily rainfall equal to or greater than the daily mean rainfall of climatological monsoon period using the following five steps:

(1) computation of daily rainfall climatology;

(2) calculation of daily mean rainfall (mm/day) over the summer monsoon period (June–September) over all years (climatology);

(3) normalization of year-wise daily rainfall by dividing by the daily mean monsoon rainfall;

(4) smoothing normalised daily rainfall time series with a 9-point Gaussian low-pass filter;

(5) identification of wet and dry spells as continuous smoothed daily rainfall >1 and <1 respectively.

3.3.2 Hydrological drivers

3.3.2.1 Analysis of hydrological time series

In this study, the 1-D discrete wavelet transform (DWT) was used to decompose river water level and discharge data to identify short-term variations and the annual cycle. This approach allows a clear comparison across years, as it gives an indication of the relative importance of the seasonal hydrological cycle compared to specific rainfall events for different flooding years. The Daubechies wavelet function is commonly used in hydrometeorological time series analysis (Chen et al., 2016; Franco Villoria et al., 2012; Pandey et al., 2017; Zhang et al., 2017). It was used here to decompose the daily water level and river flow time series from 1987 to 2019 into 6 detailed components (D1-D6) and one approximation (A6). The detailed components present the variation in 2^n (dyadic translation) where n is the level of the detailed component. The daily time series D1 to D6 therefore represent 2-day, 4-day, 8-day, 16-day, 32-day and 64-day periodicity respectively.

A trend analysis on time series of annual maxima of water level and river flow was done to investigate possible trends. The significance of the trends was assessed by using the Mann–Kendall test.

3.3.2.2 Hydrological characteristics

Floods generation processes are controlled by the complex interaction of meteorological conditions and catchment responses (Merz & Blöschl, 2003), therefore flood characteristics could be different with the resultant hydrological behavior such timing (duration), magnitude and frequency (Huang et al., 2018). To assist the current analysis, the resultant hydrological characteristics of floods is considered here as an end member. Three such end-members of different flood characteristics of the Brahmaputra: (i) long duration flooding, such as the flooding that occurred in 1998; (ii) flooding with a rapid rise in water levels, such as the flooding that occurred in 2017 and (iii) flooding with high water levels, such as the flooding that occurred in 2019 were analysed. Hydrological characteristics were studied in terms of initial water level, rate of rise of the water level, duration, annual peak water level, and synchronisation of floods. The exceedance probability of annual maximum discharge of the Brahmaputra River was calculated using the GEV distribution for both river flow and water level. This allows a discussion of the 1998, 2017 and 2019 floods in comparison to other years. Top decile of different flood characteristics—long duration floods (1998, 1988 and 2017), rapid rise floods (2017, 2019 and 1988) and high water level floods (2019, 2017 and 2016) were selected to provide a comparative discussion.

3.3.2.3 Soil moisture evolution

Soil moisture evolution and seasonal soil moisture saturation anomalies were studied for the upper layer (0 to 7 cm) based on ERA5 volumetric soil moisture. The percentage saturation was calculated using soil moisture at saturation level and respective residual moisture from the ECMWF's land surface model (HTESSEL) used in the Integrated Forecast System (ECMWF, 2018).

3.4 Results

3.4.1 Meteorological drivers

3.4.1.1 Large-scale drivers

The Brahmaputra basin receives more rainfall in La Niña conditions, as shown by the positive anomaly of the seasonal (June–September) rainfall for strong La Niña developing years (1988,1998, 2007, 2010) compared to all others (Fig. 3.2a). ENSO classification based on the SST anomaly at Niño 3.4 region is shown in Fig. 3.2b. During 1988, 1998, 2007 and 2010, seasonal rainfall was 17 %, 20 %, 8 % and 10 % higher than long-term average (1987–2016). Rainfall in the basin during the 2017 weak La Niña and 2019 neutral conditions was similar to the long-term average. The two long duration floods in 1998 and 1988 were found to occur in strong La Niña developing years. The flood durations in 1988 and 1998 were 27 and 66 days, respectively, while in the other two strong La Niña years 2007 and 2010, flood durations were 20 and 19 days, respectively. During 2009 monsoon, the basin experienced no severe flooding as it received 9 % less rainfall than the long-term average and the year is considered to be a dry monsoon. The basin received 9 % less rainfall than the long-term average during a strong El Niño year in 2009, and there was no severe foods. However, 1997 and 2015 (strong El Niño) were normal monsoon years for the Brahmaputra basin with 7 and 20 days flood durations in 1997 and 2015, respectively; for weak La Niña and neutral conditions during 2017 and 2019, flood durations were 25 and 17 days, respectively.

The analysis of the BSISO index shows evidence of a clear link between monsoon rainfall events in the Brahmaputra basin with the BSISO modes of intraseasonal oscillation. The position and amplitude of BSISO is recorded in 8 phases starting from the equatorial Indian Ocean and moving northward to the Bay of Bengal (Kikuchi et al., 2012), and an amplitude greater than 1 in phases 2 to 3 is associated with enhanced rainfall in the Brahmaputra basin (Fig. 2.9). From here on, this condition is referred as a 'BSISO event'. The average total duration of BSISO events (i.e., number of days where it is 'strong' in phases 2–3 during the monsoon season) is 25 days (averaged over 1987–2019). During the 1998, 2017 and 2019 floods the duration of BSISO events was 14, 12 and 24 days respectively (Fig. 3.3). In July 1998 rainfall events occurred during BSISO events for 14 days but in August it remained almost solely in a weak state, despite the record long duration floods. The heavy rainfall event/floods in August 2017 was associated with a strong BSISO event, but the rainfall/flood events in July 2019 occurred during the weak phases i.e., amplitude less than 1 in phases 2 to 3 of the BSISO (Fig. 3.4), and there was no flooding while it was active for 24 days in August and September.

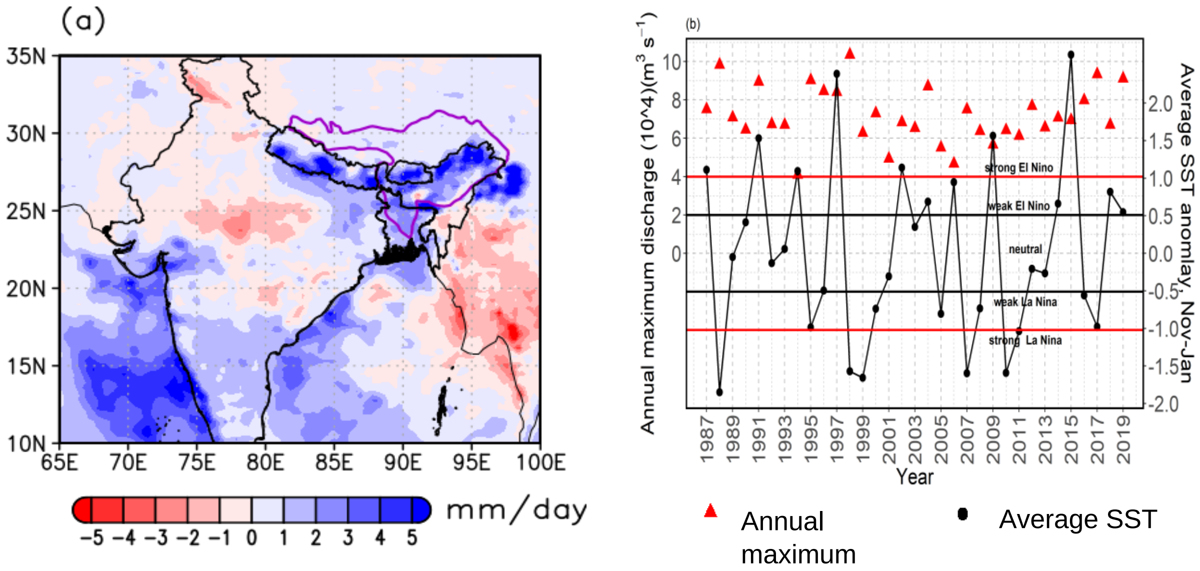


Figure 3.2. (a) Mean JJAS rainfall (mm day^{-1}) difference between strong La Niña development years (1988,1998 and 2007) and all other years over 1987–2019 (based on ERA5 reanalysis) and (b) Classification of ENSO years as strong, neutral and weak based on SST anomalies of November to January in the Niño 3.4 region (5° N–5° S, 120 W–170° W) and horizontal red and black lines are 1 and 0.5 standard deviations,respectively (NOAA, 2020). Red triangles in Fig. 3.2b show annual maximum discharge of the Brahmaputra at Bahadurabad stream gauging station.

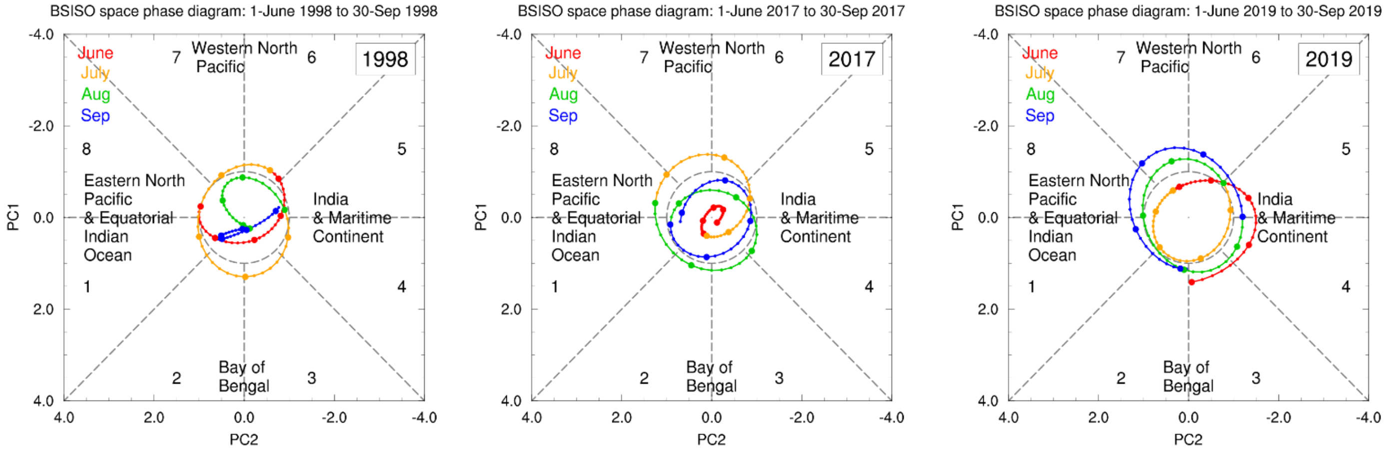


Figure 3.3. Phase-space diagram of BSISO index for the three monsoon (June–September) years(IPRC/SOEST, 2020). Smooth timelines of phase space diagram are prepared using 25-90 days bandpass filtered BSISO index.

3.4.1.2 Monsoon rainfall events

Rainfall events vary substantially across the monsoon period, and this plays a key role in triggering floods with different characteristics. The analysis shows average number of events is 5.5 during the monsoon between June to September. The rainfall events for the period 1987 to 2019 have provided in appendix 3. The number of rainfall events in 1998 (6), 2017 (7) and 2019 (5) were not exceptional; however, the duration, intensity, amount and spatial distribution of rainfall vary substantially among the different years (Table 3.1). The spatial distribution of monsoon rainfall events varies in homogeneity and coverage of the basin prior to the flood peak: in 1998 rainfall events extended across the basin for a longer duration and were more coincident with floods; in 2017 (7 to 13 August) rainfall was concentrated in small areas of the lower sub-basins (Teesta, Dharla and Dudkumar) located in Jalpaiguri, Cooch Behar, Bhutan and Bangladesh, forming a hydrological sweet spot; in July 2019 the rainfall distribution was relatively widespread across the Brahmaputra basin over an extended period (Fig. 3.4).

For the long duration floods in 1998, the annual exceedance probability (AEP) of individual rainfall events was not as extreme as those in 2017 and 2019, with the rapid rate of rise in 2017 driven by a particularly extreme event of 7 days /169 mm (24 mm day^{-1}) / 20 % AEP; with high water level floods in 2019 driven by a particularly extreme event of 12 days / 300 mm (23 mm day^{-1}) / 4 % AEP (Table 3.1). However, the total seasonal rainfall was more extreme for the long duration floods in 1998 (1% AEP) than those relatively short duration floods in 2017 (29 % AEP), 2019 (67 % AEP) (Table 3.1 and Fig. 3.5).

Table 3.1. Monsoon rainfall events average over the Brahmaputra basin (based on ERA5 reanalysis)

(Rainfall events classification has been described in section 3.3.2.2)

Year	Rainfall events	Event accumulated rainfall (mm)	Annual exceedance Probability (AEP)	Average rainfall intensity during event (mm/day)	Seasonal total (mm) (AEP)	Remarks
1998	19 June to 24 June	83	1	14	1559 (0.01)	
	4 July to 25 July	372	0.33	17		Co-occurring flood event
	30 July to 5 August	112	0.67	16		Co-occurring flood event
	10 August to 21 Aug.	199	1	17		Co-occurring flood event
	26 August to 5 September	197	0.50	18		Co-occurring flood event
	17 Sep to 21 Sep	35	1	7		
	Number of events: 6	**Total: 998**		**Average: 15**		
2017	8 June to 19 June	147	1	12	1331 (0.29)	
	29 June to 12 July	250	0.40	18		Co-occurring flood event
	20 July to 1 August	135	1	10		
	7 August to 13 August	169	0.20	24		Co-occurring flood event
	22 August to 28 August	48	1	7		Co-occurring flood event
	16 Sep to 21 Sep	45	1	8		

	23 Sep to 30 Sep	61	1	8		
	Number of events: 7	**Total: 855**		**Average: 12**		
2019	25 to 28 June	68	1	17	1276 (0.67)	
	4 to 16 July	300	0.04	23		Co-occurring flood event
	22 to 26 July	78	1	16		Co-occurring flood event
	9 August to 16 August	76	1	10		
	9 Sep to 15 Sep	94	1	13		
	Number of events:5	**Total: 616**		**Average: 16**		

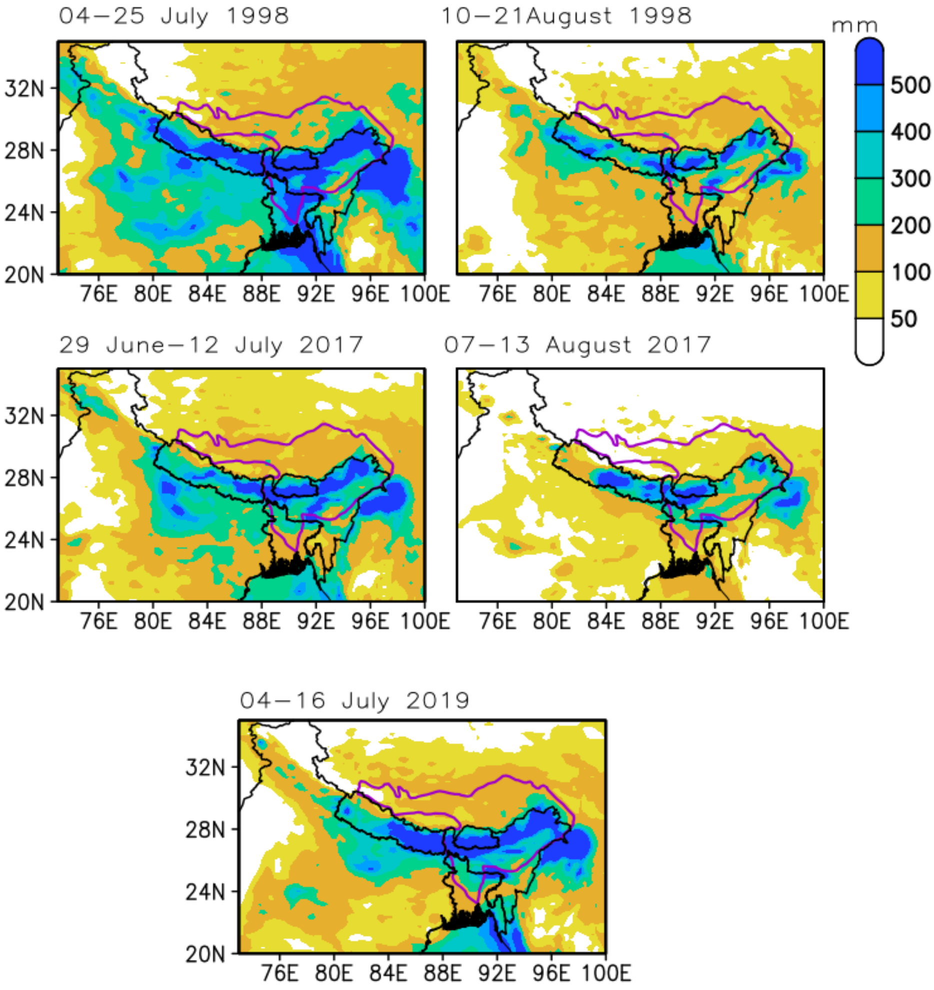


Figure 3.4. Spatial distribution of flood-triggering rainfall events in 1998, 2017 and 2019 (Source: ERA5 reanalysis).

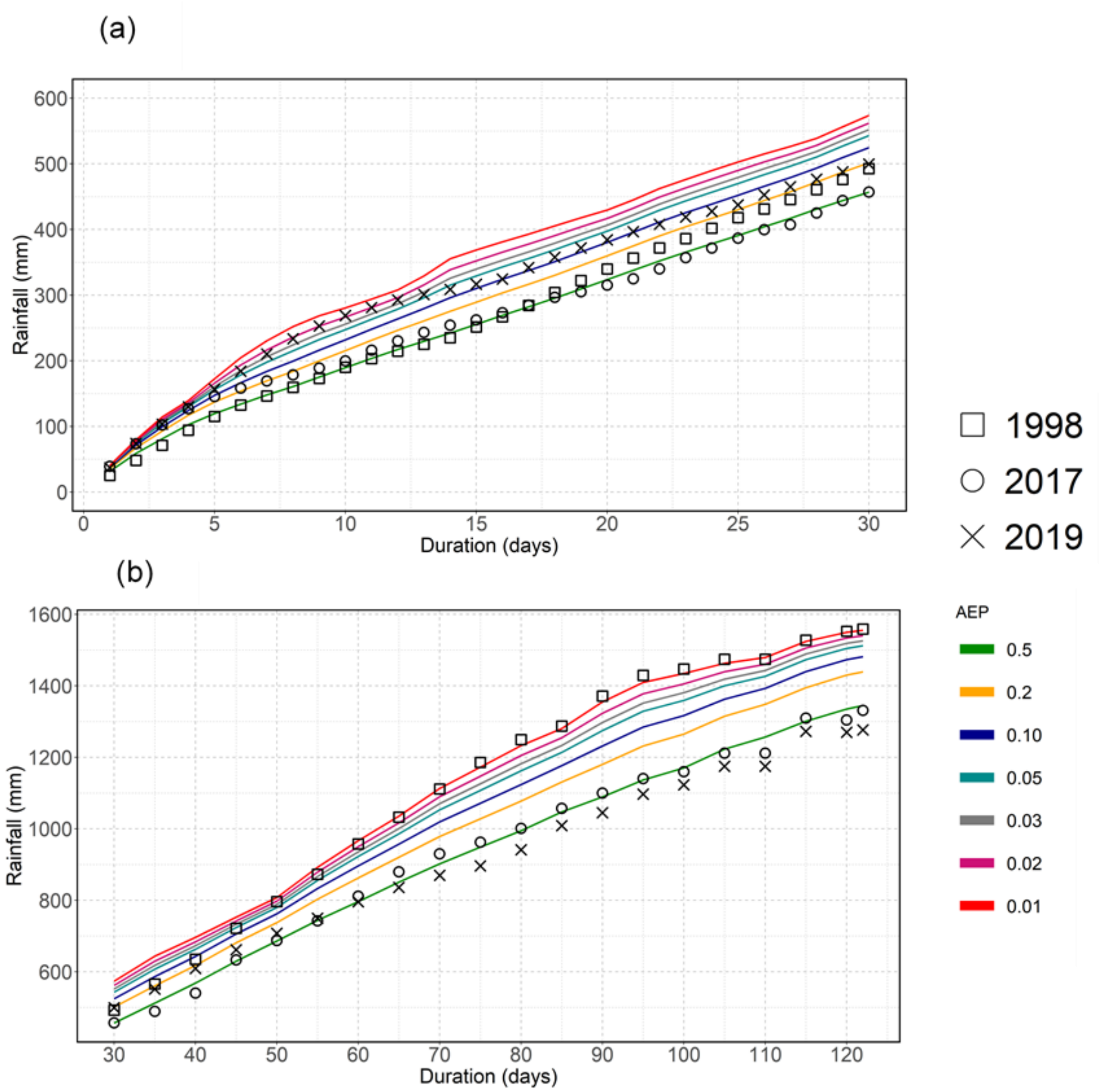


Figure 3.5. Depth-duration-frequency curve for maximum rainfall of (a) 1 to 30 days and (b) 30 to 122 days duration using generalised extreme value (GEV) distribution for the 1987 to 2019 period (Data: ERA5 reanalysis). 1 to 122 days is time period from 1 June to 30 September which presents the monsoon months June, July, August and September. The figure has been split into two parts 1 to 30 days and 30 to 122 days.

3.4.1.3 Monthly rainfall anomalies

In 1998, monthly rainfall totals in June, July and August were 18%, 22% and 48% above normal respectively, and the pattern was (almost) basin-wide (Fig. 3.6a). In 2017, the first two monsoon months (June–July) of the season were almost normal, i.e., June and July only 1.2% and 3.4% less respectively, but flooding occurred after strong positive rainfall anomalies in August 2017 in the lower part of the basin, especially in Bangladesh and adjacent areas (Fig. 3.6b). The basin received 14% more than its long-term average in August. In 2019, June (26 % less) and August (27 % less) were much drier than normal over the whole basin (Fig. 3.6c) but the above-normal rainfall across the whole Brahmaputra basin in July (27% more) caused flooding. During the 2019 monsoon, the basin received a single flood wave only in July and no floods in August, as there was no remarkable rainfall event (Table 3.1) and the monthly anomaly was drier than normal (Fig. 3.6c).

Monsoon cumulative rainfall was higher than the climatological average over the basin for the long-duration floods in 1998, with the rate of accumulation steady throughout the period (Fig. 3.6d). In 2017, the rainfall accumulation was much less steady, with a sudden jump visible in the curve in early August. Such an abrupt step-increase in rainfall rates led to a rapid rise of the river. In contrast to 1998 and 2017, the 2019 monsoon rainfall was below the climatological average as there were no remarkable high rainfall events except for the period between mid-July to the first week of August.

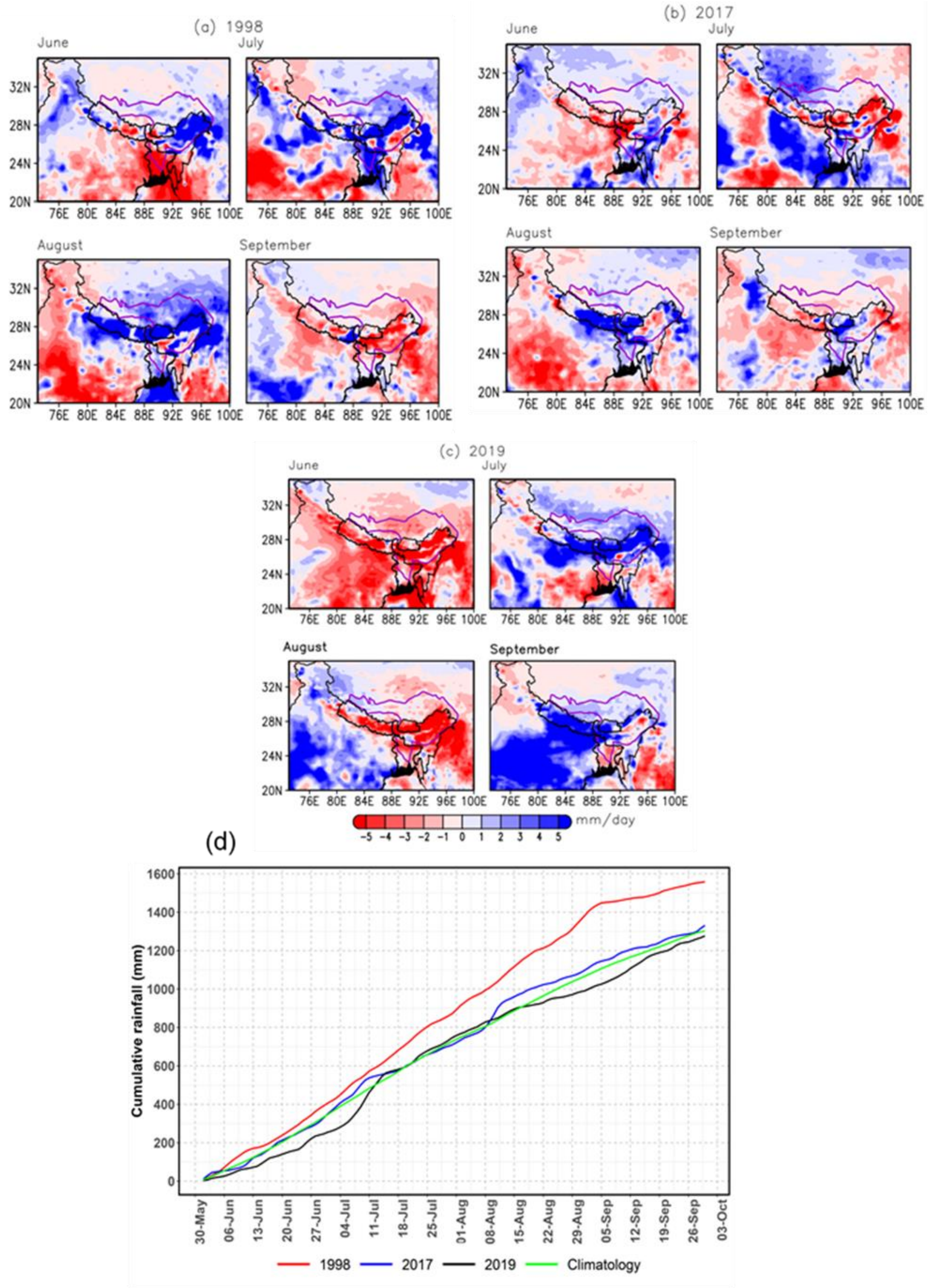


Figure 3.6. Monthly rainfall anomalies in (a) 1998, (b) 2017, (c) 2019 and (d) Cumulative rainfall (over the basin) from June to September (based on ERA5 reanalysis).

3.4.2 Hydrological drivers

3.4.2.1 Annual cycle and sub-seasonal variability of flooding

The annual evolution of the Brahmaputra River has both low and high-frequency components, representing a unimodal annual cycle with strong sub-seasonal variability on time scales of a few weeks. The water level and river flow hydrograph of the Brahmaputra River were decomposed into high-frequency (variability within the annual hydrological cycle) and low-frequency components (residual hydrograph where the high-frequency components were removed, i.e., seasonal regime or trend) to investigate the variability during the monsoon floods in different years. The wavelet technique was used to decompose at level equivalent to 16-day of periodicity (D4), which is the dominant high-frequency component that aligns with the typical time scales of wet and dry spells. The hydrological regime has a distinct unimodal annual cycle with the annual peak in water level/ river flow between July and August (Fig. 3.7b and 3.7e). The flood water usually starts to recede from the end of August, however in some years flooding continues until the second week of September (Fig. 3.7a and 3.7d). The hydrological time series show strong sub-seasonal variability within the annual cycle (Fig. 3.7c and 3.7f).

While the 1998 floods show a less pronounced short-term (high-frequency) variability (Fig. 3.7c and 3.7f), the seasonal (low frequency) component was stronger than all other years for both river flow and water level (Fig. 3.7b and 3.7e). For the 2017 floods, the seasonal regime (general trend, A6) was not exceptional (Fig. 3.7b), but in August the high-frequency component (short-term variability) reached the largest amplitude among all years (Fig. 3.7c and 3.7f). On the other hand, during the 2019 monsoon, though the water level exceeded all previous historical recorded levels (Fig. 3.7a) the high and low-frequency components were not as strong as the 1998 or 2017 floods. High frequency peak coincided with low frequency peak annual cycle peak giving highest water level, which may be important given that they were lower than in 1998 and 2017 respectively. In addition, the recorded high-water level in 2019 is not matched by the river flow, which suggests that other drivers other than the hydrometeorology are also important.

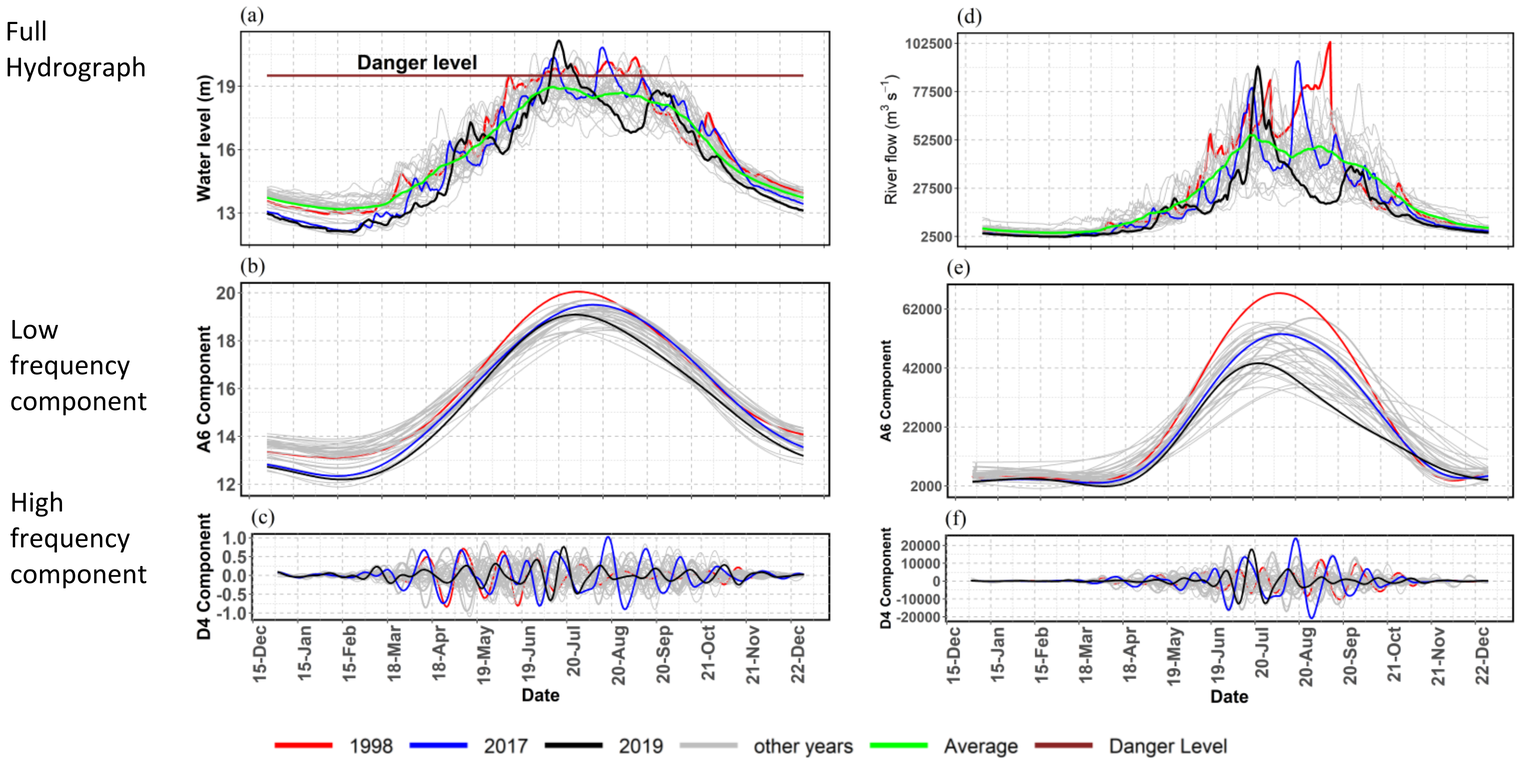


Figure 3.7. Left panel: (a) Full annual hydrograph from observed daily water level (m) at Bahadurabad gauge station (data from 1987 to 2019), (b) Low frequency component (A6) of wavelet transformed, with a six-level decomposition of daily water level and (c) High frequency component (D4) of wavelet transformed at 16-days variation. Similarly, right panel at Bahadurabad (d, e and f) shows river flow (m^3 s^{-1}) hydrograph, low frequency component and high frequency component respectively.

3.4.2.2 Antecedent water level

While pre-monsoon (April–May) water levels were higher in 1998 compared to 2017 and 2019, they were still slightly below the long-term average (Fig. 3.8). In 2017 and 2019 the water levels during the monsoon season fluctuated around the long-term average, whereas in 1998 water levels stayed well above the long-term average from mid-June to mid-September. This was driven by above-average precipitation throughout the monsoon season (Fig. 3.6a and d). Thus, the high initial water level played a role for the floods in 1998, whereas in 2017 and 2019, floods occurred starting from water levels below normal even a few weeks before the flood event. Therefore, intense short-duration rainfall events just before the floods primarily caused flooding in 2017 and 2019.

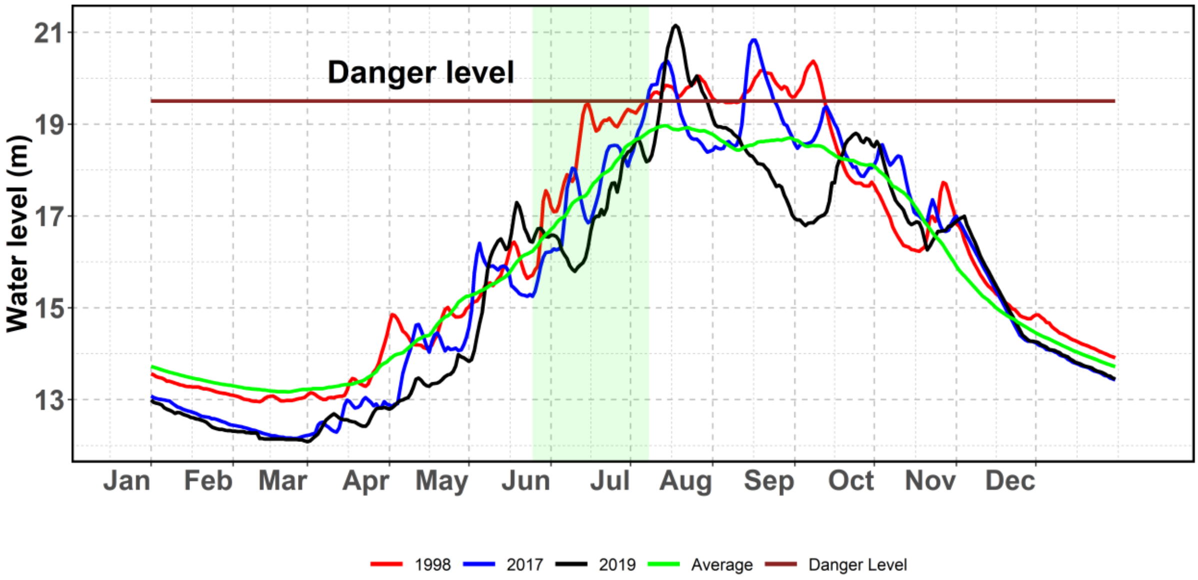


Figure 3.8. Daily mean water level of 1998, 2017 and 2019 along with long-term average water level (average water level over 1987-2016) (shaded region present before onset of floods).

3.4.2.3 Soil moisture

The soil moisture starts to increase gradually with the contribution of the pre-monsoon rainfall during April to May and reaches its annual maximum level with the monsoon rainfall in June (Fig. 3.9a). During the monsoon soil moisture is provided by successive rainfall events, and it is likely that basin-wide and frequent rainfall events maintained soil moisture above the average for the long duration floods in 1998. In 2017 and 2019 soil moisture fluctuated around this long-term average throughout the monsoon season. The basin-wide soil moisture anomalies for the entire monsoon season are quite similar for 1998 and 2017, however, for the high water level floods during the 2019 monsoon, soil moisture anomalies were negative across large parts of the basin (Fig. 3.9b) because the basin received below-normal rainfall in both June and August.

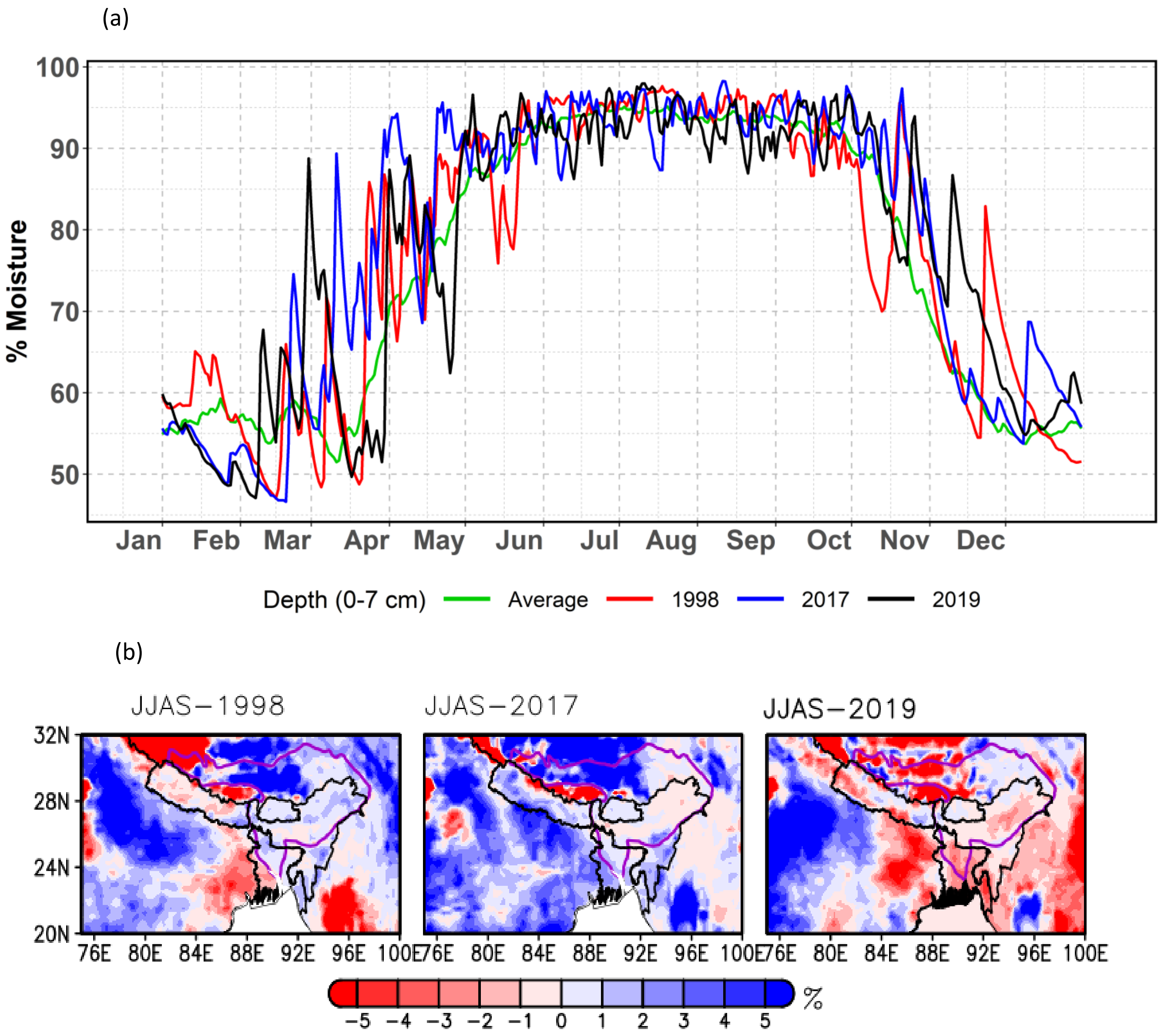


Figure 3.9. (a) Annual evolution of soil moisture (topsoil soil layer, 0–7 cm) averaged over the basin for the period from 1987 to 2019 and (b) Soil moisture anomaly during monsoon season (June-September) in 1998, 2017 and 2019 (based on ERA5 reanalysis).

3.4.2.4 Peak water level and discharge

The peak water level was the most striking feature in the 2019 flood as the Brahmaputra, along with its tributary Teesta recorded the highest annual maximum water level than their previous records (Fig. 3.10) while the river discharge was not as high compared to some other previous floods. An almost similar behaviour of water level was recorded during the 2017 floods. The water level of the annual maximum peak of the Brahmaputra at Bahadurabad stream gauging station in 1998, 2017 and 2019 was respectively 87 cm, 134 cm and 166 cm above the danger level, which correspond to annual exceedance probabilities of 10.77 % (10 year return period), 3.08 % (33 year return period), 1.54 % (75 year return period) respectively (Fig. 3.11a). When the measured discharge is not available on the day when the water level is maximum in the river, it is estimated using a rating curve. The measured discharge (water level) of the Brahmaputra River at Bahadurabad gauging station was 62,164 m^3 s^{-1} (20.94 m) on 16 August 2019, while the peak water level was 21.16 m on 18 August with an estimated river discharge of 90,239 m^3 s^{-1}. During 2017 the measured discharge (water level) was 78,525 m^3 s^{-1} (20.79 m) on 17 August 2017, while the peak water level of 20.84 m on 16 August with estimated river discharge of 93,359 m^3 s^{-1}, whereas measured and estimated maximum discharges were 102,535 m^3 s^{-1} and 103,129 m^3 s^{-1} in 1998. The peak river discharge has estimated exceedance probabilities of 1.58 %, 4.76 %, 6.35 % in 1998, 2017 and 2019, respectively (Fig. 3.11c). The estimated annual maximum discharge in 2019 and 2017 was lower than the one in 1998, despite higher water levels. The trend analysis of annual maximum water levels shows a positive trend at the 0.05 significance level (Fig. 3.11b). On the other hand, the trend in annual maximum discharge is not significant at the 0.05 significance level (Fig.3.11d). Forecasting exceeding annual peak water level can provide valuable information to flood managers to take appropriate action to prevent overtopping embankments of the river.

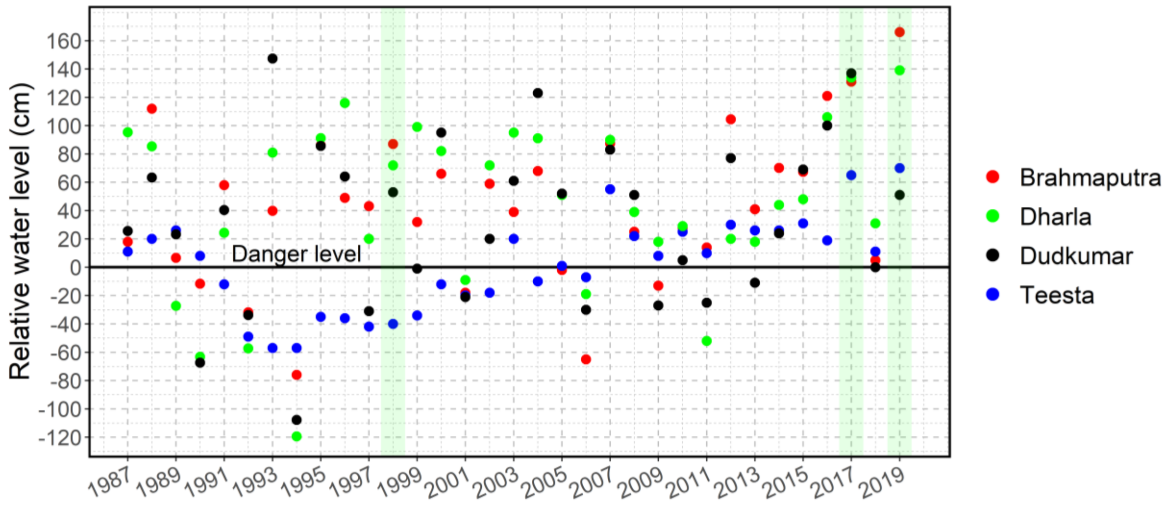


Figure 3.10. Relative water level above/below danger level (cm) for the Brahmaputra and three tributaries (Teesta, Dharla and Dudkumar).

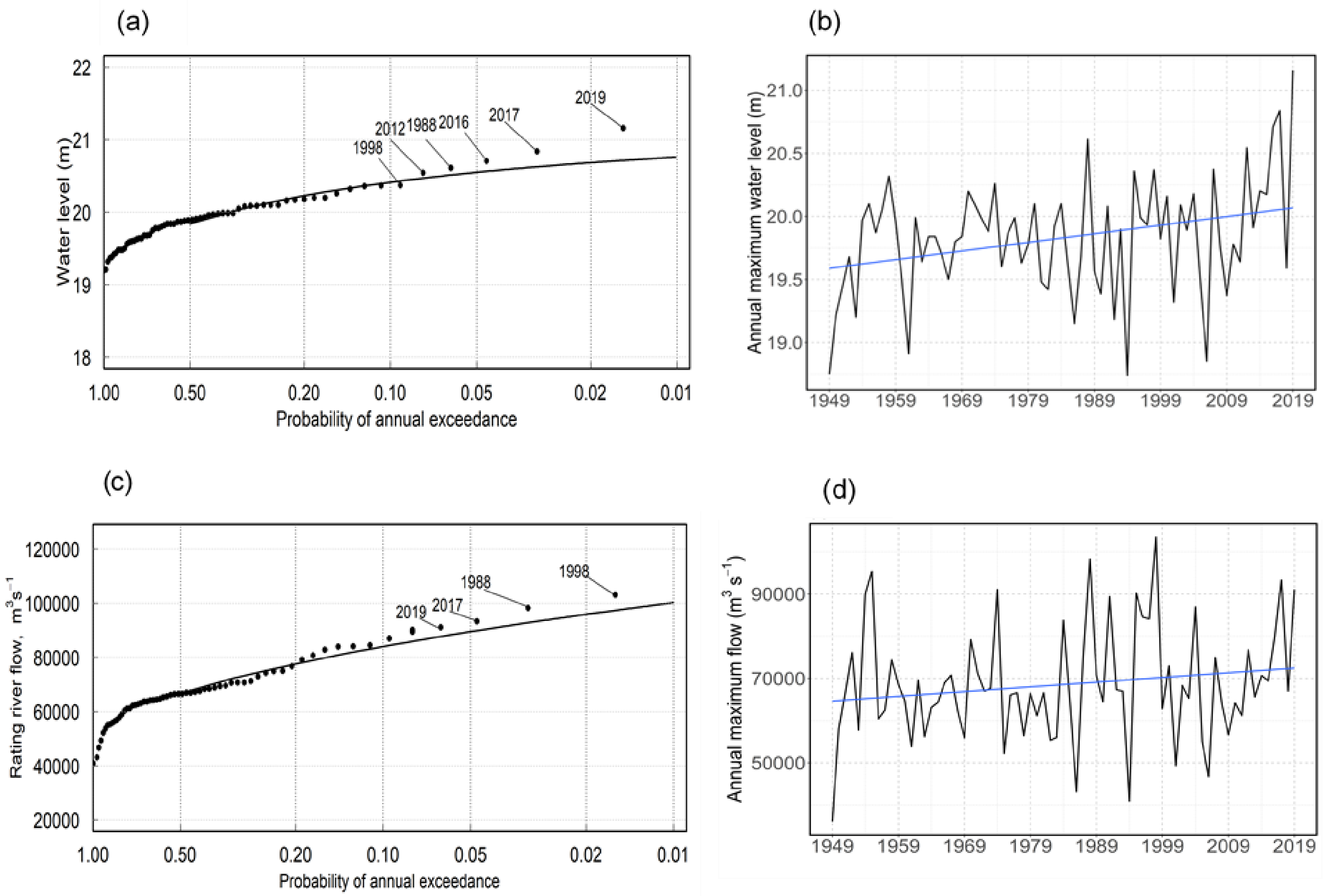


Figure 3.11. (a) Exceedance probability of annual maximum water level (m) and (b) Trend of annual maximum water level (m). (c) Exceedance probability of annual maximum river flow (m^3 s^{-1}) and (d) Trend of annual maximum river flow (m^3 s^{-1}) of the Brahmaputra River at Bahadurabad gauging station.

3.4.2.5 Rate of water level rise

The part of the Brahmaputra basin inside Bangladesh is a floodplain river delta and rivers usually gradually rise during floods. However, due to spatial variation of rainfall there can also be cases of a more rapid rise in water levels. The Brahmaputra River at the Bahadurabad station shows a higher rate of water level rise during the 2017 flood compared to all other years (Fig. 3.12a). The investigation shows that in 2017 the river experienced a rapid rise for three consecutive days (50 cm per day) compared to two extreme years of rapid rise floods in 1988 (37 cm per day) and 2019 (40 cm per day). The behaviour of water level rise of the tributaries: Teesta, Dharla and Dudkumar was almost similar to the main course of the Brahmaputra (Fig. 3.12b, 3.12c and 3.12d), suggesting that the higher rate of rise in the Brahmaputra River was due to the concurrent contributions from its tributaries (the three tributaries reached peak on the same date 13 August 2017) as result of intense rainfall on a flood-triggering hydrological sweet-spot in the lower sub-basins (Teesta, Dharla, Dudkumar). The rate of water level rise is important in order to forecast and provide timely flood warnings, as it determines how quickly the water level will cross the flood danger level and how fast decision makers and communities need to take actions ahead of floods.

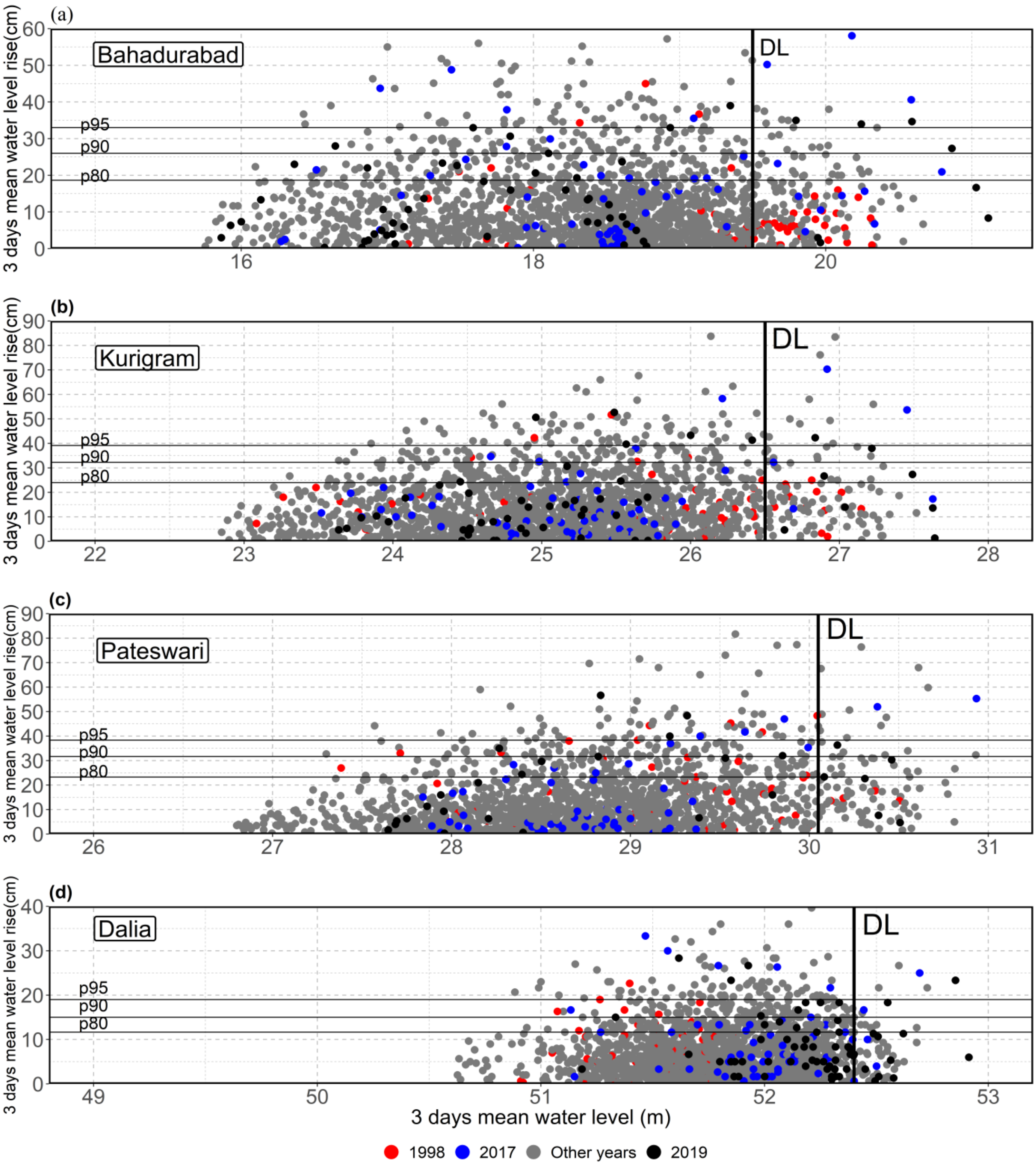


Figure 3.12. Scatter diagrams of 3-day mean water level rise (cm/day) versus water level (m) during the monsoon period in different years for the 1987–2019 period at: (a) Bahadurabad (Brahmaputra), (b) Kurigram (Dharla), (c) Pateswari (Dudkumar) and (d) Dalia (Teesta). Horizontal lines show 80th, 90th and 95th percentiles.

3.4.2.6 Flood duration

Flood duration varies annually across river networks in the basin (Fig. 3.13). The flood duration of the three tributaries the Dharla, the Dudkumar and the Teesta is usually shorter compared to main channel of the Brahmaputra (and most often below 16-20 days). The average flood duration in the tributaries (Teesta, Dharla, Dudkumar) is 8 days while in the main channel is 15 days. For the longest duration floods in 1998 (66 days), the Dharla (30 days) and the Dudkumar (11 days) experienced floods concurrently with the main channel while the Teesta did not flow above danger level (Fig. 3.13). However, the other two long duration floods in 1988 (27 days) and 2017 (25 days) flood occurred concurrently in the main channel and all three tributaries. Flood forecast information on probable flood duration in a monsoon is essential for agricultural planning and resource management for emergency operation during floods.

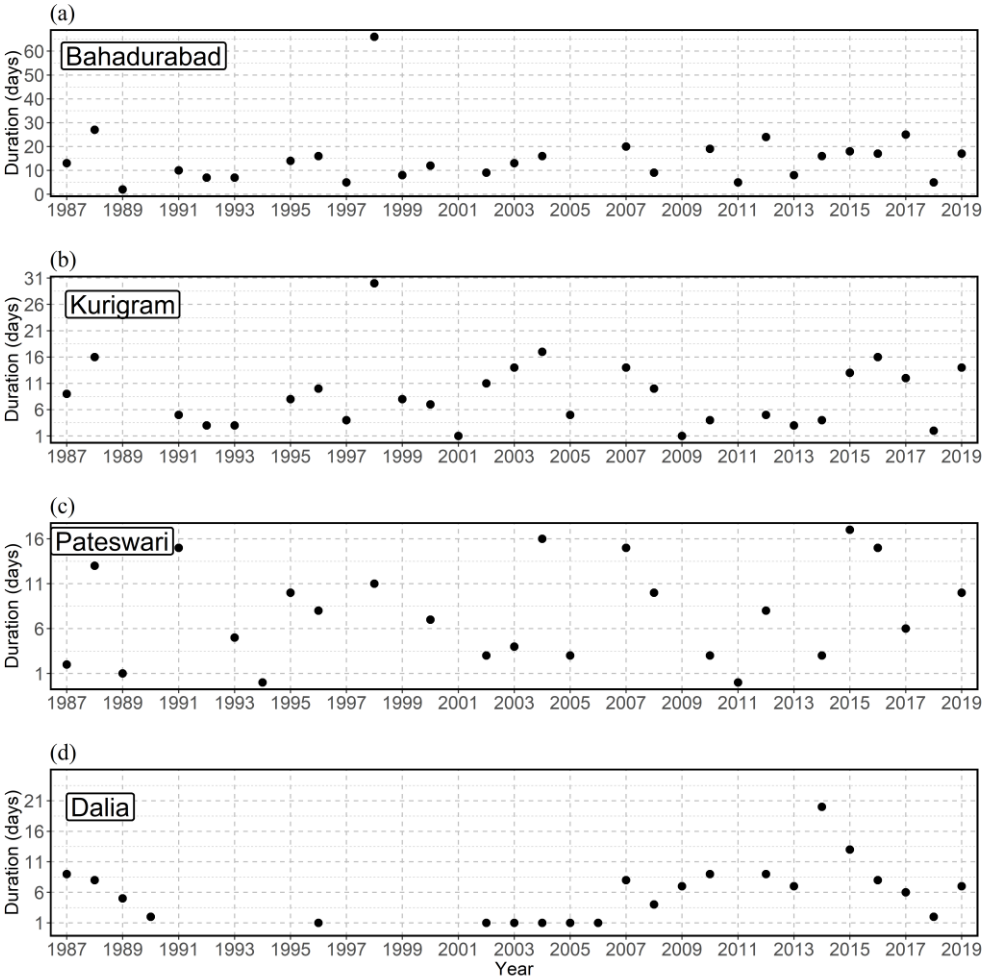
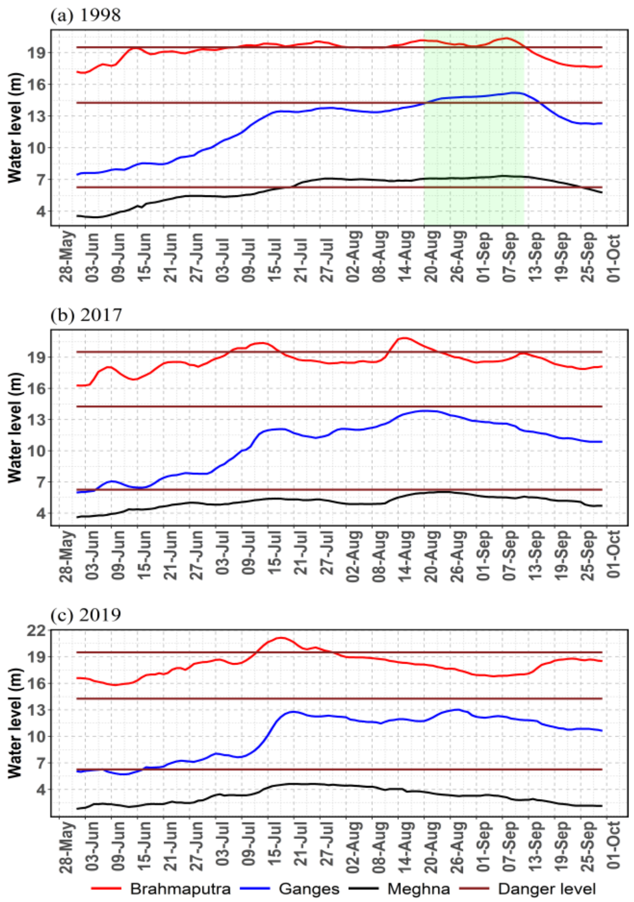


Figure 3.13. Flood duration in days above danger level from 1987 to 2019 at: (a) Bahadurabad (Brahmaputra), (b) Kurigram (Dharla), (c) Pateswari (Dudkumar) and (d) Dalia (Teesta).

3.4.2.7 Synchronization of the Brahmaputra, Ganges and Meghna floods

The flood characteristics of the Ganges, the Brahmaputra and the Meghna vary considerably in terms of timing, duration, and magnitude. Usually, there is a time lag between the flood peaks in the three basins, but sometimes the monsoon floods are synchronised along the three rivers. Among the three flood years analysed in detail here, only in 1998 did the streamflow of the three rivers exceeded the danger levels simultaneously from the end of August to mid-September (Fig. 3.14a), while in 2017 the high flows were close to synchronization but there was a time lag of 7 days between the peaks of the Brahmaputra, Ganges and Meghna (Fig. 3.14b). In 2019, both the Ganges and Meghna flowed well below the danger level at the time of the Brahmaputra floods (Fig. 3.14c). Similarly, there may be synchronization of the riverine floods with the high tides in the Meghna estuary: this occurred in the 1998 monsoon, when the tidal water levels were higher than average, while in 2017 and 2019 they stayed mostly below average (Fig. 3.14d). Along with the river flow synchronization, the high spring tide at the estuary influences the riverine flood risk creating backwater effects on the upstream river flow. Due to the long duration of the floods in 1998, the cycle of the spring tide (usually 14 days) coincided with the flooding. Anticipation of these temporal synchronization of floods among the three major rivers could be indicative for a potential long duration floods.



(d) Tidal water level

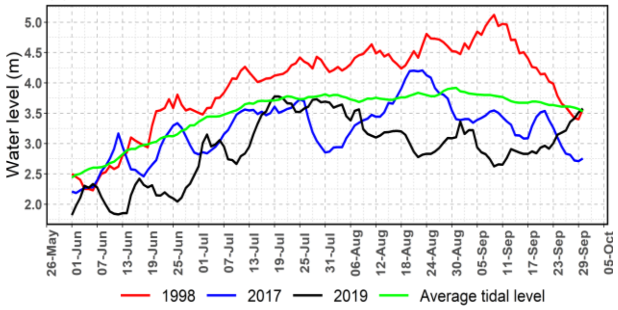


Figure 3.14. Flood hydrographs of the Brahmaputra (at Bahadurabad), Ganges (at Hardinge Bridge) and Meghna (at Bhairab Bazar) in: (a) 1998, (b) 2017, and (c) 2019. (d) Tidal water level at Meghna estuary (Chandpur) in 1998, 2017 and 2019 along with long-term average. The shaded region in the top panel (a) shows when the three rivers simultaneously exceeded the danger level.

3.5 Discussions

3.5.1 Flood types and relevant hydrometeorological drivers

There is strong interannual variability of flood characteristics based on hydrological and meteorological drivers in the Brahmaputra basin. This discussion is structured by focussing on the top decile of events in each flood type and considering possible caveats and counter examples; the drivers of these are summarised in Table 3.2. The top decile long duration floods were in 1998, 1988 and 2017; rapid rise floods were in 2017, 2019 and 1988; and high water level floods were in 2019, 2017 and 2016 (Table 2). The annual flood duration varies from a short period, i.e., two days, to more than two months. The study found that the top two long duration floods (1998, 1988) were associated with basin-wide extended-range rainfall anomalies during a strong La Niña developing year. However, a strong La Niña developing year may not always lead to the same flood characteristics; 2007 did not have exceptionally long duration floods (Table 3.2). While the total seasonal rainfall was higher in 2007 than 2017, the flood duration was higher in 2017 (Table 3.2). The rainfall varies both on seasonal as well as sub-seasonal time scales, and the results show that the basin usually receives positive seasonal rainfall anomalies during La Niña developing years. Hydrological factors such as the synchronization of floods across the Ganges-Brahmaputra-Meghna river networks, or the influence of high spring tides at the confluence, both potentially contribute to backwater effects and slow down the receding of flood water (Mirza, 2003). There was flood synchronization among the three river basins for the long duration floods in both 1998 and 1988 (Table 3.2).

For the rapid rise floods in 2017, the study found that localized rainfall on the sub-basins: Teesta, Dharla and Dudkumar created a concurrent rise of river flows in different tributaries leading to a rapid rise in the main channel. These three sub-basins are located in the lower part of the Brahmaputra basin, whose confluences with the main channel are located a short distance from each other creating a “sweet spot” condition for a synchronised rapid rise. This indicates the necessity of skilfully forecasting the spatial distribution of rainfall events with sufficient lead-time to provide early warnings in Bangladesh.

Finally, while the highest water level flood in 2019 followed an extreme rainfall event with an annual exceedance probability of 0.04%, the corresponding river discharge was not as extreme. There have been three record high water levels between 2015 and 2019, and annual maximum water levels show a significant increasing trend. However, the discharge does not follow the same increasing trend therefore other drivers such as sedimentation and other morphological changes might have played a more important role.

Table 3.2. Flood types, examples and associated key hydrometeorological conditions for the Brahmaputra River basin in Bangladesh.

Data sources: [a] Hydrological database, BWDB, Bangladesh; [b] ERA5 reanalysis (C3S, 2017); [c] Bimodal tropical ISO index; IPRC/SOEST (2020); [d]Monthly SST anomalies, NOAA (2020).

Flood Type Key elements	Long duration			Rapid rise		High water levels	
Example year	1998	Other extreme years 1988, 2017	Counter example, 2007	2017	Other extreme year. 2019	2019	Other extreme years, 2017 2016
Duration (day)	66 days	27 days (1988) 25 days (2017)	20 days	25 days	17 days	17 days	25 days (2017) 14 days (2016)
Flood peak water level [a] (m), discharge (m^3 s^{-1}) and date	20.37 m, 1,03,129 m^3 s^{-1} (8 September 1998)	(i) 20.62 m and 98,300 m^3 s^{-1} on 31 August 1988. (ii) 20.84 m and 93,359 m^3 s^{-1} 16 August 2017	20.62 m, 79,779 m^3 s^{-1}, 30 July 2007	20.84 m, 93,359 m^3 s^{-1}, 16 August 2017	21.16 m 90,239 m^3 s^{-1}, 18 July	21.16 m 90,239 m^3 s^{-1}, 18 July	(i) 84 m, 93,359 m^3 s^{-1}, 16 August, 2017 (ii) 20.71 m, 28 July 2016 89,427 m^3 s^{-1}
Total seasonal (June to Sep.) rainfall (mm) [b] and Annual Exceedance Probability (AEP)	1559 mm (AEP = 0.01)	1988: 1518 mm (0.04) 2017: 1331 mm (0.55)	1410 mm (0.29)	1331 mm (0.55)	1276 mm (0.71)	1276 mm (0.71)	2017: 1331 mm (0.55) 2016: 1249 mm (0.78)
Remarkable rainfall [b] events with APE and rainfall amount (mm); spatial distribution	4 to 25 July, 1998, 0.30 (372 mm); Basin-wide	(i) 21 to 31 August 1988, 0.14 (239 mm); Basin-wide	13 July to 31 July 2007, 0.16, (352 mm); Basin-wide	29 June to 12 July 2017, 0.40 (250 mm); Bain-wide	04 to 16 July 2019, 0.040 (300 mm); Basin-wide	04 to 16 July 2019, 0.040 (300 mm); Basin-wide	29 June to 12 July 2017, 0.40 (250 mm); Bain-wide 7 to 13 August 2017, 0.20 (169 mm); Localized
	10 to 21 August 1998, 0.70 (199 mm); Localized	(ii) 7 to 13 August 2017, 0.20 (169 mm). Localized		7 to 13 August 2017, 0.20 (169 mm); Localized			13 to 25 July 2016, 0.40, (238 mm); Basin-wide
Departure of active days of BSISO mode [c] (phase 2 to 3) during June–Sep.	-11 days	-11 days (1988)	+21 days	-13 days	-1 day	-1 day	-13 days (2017)

from seasonal average, 25 days (+ /- indicates number of days above or below the average number of days)		-13 days (2017)					+7 days (2016)
Average SST [d] anomalies (°C) Nov-Jan (NDJ) Niño3.4 region	-1.57	1988 (-1.85) 2017 (-0.98)	2007 (-1.60)	-0.98	0.55	0.55	2017 (-0.98) 2016 (-0.56)
Soil moisture [b] (Seasonal, June to Sep)	Soil moisture was high (soil moisture anomaly, Fig 9)	Soil moisture in 2010 was relatively higher than 1988 and 2017, however that did not lead to long duration floods (Fig. S7)	Soil moisture was less than 1998 (Fig. S7)	Lower part of the basin is more saturated (soil moisture anomaly, Fig. 9)	Drier than 1998 and 2017 (soil moisture anomaly, Fig. 9)	Drier than 1998 and 2017 (soil moisture anomaly, Fig. 9)	Drier than 1998 and 2017 (soil moisture anomaly, Fig. 9, and Fig. S7)
Antecedent water level [a] (June water level) (period 1987 to 2019)	June water level was 94 cm above the historical average water level of June	June water level in all other years was lower than 1998	June water level in all other year was lower than 1998	June water level was 6 cm lower than historical average water level of June	June water level was 78 cm lower than historical average water level of June	June water level was 78 cm lower than historical average water level of June	June water level was 78 cm lower than historical average water level of June
Synchronization of floods with the Ganges and the Meghna	Floods in the Brahmaputra, the Ganges and the Meghna co-occurred between 21 August to 12 September in 1998. The flood peak of the Brahmaputra (1,03,129 $m^3 s^{-1}$) occurred on 8 Sep; the Ganges (74,278 $m^3 s^{-1}$) on 09 Sep and the Meghna (10,852 $m^3 s^{-1}$) on 7 Sep.	1988: The common period of floods in the Brahmaputra, the Ganges and the Meghna between 24 August to 8 September in 1988. The flood peak of the Brahmaputra (98,300 $m^3 s^{-1}$) occurred on 31 August; the Ganges (71,800 $m^3 s^{-1}$) on 03 September and the Meghna (11,288 $m^3 s^{-1}$) on 11 September. 2017: No flood synchronization The Ganges and the Meghna river did not flow above danger level.	The common period of foods among the Brahmaputra and the Meghna, 8 Sep. to 12 Sep. The flood peak of the Brahmaputra (79,779 $m^3 s^{-1}$) on 30 July; the Ganges (52,013 $m^3 s^{-1}$) on 5 August and the Meghna (10,305 $m^3 s^{-1}$) on 5 August. The Ganges did not flow above danger level.	No flood synchronization. The Ganges and the Meghna river did not flow above danger level.	No flood synchronization. The Ganges and the Meghna river did not flow above danger level.	No flood synchronization The Ganges and the Meghna river did not flow above danger level.	No flood synchronization The Ganges and the Meghna river did not flow above danger level

3.5.2 Recommendations

Based on the results, the following important scenarios are suggested for flood forecasting and disaster management in the Brahmaputra basin.

Development of strong La Niña: Strong La Niña development years are found to be linked with larger seasonal total rainfall; long duration floods are more likely in this scenario (50% of La Niña development years flood duration was >25 days). Therefore, a forecast of a La Niña issued at the beginning of the monsoon season (June–July) after the spring predictability barrier (when predictions of ENSO are more skilful) (Chen et al., 2020; Clarke, 2014) could provide a plausible early indication of long duration floods.

Spatial distribution of monsoon rainfall: The spatial distribution of the monsoon rainfall varies significantly from more localized to basin-wide, and flood responses vary accordingly in the basin inside Bangladesh. Floods can occur from two sets of rainfall distributions; basin-wide and more localized rainfall at lower sub-basins. These distributions of rainfall events give an essential scenario to forecasters about the possible rate of rise in water level. For instance, a medium-range forecast (5-10 day lead time) of a localised rainfall event over the “sweet spot” area would indicate to forecasters that a rapid rise flood event is likely.

Climate change and disaster management perspectives: Flood events with different characteristics have different challenges and impacts, and climate change is likely to influence these flood characteristics in future. Stronger interannual variability in the monsoon is expected in a warming climate (Kitoh et al., 1997; Sharmila et al., 2015), therefore for informed climate adaptation and long-term management of disaster risk, further investigation is needed in order to understand how the two scenarios which drive interannual variability in flood characteristics might change under different climate change scenarios. It is expected that frequency of ENSO events may increase in the future under climate change conditions (Cai et al., 2014; McPhaden et al., 2020). Spatial and temporal variations of the monsoon rainfall due to climate change are important aspects that influence flood characteristics. Climate change may cause frequent extreme monsoon rainfall events by increasing the number of short-duration rainfall events (Christensen et al., 2013; Sharmila et al., 2015; Turner & Annamalai, 2012) or changing in spatial variation of rainfall (Bhowmick et al., 2019; Christensen et al., 2013) which might lead to more frequent flood pulses with rapid rise or high water level in a monsoon.

3.6 Conclusions

This study has assessed the hydrometeorological characteristics of floods which are driven by the key flood drivers in the Brahmaputra basin in Bangladesh. The drivers cause interannual variability of the flood characteristics that are linked to flood risk in the basin: duration, rate of rise and water level. The results show that long duration floods are associated with seasonal and basin-wide rainfall anomalies linked to a strong La Niña development, as well the synchronization of floods with the Ganges and Meghna rivers. The rapid rate of rise in water level, which is a challenge for early warning, is driven by more localized rainfall in a hydrological “sweet spot” that causes a concurrent contribution from the tributaries to the main channel. For the record high water levels floods in coincidence of peaks in low frequency and high frequency components of river flow was important in 2019 floods.

These drivers give a set of possible scenarios for flood forecasters to anticipate flood types during the monsoon to improve flood preparedness and risk assessment. Further study should address the potential influence of sedimentation and geomorphological changes which may have caused the recent upward trend in annual maximum water levels in the river. In addition, given the critical link between flood duration and livelihoods in the basin, it is recommended further study of how climate change will affect the interannual variability in flood characteristics in order to support climate adaptation.

Chapter 4 Users' perspectives flood early warning in Bangladesh

4.1 Introduction

Flood early warning provides a cost-effective solution in reducing flood damage through preparedness actions (Girons Lopez et al., 2017). Flood preparedness and early action before imminent flood impacts depends on accurate flood forecast information and timely dissemination of early warning messages to flood risk managers and vulnerable communities (WMO, 2003). The key elements of an early warning system consist of detecting and forecasting the event, disseminating warning messages and finally, responding to warnings (ISDR, 2004). Therefore, early warning can effectively reduce flood damage if it is properly communicated to its users for preparedness action. For example, before the onset of floods, preparedness action is considered more effective to reduce potential damages and reduce traditional emergency response expenses during floods (Coughlan de Perez et al., 2016; Lopez et al., 2020; Pappenberger et al., 2015).

The flood forecasting service has been in operation in Bangladesh since 1972 to support flood risk management along with the conventional structural measures (Chowdhury, 2000). There have been significant improvements in flood early warning in Bangladesh over the several decades since 1972. However, flood preparedness decisions based on the forecast still do not reaching their full potential to reduce flood damage. The Flood Forecasting and Warning Centre (FFWC) in Bangladesh provides 1 to 5 days deterministic forecasts, and up to 10 days medium range forecast based on European Centre for Medium-Range Weather Forecasts's (ECMWF) ensemble forecasting. FFWC also accesses the Global Flood Awareness System's (GloFAS) extended range (30 days) ensemble forecast for the major river basins in Bangladesh. These ensemble prediction system (EPS) forecasts show skill at the medium range lead time to predict river floods on a regional to global scale (Alfieri et al., 2013; Bartholmes et al., 2009; Pappenberger et al., 2011), which can provide benefit to existing early warning systems and be usefully applied in decision making for anticipatory actions through effective communication (He et al., 2011). With the scientific advancement of numerical weather prediction models, there are increasing efforts to make ensemble forecasts operational but less priority for communication and use for decision making (Demeritt et al., 2013).

EPS offers information on forecast uncertainty, allowing users to take “risk-based” decisions through the communication of the uncertainties through different tools to visualise forecast (Ramos et al., 2013). Different stakeholders are involved in flood risk management from national to community levels (Thaler & Levin-Keitel, 2016). They have different roles in developing early warning systems and responding to flood events based on forecast information. For example, national level roles involve high level policies to support the community, whereas the communities, as the vulnerable group, need to take early actions to minimise loss (UNISDR, 2006). It is therefore essential to study the perspectives of different users on their needs for better preparedness.

The existing literature (Fakhruddin & Ballio, 2013; Fakhruddin et al., 2015; Shah et al., 2012) available regarding flood responses in Bangladesh primarily focused on the community level and lack of input from other important stakeholders at national and sub-national levels. In addition, these studies were carried out in areas where customised early warnings were disseminated at the community level on a pilot basis. In this study, two flood affected communities at Kurigram and Jamalpur districts in the Brahmaputra basin were selected where no prior piloting was done to disseminate flood early warning at the community level. This study aims to understand how stakeholders involved in flood risk management at different levels (from national to community) access and use forecast information for their flood preparedness decisions in contrast to the other studies that have looked at the 'customised' warnings. This paper addresses the following questions: (i) What flood preparedness decisions are being made by different stakeholders during floods?, (ii) What information does the forecast need to provide (for example, lead-time, flood characteristics, probabilistic information) for flood preparedness? The study uses qualitative approaches, including community level household surveys and semi-structured interviews with sets of major national and sub-national officials, Non-Government Organizations (NGO), humanitarian agencies, local government working with flood preparedness and response activities in Bangladesh.

4.2 Dissemination of flood early warning in Bangladesh

Flood early warning dissemination consists mainly of a top-downward flow of information which includes flood bulletins, warning messages, and short message service (SMS) to various users. A daily flood bulletin contains information including a flood summary (how many rivers are flowing above danger level, districts are affected by floods, changes in the flood situation in the last 24 hours), warning messages, and forecasted flood situation in the next few days. These flood bulletins are produced every day during the monsoon and disseminated through email to users at national, district and community levels (Fig. 4.1). The key users include Ministry of Agriculture, Disaster Management and Relief, Water Resources, Department of Disaster Management, Department of Agricultural Extension, flood and water management organizations, district and sub-district levels administrations, local government institutions, humanitarian organizations, Non-government Organisations (NGOs), development partners and the communities. Forecast information is also disseminated through the FFWC website (www.ffwc.gov.bd). Recent innovations such as social media i.e., Facebook, Mobile app, Interactive Voice Response (IVR) message and Google Flood Alert have been introduced to increase accessibility of forecast information to wider users. As a result, people living at the community level can easily access early warning information. Flood warning messages are prepared based on the forecasted river water levels located across the river network. Therefore, it is necessary to provide location specific flood early warning for community level to answer the question when and where actual floods will occur. To meet the community requirement, the FFWC had implemented a few pilot demonstrations of flood early warning at the community level using gauge-to-gauge correlation between upstream and downstream gauges, installation of additional water level gauges in the flood plain, local level flood mapping, SMS alert system and dashboard with technical support from NGOs and community-based organisations such as civil society organisations or flood volunteers (BDPC, 2001; CEGIS, 2010; Cumiskey et al., 2014; RIMES, 2015). Flood warning messages include rainfall forecast information and river water level forecasts for 1 to 5 days. A warning message consists of rainfall and flood outlooks. For example, a typical warning message was issued on 13 July 2019 as follows.

Rainfall outlook:

“According to the forecast information of Bangladesh Meteorological Department and India Meteorological Department, there is chance of medium to heavy rainfall & in some places very heavy rainfall in the Northern and North-Eastern part of Bangladesh along with adjoining Assam and Meghalaya states of India in the next 24 to 72 hours.”

Flood outlook:

“Water level of the Brahmaputra River may continue to rise in the next 72 hours and stream gauging stations at Bahadurabad, Chilmari may cross danger level in the next 24 hours and flood situation in Kurigram, Jamalpur may deteriorate in next 24 hours.”

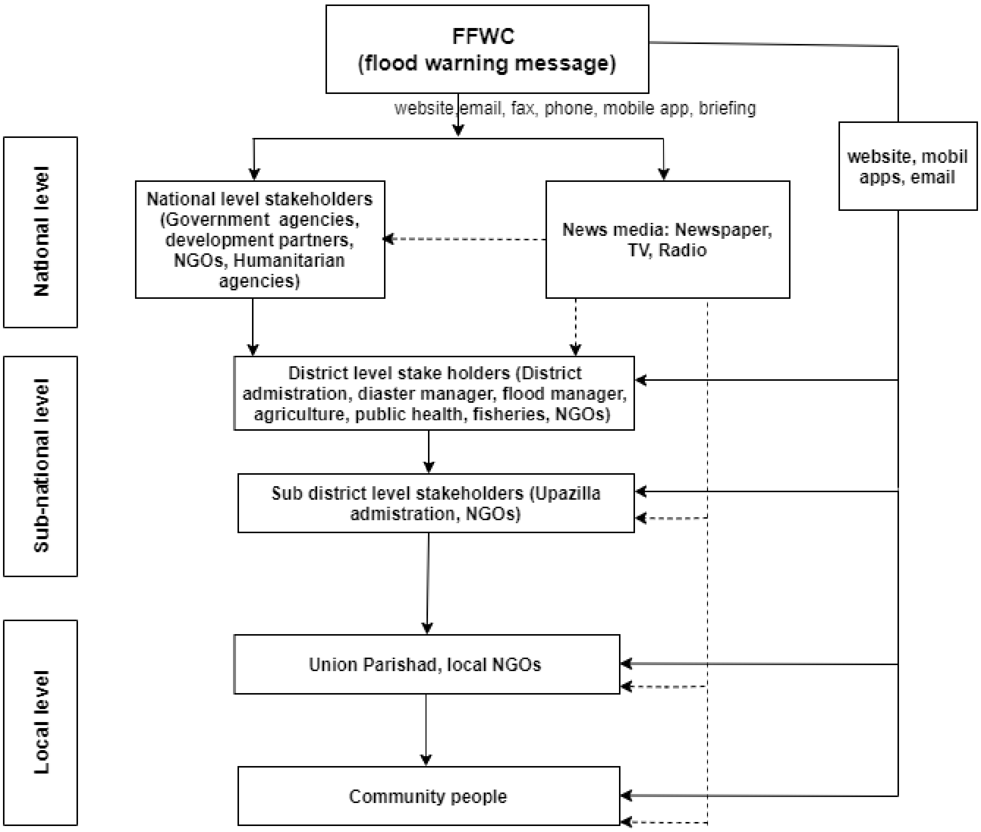


Figure 4.1. Flow of forecast information from the FFWC to users. Solid lines indicate information directly flow from the FFWC whereas dash line indicates information are pulled from news media (Flow chart is based on FFWC’s current practice).

These warning messages give potential rainfall information and forecast of likely flooding based on the water level crossing the danger level at the gauging location. The warning message lacks information for the local level on whether a community is likely to be affected by floods or not. The numerical value of forecasted water level at the stream gauging stations is also provided with the bulletins. The warning messages provided by the FFWC do not contain any uncertainty, impact information or calls to action, for example whether the community needs to evacuate. A four-colour legend is used to present the flood situation; when the water level is below 50 cm of the danger level that is called ‘normal condition’ and is presented by a green colour, within 50 cm of the warning stage by a yellow colour, a ‘flood situation’ where the water level is up to 1 meter above the danger level, and severe floods when water level exceeds above 1 m of danger level.

4.3 Study area

The community level perspectives on the flood early warning system were studied at union level (lowest level administrative unit) for two unions located in Chilmari and Islampur upazilla (sub-district) of Kurigram and Jamalpur districts, respectively (Fig. 4.2). Out of several unions of these two sub-districts, Raman and Kulkandi union of Chilmari and Islampur, respectively were chosen based on the exposure to floods, historical hydrometrorological data and the availability of the flood forecast. The total area of Ramna union is 21 km^2 with population 28,729 and Kulkandi union 28 km^2 with population 10,825 (BBS, 2011). The physical settings of the study area consist of Charlands (islands are created by sediment deposition in the main river channel). There exist flood protection embankments in the west side whereas natural levees protect from flooding from the east side of the river (Fig.4.2). Charlands are formed from sandbars that develop as island within main course of river or connected to riverbanks (Ashworth et al., 2000). Development of Charland occurs from economic activities such as crop cultivation, livestock grazing and human settlement (Sarker et al., 2003). The Charlands are highly susceptible to frequent floods due to close contact with river and not having any structural protection of floods. There are flood shelters in the Charlands where people can take shelter during the floods and embankments also act as temporary shelter for vulnerable members of the community during a disaster situation. Agriculture is the main source of livelihood of these areas; around 80% people are involved in crop production (BBS, 2011). Table 4.1 shows major crops with flood timing and probable impact of floods in the study areas. Transplanted Aman (T.Aman) is the major crop which is affected most during the monsoon floods. Besides crop cultivation, livestock and fishery are also sources of household income among the village communities. Non-farming activities include, social and personal services, small business and trades, health services, construction and transport services (BBS, 2013). Both farming and non-farming activities are severely affected by floods. River water levels start to rise with the pre-monsoon rainfall in April and reach peak between July and August. Recent floods in 2019, the river experienced high water level floods which caused overtopping and breaching the flood embankments at the west bank of the river. The high water levels caused severe flooding in the east part of the river as there is no flood embankment. This causes evacuation thousands of people to flood shelters along with their livestock.

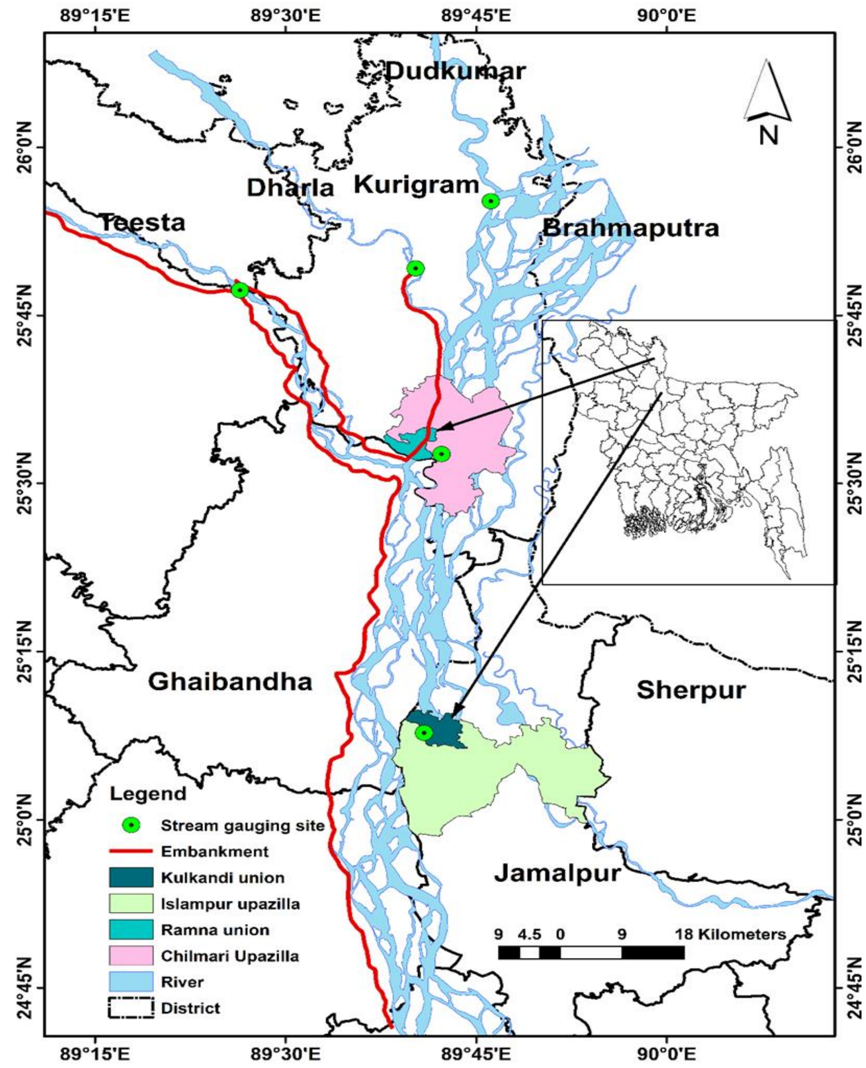


Figure 4.2. Location of the community level study areas in the Brahmaputra basin in Bangladesh.

Table 4.1. Monsoon floods timing and impacts on crops in the study area

Flood timing	**Crops in the field**	**Agriculture activities**	**Floods impacts**
End of June to Mid of July	Kharif I:Aus rice, Jute and summer vegetable	• Crops reach full growth to matured stage	• Damage to crops at matured stage • Reduced crop yield
Mid of July to End of July	Kharif I:Aus rice, Jute and summer vegetable	• Early harvest of Jute (depending on floods) • Aus harvest	
	Kharif II: T.Aman rice, late summer vegetable	• Preparation of seed beds for T.Aman. First, farmers choose higher grounds for seed beds • Harvest of Jute	• Delay in preparation of seed beds
End of July to Mid of August	Kharif II: T.Aman rice, late summer vegetable	• Harvest of rest of Jute • Young seedlings of T.Aman • Started plantation of T.Aman	• Damage to young seedlings in the seed beds
Mid of August to first week of September	Kharif II: T. Aman rice, late summer vegetable	• Plantation of transplanted Aman	• Transplanted Aman cultivation hampered • People prepare for Robi crops (winter crops) • Damage B. Aman

(Source: Crop information, (BBS, 2017), Flood timing (BWDB, 2017c, d)

Kharif I: Aus rice, Jute and summer vegetables

Kharif II: Broadcast Aman(B.Aman), Transplant Aman (T.Aman), late summer vegetable

4.4 Methods

To achieve the research objectives, the study is carried out using semi-structured interviews at national and district levels, as well as a national level consultation workshop (Questionnaires are presented in appendix 4) in Dhaka. The community level household surveys and focus group discussions were carried out to understand how the existing forecasting systems help the local level people's preparedness for flood using flood forecast information and in particular, the extended range forecast, might help better flood preparedness. The data collection took place during the 2019 monsoon flooding in Bangladesh. The interviews and discussions were recorded anonymously using code and analysed later. All the participants were asked to provide consent to participate in the interviewing and discussion process. The study has received research ethics approval by the University of Reading, UK.

4.4.1 National level interview and consultation workshop

Semi-structured face to face interviews were undertaken with 7 different stakeholders: Bangladesh Water Development Board (BWDB), Department of Disaster Management (DDM), Department of Agricultural Extension (DAE), Department of Livestock Services (DLS), Department of Public Health (DPHE), Non-Governmental Organization (NGO), Humanitarian organisation-Bangladesh Red Crescent Society (BDRCS) who use flood forecasting information for decision making at national level in flood preparedness and response activities. The interview questions were designed to study how flood forecasting information was used for flood preparedness decisions, and accessibility and understanding of early warning from higher level users' perspective. Opinions on the communication of medium to extended- range probabilistic forecasts at different levels were also collected.

A national level consultation workshop was also arranged consisting of 30 participants from different stakeholders including the FFWC (flood early warning provider) in September 2019 in Dhaka. The main objective of the workshop was to share experience of predicting the recent floods using the available extended range flood forecast from GloFAS and communicating uncertainties to users of probabilistic forecasts. The margin of error is defined as the time period between the forecasted and observed flood peak. An acceptable margin of error is the length of delay to the flood which users are still happy with. During the national workshop, it was discussed about acceptance and possible implication if flood occurs after a few days than forecasted time. Feedback from different users will help in understanding the weaknesses of the current system which is essential to improve flood early warning for better flood preparedness in Bangladesh. Participants were selected purposively who are users forecast information for decision making.

4.4.2 Sub-national level Key informant interviews

Semi-structured face to face interviews were carried out with 7 important stakeholders in the Kurigram district in the Brahmaputra basin. The interview included- flood manager, disaster manager, local government, representative from NGO, agriculture and fisheries officer and public representative who receive flood forecasting information and use for response activities. These sub-national level users play a bridging role between national and community level by implementing policy decisions. The interview covered questions on scope and limitations of existing forecast for their flood preparedness activities at sub-national level, their expectations forecast for the forecast lead-time and challenges to communicate and use of the extended range probability forecast for the flood preparedness and response activities at the sub-national level to community level. Their responses are important in developing extended range flood forecasting system in Bangladesh e.g., understanding key lead times and skill criteria.

4.4.3 Community level household survey and focus group discussion

A purposive sampling approach has been used to carry out household questionnaire survey in the two high flood risk unions in the Chilmari and Islampur upazilla (sub-district) of Kurigram and Jamalpur districts, respectively (Fig. 4.2). The target population groups were the most common profession in the village such as farmer, fisherman, day labour, small businessmen who are affected by the floods. The community level study areas were chosen in such a way that the flood forecast information is available for them.

The questionnaire was designed to understand how the existing forecasting system helps the local level people's preparedness, how the extended range forecast would help for better flood preparedness. The sample household number for the study was selected based on Nations (2008) and presented by the equation, $n_h=(84.5)\ (1-r)/\ (r)(p)$, where n_h is the sample size in terms of number of households; r is an estimate of a key indicator to be measured by the survey; p is the proportion of the total population accounted for by the target population and upon which the parameter, r, is based; In this case considering the key indicator as the percentage of people receiving flood early warning (estimated as 50% of the total population of the each union), the value of r assumed to be 0.5 with a confidence level of 95% and p=1 as all the households are target. Therefore, the sample size is 85. However, 100 household was chosen as sample size from each union and in total 200 surveys were conducted in the two unions.

In addition to this household survey, four focus group discussions (FGD) with 8-10 participants were arranged in the two study areas. The aim of FGDs was to understand how to improve community level dissemination of flood early warning and to understand what flood forecast information they need and how to use probabilistic forecast for their decision making, based on a semi-structured interview checklist. During the FGD margin of error in forecasting was discussed as floods can occur after few days than actual flood timing due to uncertainty in forecasting, therefore, community people were asked how many days delay in occurrence of floods is acceptable for them after making decision such as evacuation. The participants were purposively selected for the study consisted of different professions such as farmers, fisherman, day labour, small businessman, school teacher, Imam of mosque (local religious leader), member of Union Parishad, community health workers, who all lived in the village. The participants were selected based on the geographical location; one group of people live in the Charlands while another group of people live on relatively higher land near the bank of the river.

4.5 Results

In the following section, results of the interviews and household level surveys are presented under the sub-headings of National, sub-national and community level.

4.5.1 National and sub-national level preparedness and responses

4.5.1.1 National level

The national level includes a mixed of stakeholders with different roles and responsibilities for flood preparedness and response actions. The national level response to flooding includes an emergency operation centre within each relevant stakeholder at the national level to monitor the flood events and coordinate response activities at the sub-national level. A set of guidance notes is provided from the national to sub-national levels to accelerate the response activities and reduce the flood damage by taking various early action measures.

One of the respondents from the disaster management department of Bangladesh informed that “the DDM has response readiness for the upcoming floods such as at the national and district levels. We have stock of emergency relief items (rice, dry food). With the short-range forecast, we first try to know whether the district administration is aware about the upcoming floods and their capacity to start the response activities. Moreover, as the floods affect the most northern district, the central part and south-central part of the country get enough time to respond to flood activities.” (Representative, DDM). BDRCS also gave similar response for distribution aid among the flood vulnerable communities. They need (pre-activation of humanitarian actions) resource planning, identify vulnerable household, communicating with key stakeholders to distribute aid before floods.

The representative from BWDB talked about the flood management activities (structural measures) in the basin. He stated, “As flood is a recurrent phenomenon for Bangladesh, there is an annual plan for the flood fighting activities. BWDB is responsible for flood management activities, and we have preparedness plan for the flood management activities. As soon as we anticipate flood events, we alert the field level flood management offices to keep alert and coordinate with the relevant stakeholders”. (Representative, BWDB).

The agriculture department of Bangladesh is also equipped with flood response activities. According to the representative of DAE “we provide agriculture advisory services at the sub-national level through 30,000 lead farmers. After the flood we prepare an agricultural rehabilitation plan to provide support to the farmers at the community level (Representative, DAE).

List of agricultural advisories (Agriculture advisory bulletin on 17 June 2019, Source: DAE, (DAE, 2019)):

- Protection of seeds at home by keeping in higher place and airtight pot/packet from flood water as well as moist atmosphere during monsoon.
- If floods are anticipated, then advice for harvesting Aus (a rice variety) paddy if it is 80% ripen.
- Harvesting the matured jute.
- Start to prepare seedbed for Aman (a rice variety) paddy preferably at higher ground. If higher ground is not available prepare floating seed bed.
- Harvest corn and peanuts if they are matured enough.
- Protect pond fish by netting surrounding of the pond.
- If there is a forecast of heavy rain event, refrain from spreading fertilizer or pesticides.
- Take necessary measures for drainage facilities from croplands.

The representative from the DPHE shared the initiatives that they adopt for flood management: “We provide emergency public health services during and after the flood. We provide services on community drinking water facilities and sanitation facilities. We also distribute water purification tablets among the affected communities. The district offices inform us about the flood-affected areas and take action accordingly. In addition, we also coordinate with national wash cluster to provide better services to the community” (Representative, DPHE).

The stakeholders at the national level support and monitor the flood preparedness activities from the policy level perspective of flood risk management. Preparedness before flood event can help to avoid/minimise damage and reduce burden of relief activities during floods. These preparedness and responses actions largely depend on how a flood event is forecasted and communicated with the relevant decision makers.

4.5.1.2 Sub-national level

Sub-national institutes act as pivotal point in flood risk management between national and community levels by setting up two way communications between these two stakeholders. This mid-level stakeholder plays a key role in disaster management, for example dissemination of the forecast to the community level, building awareness and response to flood events. For example, the district relief and rehabilitation officer opined, “We arrange meeting of district disaster management committee by including all the district stakeholders. Resource assessment is important part of the of flood preparedness, which is required for emergency response activities. Therefore, we need to provide information of the available stock and requirement to national level” (Representative from district administrative).

District flood management representative, “I have to take care of hundreds kilometre flood protection embankments which protect communities from flooding. As part of the preparedness action, we collect necessary sandbags, identify weak points in the embankments, prepare contingency plan and deploy people for continuous monitoring of these embankments” (Representative of flood manager).

NGOs representative stated as “We involve in capacity development in local level such as training volunteers and based on the availability of funding we also participate in the emergency support activities during floods.”

The department of agricultural extension, livestock and fisheries services work at sub-national level with the local stakeholders who are involved in agricultural activities, fish and cattle farming. These subnational organizations provide necessary advisories to avoid potential flood damage by taking appropriate early actions based on forecast.

The interviewee responses at the subnational level show that their preparedness work is focused to protect the community from floods and expedite the preparedness activities such as evacuation before floods (taking them to flood shelters), dry foods and medical, support for recovery after floods with the anticipation of flood event.

4.5.1.3 Flood early warning national and sub-national levels users' perspectives

At the national and sub-national levels, all the stakeholders are aware of the existing operational forecasting, particularly the short-range forecast, and they acknowledged the availability of the flood forecast bulletin (Sample bulletin including flood inundation map are in Appendix 5). They also receive the flood bulletin by mail from the FFWC and were able to extract information from the website. Stakeholders have different opinion on the forecast messages in terms of understanding and applying for early actions.

According to disaster manager, "The forecast message contains which rivers are flowing above the danger level and districts are affected by floods. The direction of flood situation for the next few days. Based on this information it difficult to understand flood extent or actual inundation or affected areas as the whole district is not affected by floods. They depend on the sub-national level offices for the ground conditions." (Representative, DDM). These actually limit and delay response activities prior to floods rather need to wait to occur actual floods. The similar limitation of flood warning message was identified by the sub-national level agriculture extension officer "We have network at the union level, and they can disseminate early warning to the farmers at the community level. Therefore, forecast lead-time is important here, to reach community people in advance. And flood inundation depth and expected duration of is necessary for agricultural decisions." (Representative, DAE).

NGOs look for longer lead-time to coordinate with stakeholder and provide assistance at community level, member of Practical Action mentioned that based on the short-range forecast, "they do emergency humanitarian services during the floods. Short-term forecast is not sufficient for preparedness action; as a humanitarian agency, we need to coordinate among the different stakeholders national and international. Current medium range forecast (10 days forecast bulletin) has a lack of uncertainty information" (Representative, Practical Action). The medium range forecast bulletin should contain numerical value of probability information whether river water level cross danger level or not. Only information like "No probability of flooding is forecasted in Brahmaputra basin in the next 7 days", (FFWC medium range forecast bulletin) does not provide uncertainty information. Representative of Forecast based action program of BDRCS mentioned their understanding of uncertainty of probabilistic forecast and they used extended range and short-range forecast for aid distribution. They use GloFAS extended range from GloFAS website using forecast of exceedance of 10 year return period and RIMES medium range with 50% probability for pre-activation of humanitarian actions, while deterministic forecasts to distribute aid among the vulnerability community. He also made interesting point that if flood occurs after 5 or 10 days margin of error which is acceptable for them. Sub-national level users also gave a similar kind of understanding around the accessibility of flood early warnings for flood preparedness decisions. Sub-district level disaster manager, “We got mail every day. It is hard to perceive the impact of the flood from the water level rise or above danger level. We need impact information about whether this area will be affected or embankment breach.” (Representative, local administration).

One of the most important stakeholders is flood managers working at the sub-national level who play important role to disseminate among the other stakeholders at this level. They can translate stream gauge based forecast with the height of the flood embankment and share with the relevant stakeholders at the sub-national level. They are also familiar with the medium range forecast (10 days) and qualitative extended range outlook based on GloFAS/RIMES forecasts from forecasters. It is evident that from the national and sub-national levels interviews that only river stream gauges based water level forecast is not sufficient for taking better decisions in preparedness, and they also need spatial information of floods (detail inundation mapping) along with forecast lead time of flood event for better flood preparedness decisions.

4.5.1.4 Community level impact, preparedness and responses

To understand the community perspective on flood impacts, preparedness and early warnings 200 household surveys have been carried out. During the 2019 flood events the most frequently reported impacts were to houses (45% of respondents) and crops (55% of respondents) (Fig.4.3). The responses indicate a large variety of preparedness activities taken ahead of floods (Fig.4.4). Common activities include the storage of dry food, protection of household goods and movement to safer places (flood shelter or temporary shelter on embankment), protection of livestock and these actions resulted in significantly reduce damage due to floods. These household level early actions mostly depend on visibility (floods water becomes nearer to them or when river becomes bankful) of floods which are linked with short-range lead time of early warning. Though impact on agriculture is high preparedness activities are still limited.

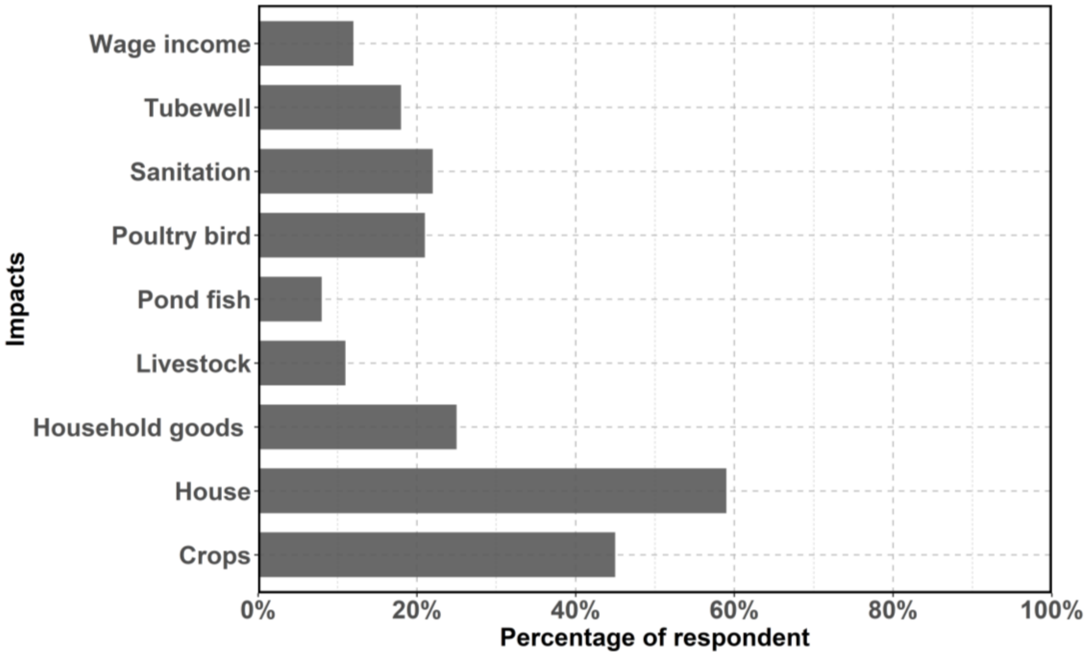


Figure 4.3. Elements or resources reported to have been impacted during the 2019 flood event, based on a survey of 200 households.

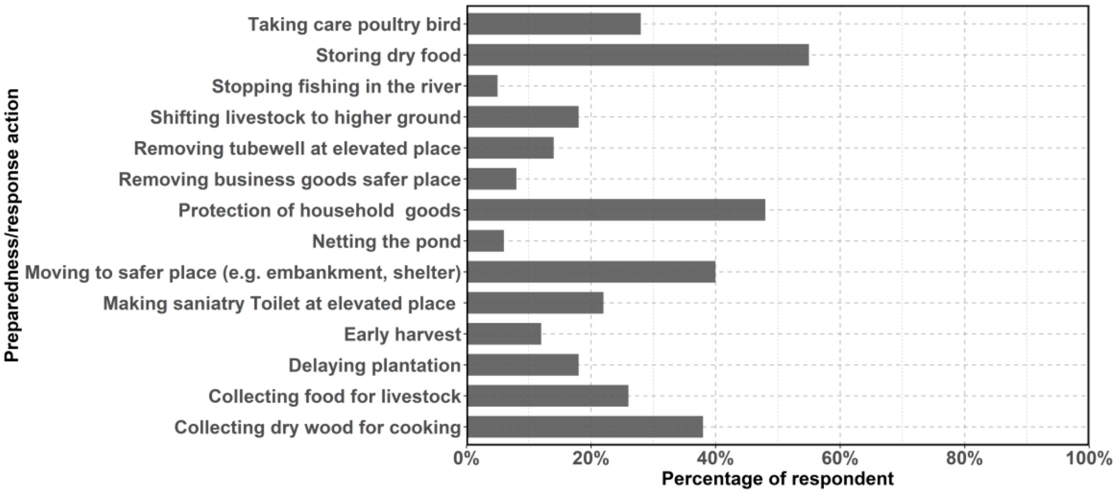


Figure 4.4. Early actions were taken by the community people based on a survey of 200 households.

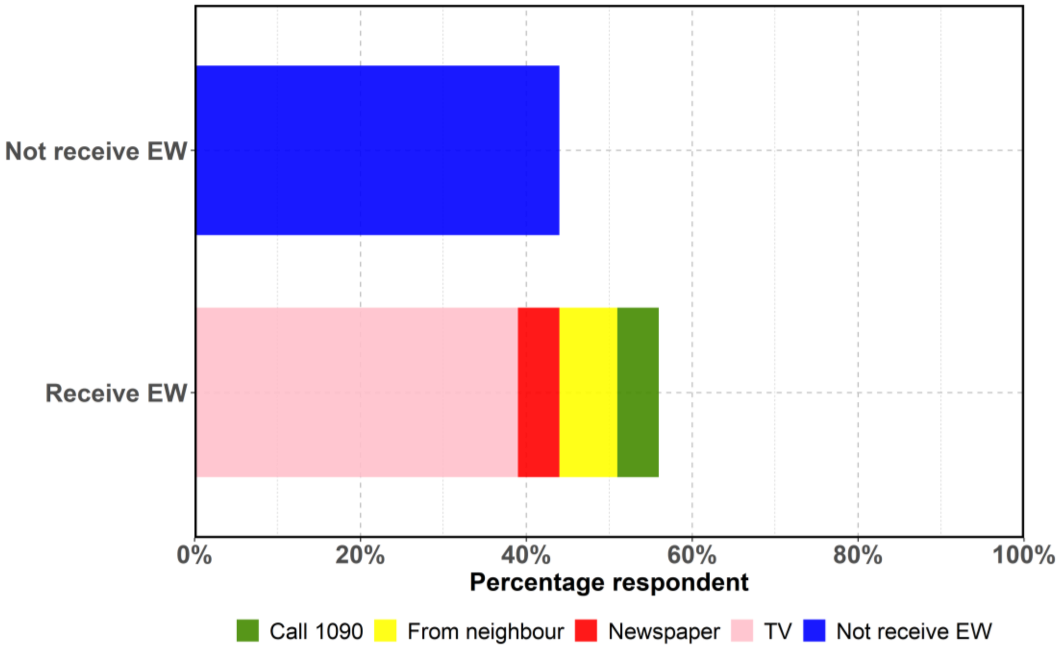


Figure 4.5. Mode by which flood early warnings were received based on a survey of 200 households.

The community people were asked about how they received early warning messages, with 58% people reporting that they received the early warning from different sources with 2 to 3 days ahead of floods (Fig.4.5). During the floods television channels (TV) broadcast flood news which is easily accessible to them and able to learn flood news upstream of their area. Local people informed that TV channels start to broadcast news about floods when an area is affected by floods. A good number of households responded that they got early warning information from neighbours which include school teachers, local religious leader, NGO workers. Pull-based information extraction from website (www.ffwc.gov.bd) is still not fully familiar at the household level except a few educated families. Due to easy access to mobile phone, people started to pull information by calling 1090 to know updated forecast information. This gives pre-recorded short information on floods. During the focus group discussions, community peopled opined their experience of anticipation of floods from local knowledge. “People living near the river anticipate the floods based on their experience such as water level rising trend, cloud movement.” They wait to see the trend of flood water. However, they are not able to anticipate flood duration which is essential for flood preparedness and for crop planning decisions to reduce potential damage (from focus group discussion). The community were not aware about the medium range (1 to 10 days forecast) that FFWC provides with the support from the RIMES. The household survey also revealed that a significant portion of household ~45% did not receive early warning. This might indicate that they were not aware of the early warning system or relied on their own experience.

4.6 Need assessment on early warning

Forecast information needs vary based on the stakeholder’s specific preparedness activities. Various forecast information such as flood timing, flood depth and flood extent are used for early actions. During FGDs, community people emphasised on timing of floods as other two parameters they can guess based on historical floods of the study areas. Community people responded during FGDs how timing is essential for preparedness as they know about the flood season between June to September. They are interested to know in sufficient time ahead “in which month floods will occur”. Table 4.2 summarises list of activities and lead time based on household survey at the community level and focused group discussions, and Figure 4.6 shows percentage of individual respond for lead times that they need for taking early actions. It is evident from the community level study that short-range time useful in response activities primarily household levels, whereas medium to extended range forecast needs mostly for agricultural decisions. Agricultural activities involve preparation of land, sowing of seed, transplantation, harvesting, nurturing of livestock, poultry and fishery. All these agricultural activities require enough time to avoid potential losses due to floods and to support a range of relevant activities. During the FGDs they explained how longer lead time is required for their preparedness actions. For example, the agricultural activities are linked with several relevant decisions from collecting seeds, to preparation of seedbeds, to transplantation. Sometimes farmers need to prepare for floating seedbeds if no higher ground is available particularly in Charlands. Their voice was “we need enough time” before floods for better preparedness”. With the increasing lead-time forecast uncertainty increases and medium to extended range forecast is provided in probabilistic format. Community people were not aware about the medium to extended range forecast in the study area.

During the household survey and FGDs, it was found that people were willing to have probabilistic forecast in their decision making processes. For example, during the FGDs it was asked how they decide on their plantation time as floods are annual phenomenon in the study areas. Flood timing for the transplanted “Aman” is important as suitable time for plantation is between end of July to August. First, if there were no floods in the first half August, then they started to prepared seed beds in higher land, or sometimes without having information they abandon cultivation fearing that floods could occur and damage transplanted crops (depends on nature's wish). "If we get information the probability is low, then we can go for massive cultivation. As flood is annual phenomenon and community people has indigenous knowledge about the floods. Therefore, forecast with the high probability will give them confidence in taking decision" (FGDs discussion). Local NGO representative mentioned that communicating probabilistic forecast could be challenging for communities and forecast bulletin should clearly contain uncertainty information otherwise it might be misleading to them.

Table 4.2. Forecast lead-time and preparedness activities at the community level

Lead time (days)	Preparedness activities
1-5	Household level preparedness (e.g., store dry food, saving money)
5-10	• Selection higher place for livestock • Collect and store fodder for livestock • Netting the pond • Harvest decision
15-20	• Agricultural decisions • Seedbed preparation, transplant to field (From seedbed preparation to transplant)

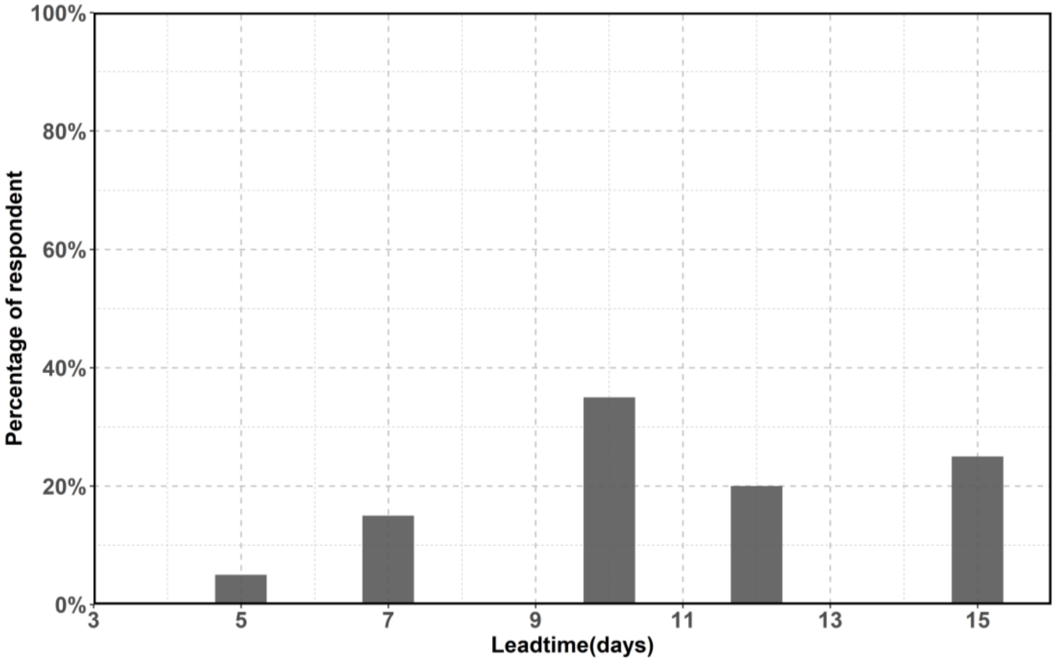


Figure 4.6. Expected forecast lead-time for flood preparedness based on a survey of 200 households.

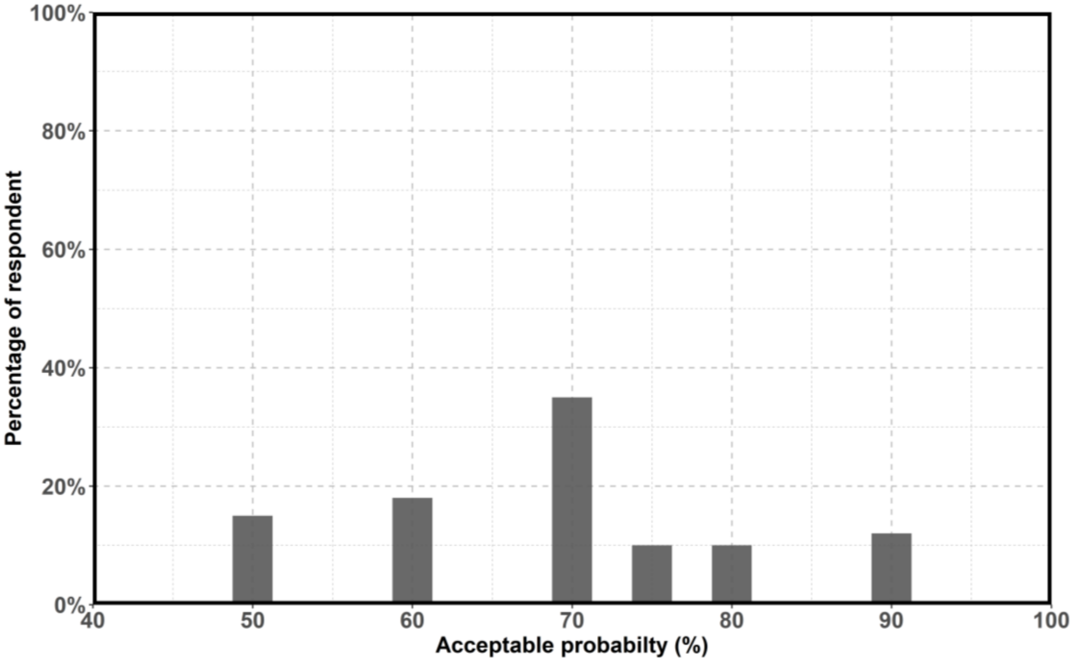


Figure 4.7. Acceptance of probability forecast for preparedness based on a survey of 200 households.

Figure 4.7 shows that community people like to have acceptance of probability forecast starting at 50% probability of a flood event. Maximum 35% of respondents reported 70% probability would lead to make preparedness decisions. However, during FGDs participants expressed their opinion about different forecast probability for decisions. For example, they expected higher probability for evacuation (70% and more) compared to crop planning (50% and more). In the national workshop, it was also given same opinion from the participants that events with 70% probability can be disseminated to the local community for preparedness actions and relatively lower probability around 50% can be shared with the policy makers, so that they can be alerted about the anticipated flood events. The forecast bulletin should contain a specific probability i.e., 70% probability to cross the danger level between the dates. There was also recommendation from the national level to concentrate on the correctness of forecast as frequent false alarm could create mistrust among the users in applying probabilistic forecast. Therefore, forecasters should focus on improving quality of forecast to build confidence across the users.

4.7 Discussions and recommendations

4.7.1 Discussions

In this study, research was undertaken with stakeholders at the three levels–national, sub-national and community levels to understand key users' perspectives on the flood early warning during the 2019 monsoon floods in the Brahmaputra basin.

The Brahmaputra basin is affected by floods annually and people are aware about the flood hazards. However, they are only able to perceive the flood events for a short time i.e., 2 to 3 days. This is consistent with previous study showing that community also depends on current environmental conditions to anticipate floods (Shah et al., 2012). While the official flood early warning is disseminated through different channels, a significant percentage of community are still not aware about the forecast. Users respond to flood warnings by taking various measures during floods based on forecasts or previous experiences. People in the community still depend on local knowledge or understanding even though short to medium-range forecasts are available. These scientific forecasts should be linked with their local knowledge e.g., people from the community can anticipate floods using their own experiences such as cloud movement, wind direction, rising trend of river water level and flood information from the upstream areas for better preparedness before floods. Short-range forecasts have more applicability in response activities at the household level rather than large scale agriculture decisions or humanitarian early actions. This statement was established when stakeholders identified that flood timing is essential for better preparedness. The extended lead time essentially tell them timing of floods, as floods may occur in multiple pulses in the basin between June to September, and timing affects their preparedness such as farmers sowing and harvesting of crops. For example, there were two pulses of floods in the 2017 monsoon both in July and August whereas a single flood event occurred in July during the 2019 monsoon. Both the floods have different types of impact on the community. In July floods are important for harvesting decisions for Aus and Jute crops and floods in August influence on the Aman transplantation. In the absent of forecast, sometimes farmers depend on nature to take future decisions for their agricultural activities. The study shows that all the stakeholders unanimously support for extended range forecast for better preparedness decisions. These extended range forecasts can provide information about anticipated flood duration, which is essential for disaster and flood managers to assess and allocate resources as well as to inform community people for early actions. The advantages of extended range forecast are that it can provide enough time for national to subnational levels stakeholders to perceive the impact of the event and finally, reach the community with early action plans.

Early warning factors such as source of information and mode of dissemination affects user decisions for response actions (Shah et al., 2012). Stakeholders at the high levels i.e., national and sub-national can easily access information from the website and get email regularly from the FFWC and they can also call to the FFWC for further clarification about the events. However, different opinions were found for the community where people receive early warning information mostly from the secondary sources such as neighbours or news media (particularly TV) during the floods as it broadcasts updated information of the ongoing floods. Now, internet is available up to community level and people have access to that information, but forecast information is not fully retrieved at the community level. For example, the medium range forecast (10 days) that is available is still not familiar to the community people. Due to improvements in numerical weather forecasting, now extended range hydrometeorological forecast is available to improve flood early warning in terms of lead-time from medium range to seasonal scale (Emerton et al., 2016). These extended range forecasts are given in the form of probabilistic format i.e., multiple ensemble instead of single deterministic style (Cloke & Pappenberger, 2009a; Demeritt et al., 2007). The probabilistic forecasts are supposed to account for the uncertainties resulting from the chaotic development of the non-linear weather system while ensemble realisations capture the stochastic properties of the forecast precipitation and temperature fields (Arduino et al., 2005). The challenge of ensemble forecast is to effective communication with the stakeholders. The ensemble forecast can be presented in different format: probability (i.e. 75% ensemble members predicts floods), plume or clustering plots (Inness & Dorling, 2012) and users need to be familiar with uncertainties of these forecasts. With the increase of forecast lead time, accuracy decreases (Wilks, 1995), therefore it is essential to be careful accuracy of forecast when issuing forecast. During the interviews, FGDs and national workshop, the stakeholders have raised these challenges of the forecaster providing probabilistic forecasts and made suggestions that forecasts should be communicated in easy and understandable way for decisions avoiding technical terms. For example, ensemble forecast given in range (maximum, mean and minimum) can be understandable to higher level audience and not perceived well by the community.

4.7.2 Recommendations

Based on this study, the following recommendations are suggested for improved early warning from flood preparedness perspective.

a. Capacity development

The flood forecasting centre looks for improvements to the early warning service including extending the forecast lead time. Therefore, capacity development of the centre is essential in terms of technical as well as human resources to generate, understand and communicate the probabilistic forecast. For example, the forecasters need to understand data uncertainties for probabilistic forecast so that they can communicate to the users effectively (Cloke & Pappenberger, 2009a). Similarly, capacity development of other local organizations such local government institutions, extension workers, NGOs that are involved in dissemination of early warning also needs to improve.

b. Early warning dissemination

Dissemination is the most challenging part of the forecasting and must reach people who are at risk for preparedness and response actions (UNISDR, 2006). The extended range forecast provides a longer horizon for providing warning dissemination and preparedness at the community level. Major stakeholders such as agriculture, fisheries, livestock, flood management, disaster management have strong network from national level to community level. This channel could be used for better dissemination of extended range early warning with specific advisory to relevant sectors (Fig.4.8). At the local level each Union Parishad has an Information Technology (IT) centre locally known as “digital” centre plays which can play important role in disseminating early warning. Community people frequently visit this centre for different purposes, and it can disseminate forecasts among the community. Usually, conventional media such as TV get more attention when floods are visible, and people get updated flood information from this news media. However, for extended range forecast i.e.,15-20 days ahead of actual flood event is recommended to disseminate through relevant line stakeholders as well as Union Parishad for effective preparedness. As uncertainty in the forecast cannot be avoided and forecast accuracy decreases with the increase lead-time this poses a challenge (Wilks, 1995), therefore, warning message could split into two time spans i.e., 10 days.

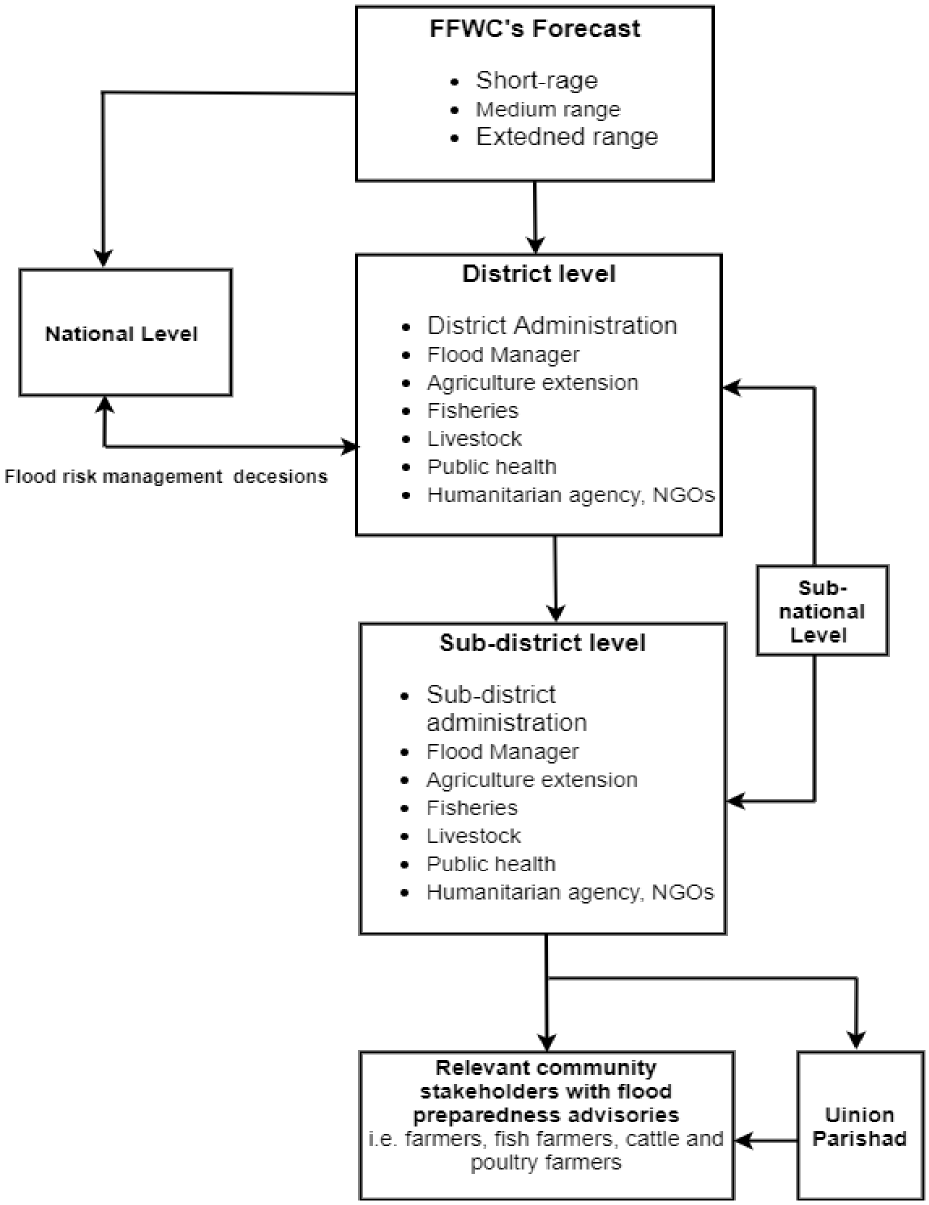


Figure 4.8. Forecast information flow from FFWC to community level through respective stakeholders.

c. *Location specific forecast and impact based forecast*

The FFWC provides forecast based on the river water level whether a particular river gauging station crossed danger level is regarded as floods. A typical forecast message might be, “The river water level in rising trend. The Brahmaputra River at Chilmari and Bahadurabad may cross danger level in next 24 hours. Flood situation in Kurigram, Jamalpur districts may deteriorate in next 24 hours.” Therefore, a translation of the forecast information is necessary for the community for take action and in the absence of more information from the FFWC people try to correlate with the river stage and water level near to their flood plain. Location specific forecast information based on flood inundation is of utmost importance for better flood preparedness. Disaster managers also request such information for their emergency operation.

d. Evaluation forecast skill of extended range probabilistic forecast

The FFWC in Bangladesh is using GloFAS extended range forecast in addition to their operational short and medium range forecast to anticipate flood event. The 2019 monsoon floods were well forecasted by GloFAS in terms of the flood timing and potential duration. This extended range forecast is expected to play an important role in improving flood early in Bangladesh by providing a cross border flow forecast of the transboundary river basins and also as input for the boundary conditions of the hydrodynamic model. It is therefore recommended to evaluate the forecast skill of the extended-range forecast to find false alarm and reliability of GloFAS to build confidence in the usefulness of the forecast model for different stakeholders.

4.8 Conclusions

The study highlighted early warning for flood preparedness from different stakeholders' perspectives based on their responses. The common response approaches to floods (Fakhruddin & Ballio, 2013; Fakhruddin et al., 2015; Paul & Routray, 2010; Shah et al., 2012) are based on inherent natural coping capacity for a historically flood prone country in Bangladesh. However, the community are not fully aware about the early warning beyond a certain lead time hence, responses and preparedness are very limited. Current gauge based forecasts cannot explicitly provide local level flood inundation information to communities who live far away from river gauge. In addition, flood extent mapping is unable to provide inundation information at the community level. Therefore, higher spatial resolution flood mapping is required to provide better inundation forecast to inform community whether they are going to be affected or not. The study findings show stakeholders need extended range forecast for better preparedness. There is also an important aspect in how the forecast is communicated, as it is associated with uncertainty. This is particularly a challenge for the extended range forecast when given a long time horizon. For example, flood peaks may occur one or two days earlier or later than forecasted dates. An extended range forecast which can provide information about flood timing and duration are the most important for flood preparedness perspectives. There are temporal variations of floods annually in the study area and community people need to know the timing and duration, particularly for agricultural decisions. The community needs to be familiarised with the longer lead time forecasts (medium to extended range) to help them understand forecast uncertainties and the potential application for their own flood preparedness decisions. The subnational level stakeholders that directly work with the community can come forward in a regular capacity building process.

The study investigated stakeholders' perceptions— their existing motivations and expectations of flood early warning for their preparedness and response activities. The insight thus gained can be used to design and develop improved flood early warning in Bangladesh focusing on different stakeholders' context. In additional to this, the study will also help policymaker or development workers to project stakeholders' preparedness actions at multiple levels in ahead of floods to reduce potential flood damage. The next step, it is recommended to study the response behaviour of community stakeholders on probabilistic forecast based on some pilot dissemination, that will help to understand the users' actual decision making using probabilistic forecast.

Chapter 5 Evaluation of GloFAS Forecast skill

5.1 Introduction

Global flood forecasts are now available from a few days ahead to the seasonal (Emerton et al., 2016) and can support a variety of anticipatory actions such as evacuation of vulnerable people, management of flood deference structures, crop planning decisions and emergency aid distributions (Coughlan de Perez et al., 2016; Emerton et al., 2020). Scientific and technical changes to the flood forecasting models are regularly implemented in order to improve forecasts. The impacts of these changes on model performance and forecast quality are evaluated with skill assessments to ensure robust system developments and build the confidence of decision makers. However, forecast responses to model changes can be complex in these computationally expensive systems and evaluation of improvements remains focussed on generalised forecast skill and not on the impact of these changes on the different anticipatory decisions being made by a variety of organisations (Cloke et al., 2017).

The Global Flood Awareness System (GloFAS) has been developed jointly by the Joint Research Centre (JRC) of the European Commission and the European Centre for Medium-Range Weather Forecasts (ECMWF) as part of the Copernicus Emergency Management Service (CEMS), to anticipate upcoming floods for river basins all over the world with 30 day lead-time, and the system has been operational since 2011 (Alfieri et al., 2013). Global scale evaluations suggest GloFAS has skill when simulating floods for the large river basins in the world, for example the Pakistan flood of 2010 (Alfieri et al., 2013; Harrigan et al., 2020a) for lead-times 1 to 15 days (Bischiniotis et al., 2019).

GloFAS forecasts are used to support humanitarian decision-making in countries such as Uganda and Mozambique (Coughlan de Perez et al., 2016; Emerton et al., 2020). In Bangladesh, the Flood Forecasting and Warning Centre (FFWC) has been using GloFAS extended-range forecast to predict flood events during the monsoon since 2016. Humanitarian agencies such as the Bangladesh Red Crescent, United Nations Food and Agriculture Organisation (FAO), United Nations Office for the Coordination of Humanitarian Affairs (UNOCHA), United Nations Population Fund (UNFPA) also use GloFAS forecast to support their aid distribution decision at lead-time 10 days before the onset of floods.

There have been several model versions implemented in the GloFAS flood forecasting system since 2011 (Harrigan et al., 2020a). The recent upgrade to version 3.1 included a major change to the modelling approach; GloFAS 3.1 is based on the LISFLOOD hydrological model (Alfieri et al., 2013; Thielen et al., 2012), while GloFAS2.1 was coupled with ECMWF's land surface model HTESSEL (now known as ECLAND) using the channel routing component of LISFLOOD (Wiki, 2021).

For the many different agencies using GloFAS in Bangladesh it is important to understand how the implementation of GloFAS3.1 affected the ability to predict floods in the Brahmaputra basin, and how it might change the robustness of any early action decisions required for flood preparedness. To address these, the objectives of this research are as follows:

(i) Understand any differences in simulated flood behaviour in GloFAS2.1 and GloFAS3.1 in terms of flood magnitude and the rise and decay of the annual flood wave.

(ii) Evaluate forecast skill against lead time for GloFAS2.1 and GloFAS3.1 with and without lead-time dependent thresholds (Zsoter et al., 2020) against the bankfull threshold (90th percentile).

(iii) Evaluate forecast skill for different flood preparedness decisions considering several thresholds of impact based on observed river discharge and water level.

This study aims to achieve these objectives by using GloFAS reforecasts and observed data from the Bahadurabad river gauging station on the Brahmaputra River in Bangladesh. The Kling-Gupta Efficiency (KGE) was used to study model performance and False Alarm Ratio (FAR) and Probability of Detection (POD) were calculated to investigate forecast skill considering different early action decision criteria such as lead-time, flood thresholds, forecast probability and acceptable margin of error.

Note[3]

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[3] An article has been published in the special issue of Flood Risk management Journal. The abstract of the article has been provided in appendix 2.

5.2 GloFAS flood forecast system

GloFAS provides operational (real-time) forecasts daily for the whole world at 0.1° resolution and with 51 ensemble members (Harrigan et al., 2020a). Forecasts are made freely available through a web interface, with different forecast layers available including the probability of exceeding different return period flows out to 30 days. GloFAS uses global scale numerical weather predictions and a hydrological model to generate flood forecast information. Daily meteorological forcing is provided from the Integrated Forecasting System (IFS) ensemble of the ECMWF weather forecasts, with 51 ensemble members (50 perturbed and 1 control simulation) with variable grid resolution; ~18 km and ~36 km horizontal resolution for up to 15 days and 16 to 30 days respectively (Alfieri et al., 2013; Harrigan et al., 2020a). To initialise the hydrological simulation, GloFAS uses ERA5 reanalysis river flow data along with the first day of the control member of the ECMWF ensemble forecasts (Fig. 5.1).

In GloFAS2.1 (and previous versions) the hydrological component consists of ECMWF's land-surface scheme ECLAND (previously known as HTESSEL) (Balsamo et al., 2009; Pappenberger et al., 2010) coupled to a spatially distributed hydrological river routing model (Van Der Knijff et al., 2010) (Fig. 5.1a). The surface and sub-surface runoff are generated from ECLAND while LISFLOOD performs ground water mass balance and river flow routing. On 26 May 2021 the GloFAS operational system was upgraded to version 3.1, using a fully configured LISFLOOD model (both surface and routing components) instead of the coupled ECLAND / LISFLOOD approach (Wiki, 2021) (Fig. 5.1b). The LISFLOOD routing and groundwater model parameters were calibrated in GloFAS2.1 using daily observed streamflow data from 1287 stations over 795 catchments worldwide (Hirpa et al., 2018). However, the calibration did not cover the Indus, Ganges or Brahmaputra River basins in South Asia. The LISFLOOD hydrological model adopted for GloFAS3.1 is calibrated across more catchments (1226 river basins), including the Ganges and Brahmaputra) (Alfieri et al., 2020).

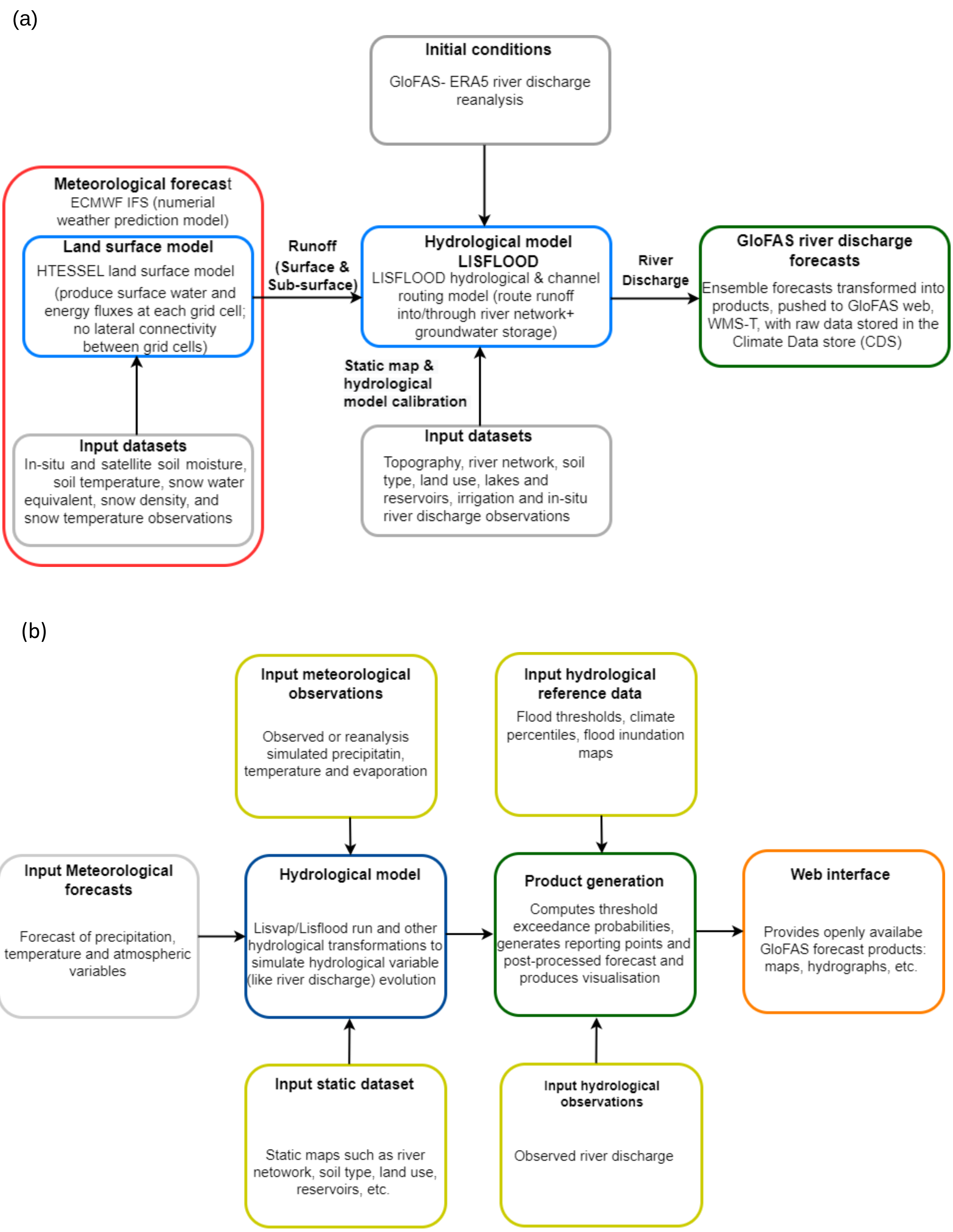


Figure 5.1. Schematic of GloFAS 30-day flood forecast system (a) version 2.1 (Harrigan et al., 2020a) and (b) version 3.1 (GloFAS, 2021).

5.3 Data

Forecast datasets from two different model versions were compared against observed river discharge (both direct and derived) and water level observations at Bahadurabad on the Brahmaputra River.

5.3.1 Observed river discharge and water level data

River discharge and daily water level were collected from the hydrological division of the Bangladesh Water Development Board (BWDB) at the Bahadurabad gauging station on the Brahmaputra River in Bangladesh. This station is the only discharge measurement stream gauging station of the Brahmaputra River inside Bangladesh and has a long record of water level and discharge data. The water level at is collected manually every 3 hour interval five times in a day, starting from morning 06.00 AM to 06.00 PM with no data at night. River velocities and cross-sections are measured by BWDB usually twice in a month. Daily discharge is calculated using a rating curve. Prior to 2016 river discharge was calculated using observations from a current meter, but since this date velocity observations are collected with an Acoustic Doppler Current Profiler (ADCP).

5.3.2 Flood forecast data

Reforecasts for each model version (GloFAS2.1 and GloFAS3.1) are available for a common period from 1999 to 2018. These provide forecast data from a consistent model version and a long time period which is required for robust system evaluation (Harrigan et al., 2020a). GloFAS reforecasts are produced twice per week on Monday and Thursday respectively, using ECMWF weather reforecasts and initialised by ERA5 reanalysis flow (Harrigan et al., 2020b). Reforecasts are available for a long time period (20 years) but with only 11 ensemble members instead of 51 up to 30 days lead-time at daily time step due to computational constraints (Harrigan et al., 2020a).

5.4 Methods

The study approaches are divided into three parts. First, evaluation in the changes in simulated flood behaviour between GloFAS2.1 and GloFAS3.1 with respect to observed river flow were carried out. Then, forecast skill is assessed by calculating FAR and POD with and without applying lead time dependent correction. Finally, the forecast skill is evaluated against decision-making criteria for GloFAS2.1 and GloFAS3.1.

5.4.1 Comparison between observed and simulated floods

The ability of GloFAS2.1 and GloFAS3.1 to simulate flows in the Brahmaputra River is compared. Model performance is assessed using the Kling-Gupta Efficiency (KGE) (equation i) which includes three components: correlation, variability, and bias (Gupta et al., 2009; Kling et al., 2012) and is well used as objective function for hydrological model calibration and evaluation (Knoben et al., 2019; Liu, 2020).

$$KGE = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(i)}$$

$$\beta = \frac{\mu_{sim}}{\mu_{obs}}, \; \alpha = \frac{\alpha_{sim}}{\alpha_{obs}}$$

where r represents the correlation between observation and simulation, β is the bias ratio and α is the flow variability ratio. The optimal value for these components is 1. Here, α_{obs} and α_{sim} are the standard deviation in observation and simulation, whereas μ_{sim} and μ_{obs} are simulation and observation mean respectively. A KGE equal to 1 indicates perfect agreement between simulation and observation, while KGE< 0 indicates that the mean of observation provides a better estimate than the simulation (Castaneda-Gonzalez et al., 2018; Koskinen et al., 2017).

The KGE is decomposed into its three components to assess linear correlation, model bias and variability error of two reforecasts data sets against observed discharge for lead-time 1 to 30 days. The linear correlation (r) identifies any linear relationship between observed and simulated discharge (Moriasi et al., 2007) but is sensitive to outliers (Legates & McCabe Jr., 1999). The Bias ratio (β) of the KGE can be converted to percent bias (Pbias) by $(\beta - 1) * 100$ (Harrigan et al., 2020b) and provides information on model overestimation or underestimation. The variability ratio (α) is used to measure relative variation of simulated and observed flow (Gupta et al., 2009), and α >1 indicates more variability in the simulated results than in the observed data. Assessing all these three components together is important to understand how effectively the model represents the real world.

Flow duration curves are used to explore the temporal distributions of river flow in the reforecasts, and examine the duration of extreme flow above 90th, 95th and 99th percentiles. Three different lead times were selected that are relevant for early action: shorter lead-time (5 days), medium-range lead-time (10 days), and extended-range lead-time (15 days). The annual cycle of the observed and simulated floods are examined through the long-term mean for each of these three lead-times to provide a comparison of how the simulations capture the rise and decay of the annual flood wave.

5.4.2 Forecasting skill for observed flood events

The objective of GloFAS is to provide early information on flood events and bias in the magnitude of flows is acknowledged but not considered to be problematic. This is because GloFAS adopts an approach whereby flood threshold exceedance probabilities within GloFAS are calculated based on simulated flows, with the assumption that when a GloFAS forecast indicates that the simulated 1 in 5 year flow (20% annual exceedance probability of annual maximum flow) threshold will be exceeded this corresponds to a real-world 1 in 5 year flow threshold exceedance. For instance, for the Brahmaputra River at the Bahadurabad gauging station the 1 in 5 year observed flow is 75,000 $m^3 s^{-1}$ based on GEV fit of annual maximum flow whereas the 1 in 5 year GloFAS threshold is 93,000 $m^3 s^{-1}$. Given this, any evaluation of the GloFAS forecasting skill also needs to follow this approach. Any evaluation of model performance should consider specific thresholds which classify flood events i.e., flow above a threshold. In this study, assessment of GloFAS skill is done using a threshold of bankfull discharge (90th percentile which is considered as 2 year return period flow) as defined by the FFWC. Operationally, the FFWC declares floods if a forecast exceeds this threshold at the Bahadurabad gauge. This provides a decision-relevant threshold while also giving a large enough sample to conduct a robust evaluation.

To undertake the evaluation river discharge is considered a dichotomous variable (yes or no events) and a 2x2 contingency table is calculated depending on whether the above threshold is met (Table 5.1). The GloFAS forecast skill was evaluated for lead-times from 1 to 30 days from 1999 to 2018 using a 50 % forecast probability that river discharge exceeded the 90th percentile on a particular day. Based on the contingency table, the probability of detection (POD) (equation ii) and false alarm ratio (FAR) were estimated (equation iii), similar to (Bischiniotis et al., 2019; Passerotti et al., 2020). POD gives the percentage of flood events that are forecasted, whereas FAR provides the percentage of forecasted floods where no flood is observed.

Table 5.1. Forecast contingency table for yes/no dichotomous method

		Observed		
		Yes	No	Total
Forecast	Yes	Hits	False alarms	Forecast yes
	No	Misses	Correct Negative	Forecast no
Total		Observed yes	Observed no	Total

$$POD = \frac{hits}{hits + misses} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(ii)}$$

$$FAR = \frac{false\ alarms}{hits + false\ alarms} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(iii)}$$

In the operational uses of both GloFAS 2.1 and 3.1 the thresholds are kept static across all lead times, but Zsoter et al. (2020) found an improvement in forecast skill by taking into account how the thresholds changed for each lead time. Within this study, GloFAS forecast skill for each model version was calculated using lead time dependent thresholds similar to Zsoter et al. (2020).

5.4.3 Decision-led flood forecast evaluation

Different flood preparedness decisions have different requirements for acceptable forecast skill. A decision-led evaluation were performed by taking into account the following requirements for different decisions: (a) flood threshold both for discharge and water level, (b) lead-time, (c) forecast probability for trigger early action and (d) margin of error (how much later the flood can arrive, and it still count as a ‘hit’). Different acceptable thresholds were selected for each criterion based on consultation with the key stakeholders (Table 5.2), including humanitarian organizations, government agencies working for disaster and flood management and the local community in flood vulnerable areas.

There is a wide range of lead-times for the decisions, from 3 days for the evacuation of people to a flood shelter through to 15 days for humanitarian organisations and 18 days for agricultural planning decisions. Short margins of error for the evacuation of people and livestock reflect the impact that extended time away from their livelihoods will have, whereas larger margins of error are acceptable for humanitarian agencies because the aid will still have a benefit even if the flood arrives later. Likewise, the acceptable FAR for evacuations is lower than for humanitarian operations because of concerns over maintaining trust in the forecast in the long-term. The forecast evaluation framework used in this study has been presented in Figure 5.2.

Table 5.2. Decision-led criteria for forecast evaluation

Decision number	**Decisions**	**Lead-time (days)**	**Flow Threshold (percentile)**	**Acceptable delay in flood timing (days)**	**Acceptable False Alarm Ratio (FAR)**	**Acceptable Probability of Detection (POD)**
d1	Evacuation of flood vulnerable people to flood shelter (people on relatively higher land)	3	99th	2	0.30	0.60
d2	Evacuation of livestock to safe place (livestock on relatively higher land)	4	99th	2	0.30	0.60
d3	Evacuation of flood vulnerable people to flood shelter (people on low lying *Char Island*)	3	95th	2	0.30	0.60
d4	Evacuation of livestock to safe place (livestock on low lying *Char Island*)	4	95th	2	0.30	0.60
d5	Household level preparedness (protecting household goods- wrapping and shifting to a safer place, storing dry foods, collecting, and saving money, storing cooking wood)	2	95th	2	0.30	0.50
d6	Pre-activation trigger for aid distribution by humanitarian agencies	15	99th	10	0.50	0.50
d7	Communication flood preparedness and response decisions of the Government agencies such as disaster management, flood management, agriculture extension at national and sub-national levels. Key decisions include for flood management– preparation of contingency plan, identification of weak points in the embankments, collecting of necessary sandbags and deployment people for continuous monitoring of flood protection embankments	10	95th	3	0.50	0.50
d8	Agriculture (aman rice) planning decisions by farmers (seedbed preparation to transplantation in field)	18	95th	7	0.50	0.50

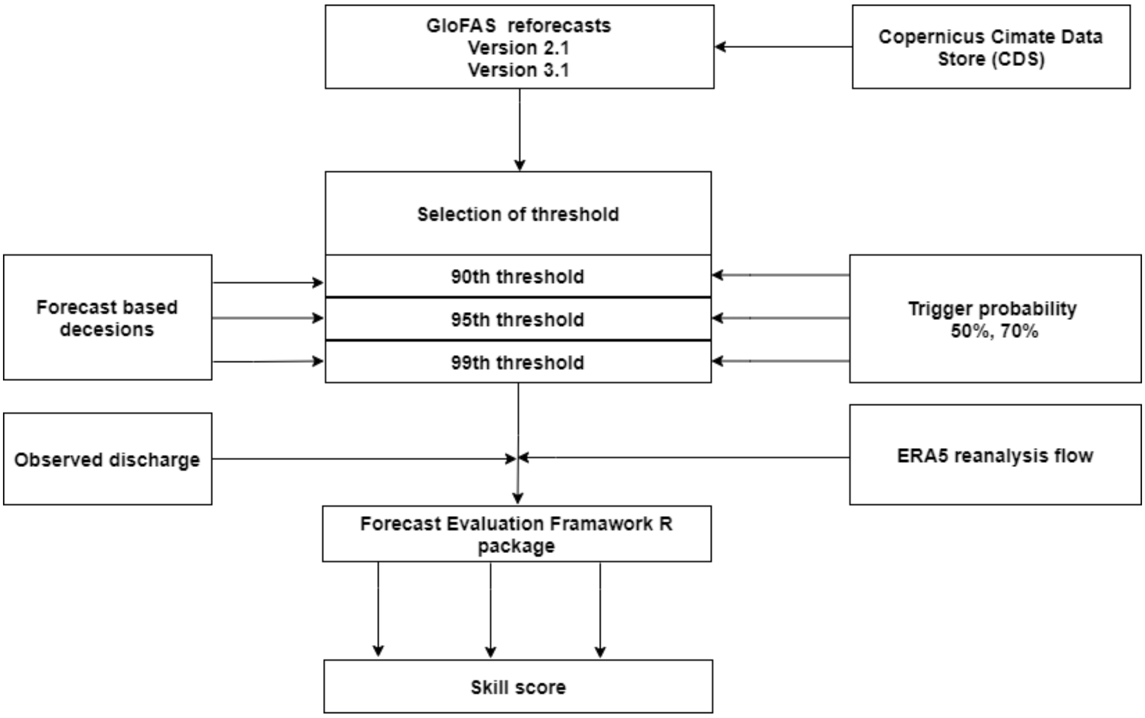


Figure 5.2. Forecast evaluation framework used in this study.

5.5 Results

First, a comparison of simulated flood behaviour in the GloFAS model versions is presented at different lead-times compared to the observed river flows. Then, evaluation of the forecast skill for different lead-times and decision perspectives are carried out. From this point, for ease of reading, v2.1 and v3.1 are used for GloFAS 2.1 and GloFAS 3.1, respectively.

5.5.1 Comparison between GloFAS reforecast version 2.1 and 3.1 with observed river flow

v2.1 shows better performance than v3.1 for the KGE and all its three components (Fig. 5.3). KGE values range from 0.68 to 0.81 for v2.1, and 0.52 to 0.64 for v3.1 over lead-times of 1 to 30 days. Interestingly, the KGE values demonstrate improvements in performance at longer lead times, especially in v2.1, driven by improvements to the variability and bias components.

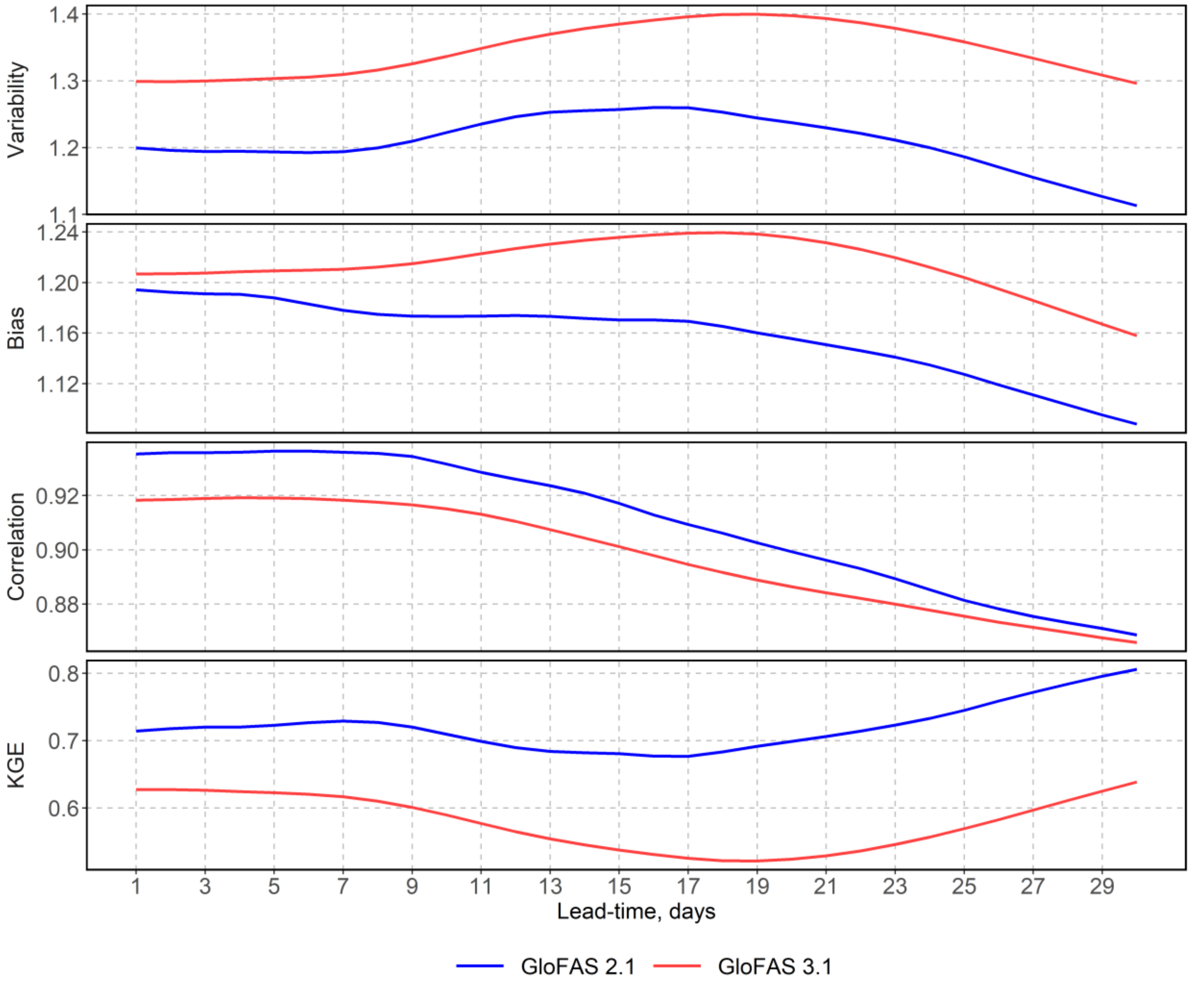
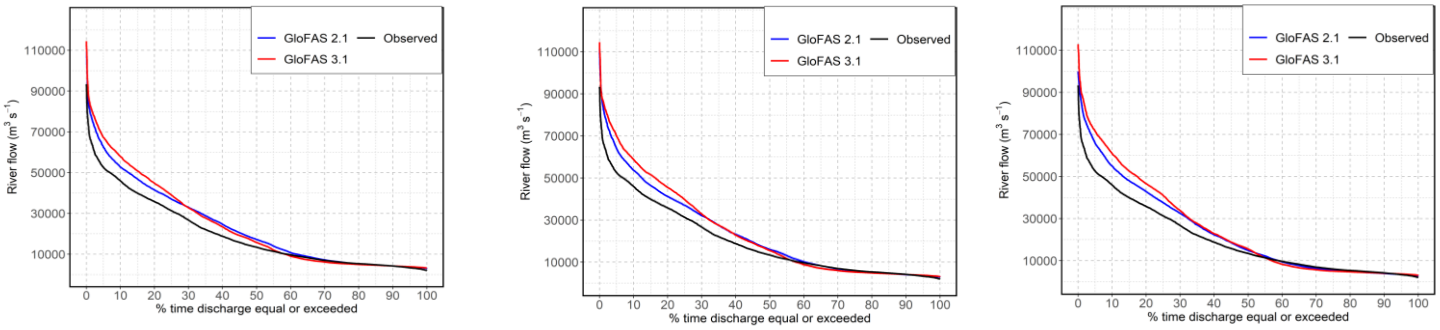


Figure 5.3. Evolution of KGE and its three components: variability, bias and correlation across lead-times 1 to 30 for GloFAS 2.1 and GloFAS 3.1 compared to the observed data for Bahadurabad gauging station on the Brahmaputra River.

The bias component of the KGE shows that bias changes with lead-time, with average positive percent bias 16% and 21% in v2.1 and v3.1, respectively, meaning that flow is being overestimated. Bias in v3.1 increases with lead-time before dropping from lead-time 18 days onwards, whereas in v2.1 the bias reduces with lead-time. For a global model, bias ±20% is considered acceptable (Lin et al., 2019) and ±25% is also measured as a good model simulation (Khoshchehreh et al., 2020). Here, the maximum positive bias in v2.1 and v3.1 is 19% and 24%, respectively.

The variability component of the KGE in both v2.1 and v3.1 is higher (variability ratio >1) than the observed discharge for all lead-times (1 to 30 days). In both v2.1 and v3.1 the variability increases from day 7 and falls again from day 17 (v2.1) and day 19 (v3.1). The percent variability has greater differences between versions than the bias, with mean values in v2.1 and v3.1 of 21% and 35%, respectively. The correlation component of the KGE score shows that simulated and observed discharge are strongly correlated for both versions of GloFAS (r> 0.87). This is perhaps unsurprising given the strong seasonal cycle. The correlation varies from 0.94 to 0.87 in v2.1 (above 0.9 for 19 days), while it ranges from 0.92 to 0.87 in v3.1 (above 0.9 for 15 days). Whereas the percent bias describes an overall bias in the model, the flow duration curves (Fig. 5.4a-c) can indicate where in the flow duration curve any bias is located. In this case the flow duration curve shows that the observed wet biases in the KGE are connected to the upper tail of the flow duration curve. For the behaviour in the annual cycle (Fig. 5.4d-f), the rising-limb and peak flow are overestimated while flows in the decaying phase of the annual cycle are underestimated.

(a) 5 day lead-time (b) 10 day lead-time (c) 15 day lead-time



(d) 5 day lead-time (e) 10 day lead-time (f) 15 day lead-time

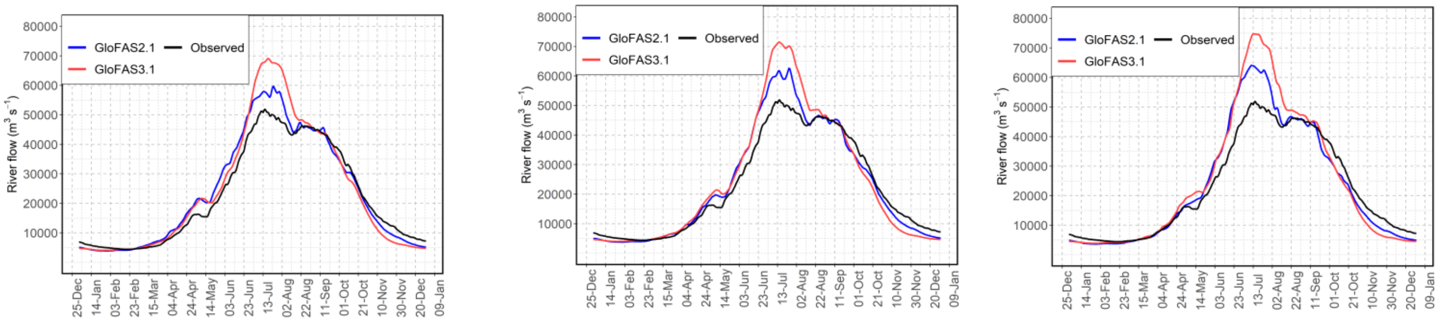


Figure 5.4. Flow duration curve of GloFAS reforecasts v2.1 and v3.1 and observed river flow (a) 5 day lead-time, (b) 10 day lead-time and (c) 15 day-lead-time. Horizontal dashed green, orange, and red lines are 90th, 95th and 99th percentile flow respectively of the Brahmaputra River. Annual cycle of

observed flow and the GloFAS reforecasts v2.1 and v3.1 for lead-time, (d) 5 lead-time day, (e) 10 day lead-time and (d) 15 day-lead-time based on long-term mean 20 year from 1999-2018. Blue, red and black lines are GloFAS v2.1, v3.1 and observed, respectively.

5.5.2 GloFAS flood prediction skill with lead-time

For forecasts of bankful discharge threshold (90th percentile) the FAR and POD increase and decrease respectively with increasing lead time, in line with an expected deterioration in forecast skill with longer lead times (Fig. 5.5). The FAR in v2.1 is lower than for v3.1 across all lead times and in both uncorrected and lead-time corrected versions (Table 5.3). For POD, all model versions show a similar result out to about 8-10 days, but beyond that the POD is higher for v3.1 (uncorrected). The lead-time correction provides improvement (reduction) in the FAR (0.43 to 0.4) for v3.1 from a lead-time of 11 days onwards (Table 5.3), but this is mirrored by a degradation (reduction) in the POD (0.67-0.6). A similar trend in FAR and POD is found for the 95th percentile threshold with slightly higher FAR and lower POD compared to 95th percentile threshold (Fig 5.5 c-d). Acceptable FAR is found below 0.50 for lead time up to 13 days in v2.1 and after applying correction, it is found improvement in FAR up to 19 days in version 2.1 (Fig 5.5c). Similarly, FAR improves for lead time above 10 days in v3.1 after applying correction (Fig. 5.5 c). At higher lead time (>15 days) POD improves in version 3.1 compared to v2.1 (Fig 5.5d). However, for extreme thresholds 99th percentile models performance is not consistent and behaves erratically which may be due to low number of observed events (Figure 5.5 e-f). The lead time correction accounts for changes in the bias of the models at different lead times (Fig. 5.5a-d), with the increase in FAR and POD for longer lead times in v3.1 likely to be due to the larger bias in the model at these longer lead times. The lead-time corrected models show similar skill to uncorrected for shorter lead-time e.g., 5 days as suggested Zsoter et al. (2020).

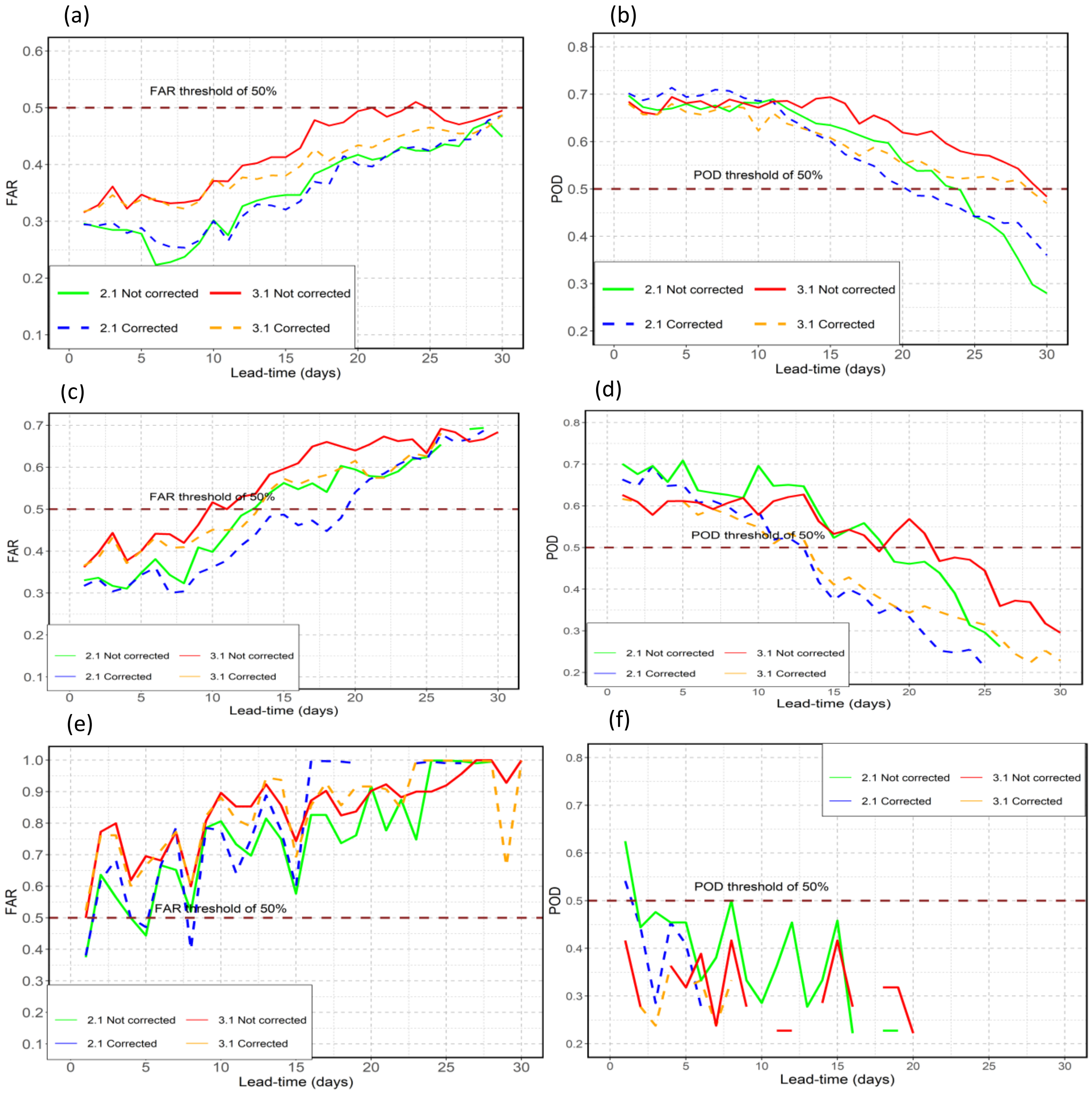


Figure 5.5. FAR and POD GloFAS v2.1 and v3.1 reforecasts for lead-time 1 to 30 days for 90th, 95th and 99th percentile threshold discharge at 50 % forecast probability (a) FAR at 90th percentile, (b) POD at 90th percentile, (c) FAR at 95th percentile (d) POD at 95th percentile, (e) FAR at 99th percentile and (f) POD at 99th percentile. Green and blue colour lines are for v2.1 and red and orange colours are for v3.1 for both FAR and POD. Dashed lines represent lead-time dependent correction for FAR and POD while solid lines are not corrected FAR and POD. The horizontal brown dashed line shows the 50 % threshold for FAR and POD.

Table 5.3. Average FAR and POD for different lead-time clusters at threshold 90th percentile

Leadtime (days)	Lead-time - not corrected v2.1		Lead-time corrected v2.1		Lead-time - not corrected v3.1		Lead-time corrected v3.1	
	FAR	POD	FAR	POD	FAR	POD	FAR	POD
1-10	0.2	0.68	0.28	0.70	0.34	0.68	0.34	0.70
1-15	0.29	0.67	0.29	0.68	0.36	0.68	0.35	0.70
11-20	0.36	0.63	0.34	0.59	0.43	0.67	0.40	0.60
21-30	0.44	0.44	0.44	0.45	0.49	0.57	0.46	0.50

5.5.3 Forecast skill for preparedness decisions

In this final section of the analysis, a decision-led analysis of forecast skill is presented in the two GloFAS model versions against the criteria for each decision as presented in Table 5.2. In Figure 5.6, where FAR and POD values inside the shaded box then the skill is sufficient for that decision. The same analysis but against water level rather than discharge is provided in Figure 5.7. Note that for these decisions, the evaluation also includes evaluation against the 95th and 99th percentile river flows and water level. Results show that using GloFAS for decisions d1 and d2, which support evacuation of people and their livestock living in areas of relatively higher land is not feasible with either v2.1 or v3.1. Similarly, the pre-activation of humanitarian action before floods at 99th percentile threshold and 15 days lead-time is also not feasible with either version (d6, Fig. 5.6a and 5.6b). The decisions for the low-lying *char* Islands (d3 and d4) are feasible using both v2.1 and v3.1, as are the longer lead time actions of communication to government agencies and agricultural planning decisions (d7 and d8). Household level preparedness actions (d5) are feasible in v2.1, but not in v3.1 due to a slightly higher FAR than acceptable limit.

The evaluation against water level provides a more relevant assessment of whether the system can forecast impact. For v2.1 the results are similar to the evaluation against discharge (Fig. 5.7a), but there are differences for v3.1, with d3 and d4 no longer feasible (Fig.5.7b). The decision maker could choose any forecast probability as a threshold provided that the FAR/POD score lies within the shaded box. For longer lead times a larger spread in the ensemble means that the choice of probability threshold makes a larger difference than for shorter lead times when the spread is small.

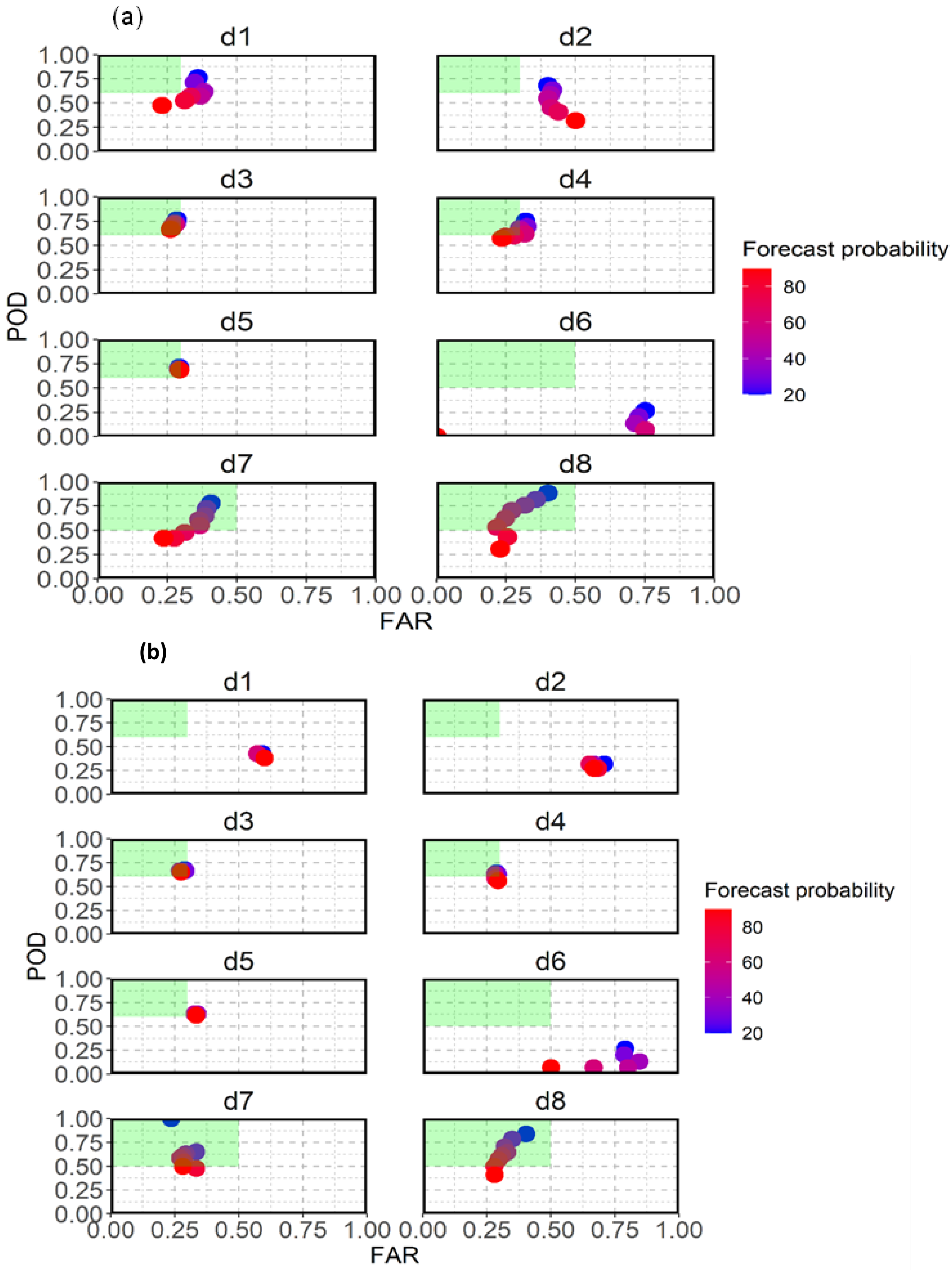


Figure 5.6. FAR and POD for each forecast probability and each decision based on discharge threshold for (a) GloFAS v2.1 and (b) GloFAS v3.1 (both using lead-time dependent thresholds). Where forecast falls inside the shaded box, the forecast meets the skill requirements for each decision d1 to d8 (details of the decisions are provided in Table 5.2).

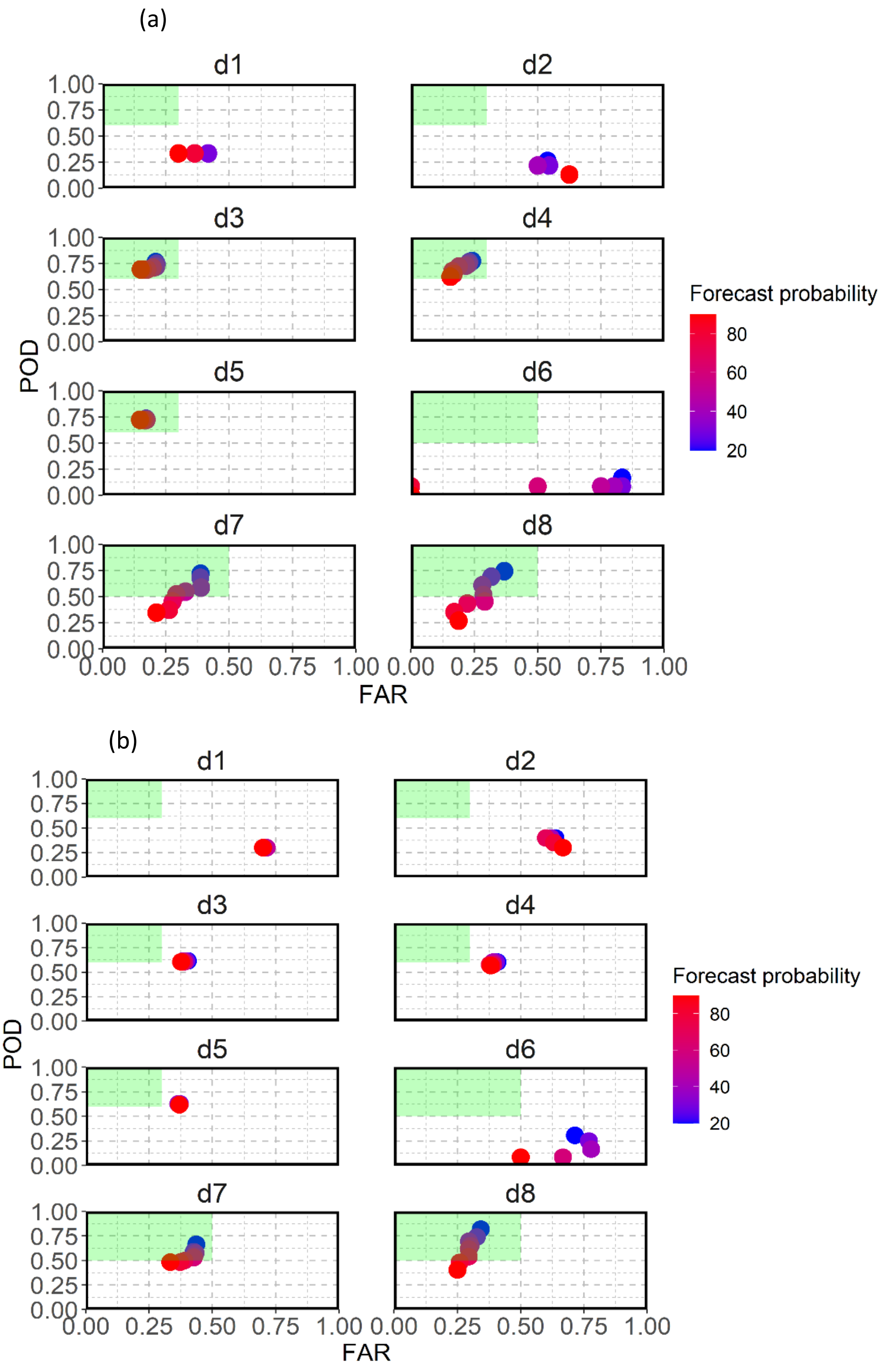


Figure 5.7. FAR and POD for each forecast probability and each decision based on water level threshold for (a) GloFAS 2.1 and (b) GloFAS 3.1. Where forecast falls inside the green box, the forecast meets the skill requirements for each decision d1 to d8 (details of the decisions are provided in Table 5.2).

5.6 Discussions and recommendations

5.6.1 Discussions

This study provides an evaluation of the skill of the two most recent GloFAS model versions, v2.1 and v3.1, for the Brahmaputra River in Bangladesh, based on observations for the period from 1999 to 2018. The evaluation includes (a) the model's capability to simulate observed river discharge, (b) predicting skill for flood events and (c) forecasting skill for different early action decisions based on specific criteria.

Both GloFAS v2.1 and v3.1 perform relatively well in that they simulate the hydrological behaviour of the Brahmaputra River with a KGE higher than 0.50 for all 30 days lead-time (considered acceptable as per (Franco et al., 2020; Khoshchehreh et al., 2020)). v2.1 performs better than v3.1 with respect to all three components of KGE such as bias, variability and correlation. Analysis of the bias shows that flows are somewhat overestimated in v2.1 and v3.1. The variability component of the KGE, which measures the differences in standard deviations of flows between simulated and observed was higher in v3.1. However, both versions have a strong correlation ($r>0.8$) with the observed discharge, though this is largely indicative of the model being able to simulate the annual cycle. This aligns with previous work which found that GloFAS shows higher correlation for catchment areas greater than ten thousand square kilometres, with this correlation increasing with the upstream area (Alfieri et al., 2013). The flow duration curves and annual cycle show an overestimated discharge with potential timing error on the rising limb of the flood wave, with higher bias in v3.1 than v2.1.

Through the use of a threshold-based approach, biases are accounted for when it comes to decision-making in GloFAS (i.e., by taking the 95th percentile of simulated flows and comparing to the 95th percentile of observed flows). However, variations in the timing of the flood wave will impact forecast skill scores. The analysis shows that GloFAS is able to predict flood events above the FFWC-defined danger level (90th percentile) on the Brahmaputra River out to 30 days ahead, with a FAR of less than 50%. Out to around 10 days lead time the GloFAS performance is consistent with little change over lead time in POD and FAR forecast skill scores for both v2.1 and v3.1. This is expected, since for a large river basin changes in discharge occurs at a slow rate and stream flow prediction does not change substantially for lead-time 1-10 days from a forecast of persistence (Alfieri et al., 2013).

The use of lead time dependent thresholds improves FAR while decreasing POD, especially at longer lead times. The use of lead-time dependent thresholds is a method of accounting for the change in bias with lead-time, therefore is expected that a positive change in FAR would lead to a negative change in POD, and vice versa.

Different stakeholder decisions for early action require different flood magnitude thresholds, lead times, and criteria for acceptable forecast skill. Of the 8 decisions evaluated in this study, 5 were feasible when using GloFAS v2.1 and 4 for GloFAS v3.1. Counterintuitively, because the decisions made at longer lead times had less stringent criteria for forecast skill, these were the decisions that were feasible, and not the shorter lead time decisions such as evacuation.

5.6.2 Recommendations

Based on this study, the following recommendations for model developers and users to improve further development and application for better decisions.

Model development perspective

There are clear differences between versions 2.1 and 3.1 in terms of simulated discharge as well as flood forecast skill. Though both model versions are predicting the normal flood thresholds (90th percentile) with acceptable skill; for extreme floods there are more false alarms in v3.1 which limit the usability of the forecast. Therefore, more model development effort is required to improve model skill for extreme floods at shorter lead-times, for example to support evacuation. The web interface of GloFAS v3.1 includes model performance (KGE) and forecast skill Continuous Ranked Probability Skill Score (CRPSS), and this evaluation is against benchmarks of persistence and climatology forecasts (ERA5 reanalysis discharge 1979-2018) (Harrigan et al., 2020a). This is less useful for decision-makers, and so a recommendation that in addition FAR and /or POD should be added so that potential users have the opportunity to look at relevant performance indicators before use. To develop the confidence of users in new version, it is necessary to test models with historical observed floods before new version is implemented operationally. Developers of global forecast models should collaborate with national hydro-meteorological organizations and in-country partners to ensure that decisions that are being made are still robust when using new model version.

Application for improving forecast lead time in Bangladesh

Increasing the lead time of skillful forecasts is a challenge in a transboundary basin where major flows come from upstream catchments where there may be limited access to upstream hydro-meteorological information. Skillful global models provide a source of forecast information for such transboundary river basins. GloFAS is able to predict normal floods (90th percentile) at short to medium range (1 to 10 days) and extended range (11 to 30 days) time scale with a FAR <0.5. Models also show acceptable forecast skill for medium threshold floods (95th percentile) for a reasonable lead time maximum 20 days. For thresholds low and medium thresholds floods, there is also an indication of improvement in skill by applying lead-time dependent thresholds. Overall, both the model versions show acceptable forecast skill to anticipate flood events with short to extended range lead-time for low to medium range floods which can support a wide range of decisions ahead of extreme flooding events. This can help in capacity development of national flood forecasting centre to improve lead time.

Recommendation for decision makers

Decision makers must find a balance between the acceptable number of missed events and false alarms. For a global forecasting system, a new model version poses a challenge because overall improvements in skill do not necessarily mean that the same skill changes are seen in individual river catchments. In this case, the update from v2.1 to v3.1 limits the number of decisions that can be made from GloFAS in the Brahmaputra basin, especially at shorter lead times. In this case, FFWC forecasts are available at these lead times, but working closer with GloFAS developers allows issues with the model to be dealt with more efficiently.

5.7 Conclusions

Model upgrades take place as part of a continuous cycle of developments and updates. The upgrade to GloFAS3.1 included the use of a stand-alone hydrological model instead of previous coupled land-surface and hydrological routing components; a significant change. The relevance of changes in forecast skill following this upgrade becomes clear when evaluating against specific decisions. Decision-based evaluation of a forecast model aims to look at forecast performance from the perspective of different early action decisions that are being taken. In this study the forecast skill of two versions of GloFAS is assessed by using 20 years of reforecast data, and with and without the use of lead-time dependent thresholds.

Although the new v3.1 has been calibrated for the Brahmaputra River by GloFAS developers, there is no improvement in the skill of simulated flow compared to the previous version 2.1, and even a deterioration in some components of skill. By assessing forecast skill against the criteria for different anticipatory action decisions, the study finds that, the new GloFAS version v3.1 shows acceptable skill for fewer decisions than v2.1, and this means the loss of the ability to provide information that could be used to prepare households for flooding. The decision-led evaluation has provided counterintuitive results, showing acceptable skill for decisions such as aid distribution and communication which are made at longer lead times, but not for the short-lead time evacuation decisions. This underlines the importance of decision-led evaluation, not only to give confidence in forecast use, but also to ensure that forecast “upgrades” do in fact lead to gains in decision-making ability.

Chapter 6 Discussions

6.1 Introduction

The aim of the thesis focuses on to improve flood early warning by assessing the flood characteristics that vary annually due to different hydrometeorological drivers of floods and the global extended-range flood forecast skill to support decision makers to undertake flood preparedness activities, taking into account the users' perspectives on flood forecasting in the Brahmaputra basin in Bangladesh.

While the monsoon season is almost fixed (June to September) in the basin, the flood characteristics significantly vary from year to year as well within the season; these characteristics impact societal activities (e.g., high impact long duration floods in 1998 in the Brahmaputra basin). Flood characteristics vary due to complex interactions between hydrological and meteorological processes (Gaál et al., 2012; Garner et al., 2015).

The seasonal total rainfall is commonly considered in hydrological studies where a strong annual cycle is present, giving limited information for intra-seasonal flood characteristics such as high water levels or rapid rise floods. The large scale driver ENSO influences seasonal scale monsoon rainfall over the south Asian monsoon region (Krishnamurthy & Kinter, 2003; Krishnamurthy & Shukla, 2007), with La Niña years usually wetter compared to El Niño, however floods occur in both ENSO years, particular flood characteristics are associated with ENSO years. Drivers of intraseasonal scale variation of monsoon rainfall and its association with flood events are not well studied for the Brahmaputra basin. These are essential for developing flood early warning.

In addition, flood preparedness decisions each has their own forecast criteria, such as forecast lead-time and requirements for forecast skill (such as concerns over "acting in vain") (Stephens et al., 2015b). For instance, lead time is different for crop planning than that for evacuation of flood-vulnerable community. Forecasting floods of different characteristics, i.e., low, medium and high threshold floods, is a challenging task for a transboundary river like the Brahmaputra where there is limited access to upstream hydrometeorological information. Due to recent advancement of NWP models, freely available global scale flood forecasts are an additional forecasting system which is often less expensive for national hydromet agencies. GloFAS is such a global scale flood forecasting model which has been operational almost for a decade (Alfieri et al., 2013; Harrigan et al., 2020a). However, recent upgrades to the model version mean that the corresponding changes in forecast skill for GloFAS is not well understood, particularly from decision making perspectives for the Brahmaputra basin. For flood preparedness activities based on early warning, study of users' perspectives information like forecast lead time, accessibility of forecast, communication of early warning are required for developing or evaluation of an early warning system (UNISDR, 2006). There is currently limited understanding of early warnings and preparedness decisions from users' perspectives in the Brahmaputra basin in Bangladesh.

The research presented in this thesis has been designed to understand how hydrometeorological drivers cause variation in flood characteristics, and how global forecasting system has made progress in skill for flood preparedness decisions in the Brahmaputra basin with the following objectives:

(i) To assess the hydroclimatological characteristics of flooding in the Brahmaputra basin;
(ii) To study users' perspectives on and needs for flood early warning information in the Brahmaputra basin for flood preparedness decisions;
(iii) To assess GloFAS performance and capabilities to meet user decision needs.

The thesis has been structured based on the above three research objectives. The following sections summarise key findings and discussion of the results, scientific novelty, limitations, and recommendations for future research.

6.2 Summary of the research outcomes with respect to research objectives

6.2.1 Objective 1: Assessment the hydroclimatological characteristics of flooding in the Brahmaputra basin

The first objective of this research has been presented in chapter 3. It includes a comprehensive assessment of flood characteristics due to key hydrometeorological drivers. To achieve this objective, three extreme flood types: long duration, high water level and rapid rise water level floods were selected from the available flood records for 33 years for analysis of relevant meteorological and hydrological drivers. Nearly every year the Brahmaputra basin experiences flooding due to the monsoon climate (approximately 20% inundation is considered normal floods in Bangladesh) (Mirza, 2003). However, the floods that do occur can be very different in their characteristics and thus, classification of these differences provides useful understanding of how they are linked to different hydrometeorological drivers, and in turn provides information that can be used for better flood prediction.

The results presented in this thesis show that the large scale driver, La Niña, was associated with the long duration floods (flood events in 1988 and 1998) in the basin (Section 3.4.1.1, Table 3.2). La Niña conditions were found to occur with a positive rainfall anomaly, and wet conditions can also prevail during the weak La Niña and neutral condition (Section 3.4.1.1) (Chowdhury, 2003; Pervez & Henebry, 2015). ENSO affects the total amount of seasonal rainfall (Section 3.4.1.1, Fig. 3.2), however the temporal, and spatial distribution of rainfall play important roles for other characteristics of floods. The effect of La Nina on the Indian monsoon is becoming less strong due to warmer SST at the eastern equatorial pacific which weakens the Walker circulation (Samanta et al., 2020). Further research is required into how this can influence future flood events in the monsoon regions.

The research in this thesis details how during the monsoon, several rainfall events occur over the Brahmaputra basin (Section 3.4.1.2, Table 3.1, appendix 3) and thus there is intraseasonal scale variation in the monsoon rainfall (Goswami & Mohan, 2001; Krishnamurthy & Shukla, 2000). The data set of BSISO (an intraseasonal mode oscillation which causes northward propagation of convection) shows some flood events are associated with BSISO phases (Table 3.2). Short duration and high intensity extreme more localised rainfall over the lower part of the basin that leads to rapid rise flood events (2017 flood events) (Fig. 3.4). These type of rainfall events are often associated with northward shifting of the eastern end of the monsoon trough towards the foothills of the Himalayas in Assam and sub-Himalayas i.e. lower part of the basin (Dhar & Changrani, 1966). In this part of the basin, concurrent contribution from three tributaries plays a crucial role in the rapid rise in water levels in the main river, indicating the importance of the spatial location of extreme rainfall. The exact nature of the floods in a particular monsoon month, i.e., July or August, depends on how extreme rainfall events are (co-occurring rainfall events are floods) (Table 3.1). Basin wide rainfall and seasonal extreme caused the longest duration floods in 1998 in the Brahmaputra basin in Bangladesh.

Antecedent conditions were found to be important for large scale floods (Schröter et al., 2015); for long duration floods river antecedent conditions were high before the onset of the floods (in June, the first month of the monsoon) (Fig. 3.8 and Table 3.2). However, the research in this thesis shows that antecedent conditions are not a major control for high water level floods or rapid rise floods. Irrespective of river antecedent conditions the river can experience maximum water level floods (Section 3.4.2.2). There has been a recent positive trend in floods even though the average river discharge has remained stationary (Fig. 3.11). The flood events in 2016, 2017, 2019 exceeded previous historical annual maximum water levels.

For two long duration floods in the Brahmaputra (1988 and 1998) there was a synchronization of floods with the other two river basins (the Ganges and the Meghna) in Bangladesh (Fig. 3.14a and Table 3.2). However, the third highest duration floods (2017 floods) occurred without flood synchronization with the Ganges and Meghna (Fig. 3.14b, Table 3.2). Therefore, long duration floods in the Brahmaputra can also occur without hydrological synchronization, and instead from basin wide and frequent extreme rainfall events (Table 3.1, Fig. 3.4, 2017 rainfall events). Floods in the Brahmaputra basin towards the end of August are more likely to synchronize with the Ganges and Meghna basins influencing potential backwater effect. These flood drivers are important to understand for flood forecasting to enable anticipation of floods of different types: long duration, high water level or rapid rise.

6.2.2 Objective 2: Users' perspectives on and needs for flood early warning information in the Brahmaputra basin for flood preparedness decisions

The second objective of this thesis is to assess the key information that needs to be included in an early warning message for flood preparedness. Through the stakeholders' involvement in the research process at different levels, essential information on the existing early warning and the needs for better flood preparedness can be gathered, for instance, the objective to determine the lead time for various early actions before onset of floods and how they receive early warnings or use probabilistic forecasts in the decision making process.

Flood preparedness decisions vary at different levels: national, sub-national and community. Higher level users' preparedness is focused to protect community through aid distribution or protect from adverse impacts of floods (Section 4.5.1.1 and 4.5.1.2), while community try to cope with floods by taking various measures during or before onset of floods (Section 4.5.1.4). Research in this thesis shows that users are aware about the monsoon season, however, they are not quite sure about the timing of floods i.e., whether floods are likely to occur June, July, August, or September in a typical monsoon (June-September) and sufficient lead time can allow people for preparedness and early actions (Section 4.6).

Currently the flood forecast is provided in the form of hydrograph, or as a numerical value of water level. This does not give a clear message for the community about individual impacts which is essential for early actions. The community often follow a "wait and see" approach during floods (Section 4.5.1.4**)**. Upon the onset of floods community people look for forecasts from different sources. Though FFWC provides forecasts in the short to medium range (with the technical support from RIMES), people within the community are not fully aware about these forecasts and therefore they anticipate floods from the current state of the environment— trend in water levels just a few days before onset of floods. TV is the popular media of dissemination mode which broadcasts the flood news and the onset of floods (Fig.4.5). Lead-times vary depending on the early actions. Household level preparedness depends on short-range forecasts and deterministic forecasts by the FFWC with 1 to 5 days lead time is quite useful for these early actions (Table 4.2). The research findings show that farmers require longer a lead-time for crop planning compared to other preparedness actions (Table 4.2). A lead-time for preparedness of around 3 weeks for farmers provides a sufficient window of time for their agriculture planning (Table 4.2) and they need to use probabilistic forecasts in the decision making processes.

Each national level user has a network which connects to community level (national<sub-national<community level). When a flood is anticipated, it needs to reach to the community level at the earliest possible time that gives sufficient lead-time for early action and preparedness. This involves a "top down approach for dissemination" to inform the community and provide guidance for early action for the anticipated floods. For example, communication probabilistic forecast with the community level users in a way that helps them make informed decisions (Section 4.6, Fig. 4.7). Short-range forecast-based decisions such as evacuation is actionable by the community before floods occur. Probabilistic forecasts include uncertainty information (Cloke & Pappenberger, 2009b), and this is essential to

communicate with the users as is the necessity for them to understand the costs and losses associated with taking or not taking such an action. For example, a low probability but extremely impactful event might be worth evacuating for. Flood probability around 50% (probability of floods to occur) issuing of warning message and need to communicate with the users (Section 4.6). It is important for the community to understand that they may need to “act in vain” in order to make sure that when a bad flood does occur that they take the right action (Coughlan de Perez et al., 2015).

6.2.3 Objective 3: Assessment GloFAS performance and capabilities to meet user decision needs

GloFAS was upgraded to version 3.1 from the previous version 2.1 through a significant change in the hydrological model component. The version 3.1 uses a fully configured LISFLOOD model (both surface and routing components) instead of the coupled ECLAND/LISFLOOD approach which was used in version 2.1 (Section 5.2). In Chapter 5, the two GloFAS model versions have been evaluated to study the capability of simulating flood behaviour and forecast skill of the Brahmaputra River, using long records of reforecast data (20 years). The results show both model versions can capture the annual flood peak and simulation of low, medium and high threshold floods. The evolution of the annual cycle is presented correctly both in terms of rising, peak and falling river flow from short (5 days) to extended lead-times (15 days).

In terms of performance metrics, the KGE value for version 2.1 shows better performance than version 3.1 though both are capable of capturing peaks and simulating flows above a threshold. For instance, despite strong correlation between observed and the two model versions, bias (positive bias) and variability is higher in version 3.1 than version 2.1. However, for a global model 20 to 25% bias is acceptable (Liu, 2020). The results suggest that this model can be used for flood characteristics for other rivers in Bangladesh particularly where long records gauge data is not available due to lack of measurements.

For low (90th percentile) and medium (95th percentile) threshold floods both the models skilfully predict floods with acceptable FAR and POD for taking flood preparedness decisions such as crop planning (Fig.5.5, Table 5.3). Evaluation of skill for high threshold floods (extreme events, 99th threshold floods) does not provide robust results. This could be due to smaller number of extreme events were available to analyse. Humanitarian agencies are interested in forecasts for extreme flood events (99th threshold) at lead times of around 15 days (with a 10 days margin of error) in order to take actions such as distribution of aid among the vulnerable people in the basin. With the version 2.1 humanitarian agencies were able to use 10 day lead-time for aid distribution in the 2016, 2017 and 2019 floods (Dr. Ahmadul Hassan, Climate Centre, the Netherlands, personal communication). An acceptable FAR can be useful for humanitarian decisions (Coughlan de Perez et al., 2015) which quantifies how often decision makers need to "act in vain" based on a forecast (Table 5.2). Forecast skill varies with the forecast probabilities and acceptable FAR and POD are consistent for a range of forecast probabilities (Fig.5.6). A decision maker can select a higher forecast probability (above 70%) for triggering an early action. Though version 3.1 has acceptable FAR, it is higher than version 2.1, highlighting that users will end up acting more often in vain now that the new version 3.1 is operational. The structural differences between the hydrological model versions likely cause the variation in flood behaviour, because the ECMWF weather model forcing has remained virtually equivalent. This could be something to do with the storage or runoff process characterisation or parameterisation, but this needs further study.

After the introduction of the new version, the Brahmaputra basin inside Bangladesh has not experienced extreme floods and forecasters have not yet been able to test in real time how the new version predicts extreme flood events. However, it is hoped that the information in this thesis has gone some way to provide useful information to anticipate such a flood event.

Both model versions are suitable for agricultural decision-making such as the plantation of "Aman" rice, which also needs a longer lead time and the maximum allowable margin of error is 7 days (Section 5.5.3, Fig. 5.6 and Fig. 5.7). By allowing for a margin of error the acceptability of the forecasts increases. However, the margins of error are small for decisions such as evacuation of vulnerable communities. Recent large floods show that huge numbers of people might need to evacuate. For these communities a higher margin of error is not acceptable because the nature of the decision is time-critical; there will be critical loss in income if the flood arrives later than forecast. On the other hand, humanitarian agencies and the national disaster management authority would accept a greater margin of error which allow more time for better preparedness as their decisions are more oriented to resources planning and identification of vulnerable communities.

6.3 Contribution to knowledge

The research presented in this thesis helps to improve flood early warning in Bangladesh by understanding hydrometeorological drivers causing different flood characteristics, extended-range forecast skill and users' perspectives of early warning for preparedness actions. The specific contributions of this thesis to current knowledge are:

(a) an enhancement of the current understanding of flood types: duration, magnitude and rapid rise during the monsoon. The database developed on flood types can be used to provide plausible scenarios (Schröter et al., 2015) of extreme events.

(b) a new understanding of the recent flood behaviour of the Brahmaputra River which demonstrates a positive trend in high water level floods irrespective of river antecedent conditions (Fig. 3.11a). This indicates that the river can experience frequent exceedance of annual maximum water level floods (2016, 2017 and 2019 floods are examples of when the river exceeded previous records).

(c) a new understanding of Intraseasonal scale mode weather events and floods events in the Brahmaputra basin.

(d) understanding users' aspects in flood preparedness using flood forecast information which is essential for developing an efficient early warning system.

(e) application of a Global scale hydrological model to study flood characteristics of a large transboundary basin.

(f) global model skill for improving flood early warning in Bangladesh particularly with respect to lead time and decision makers perspectives. Flood events can be anticipated with lead time 15 to 20 days below acceptable FAR value (FAR less than 50%). Models are skillful for decision makers at national level and agricultural decision with sufficient lead time and acceptable FAR value (FAR less than 50%).

(g) characterisation of forecast skill and model performance variation due to changes/upgrades in model versions. There are clear differences between GloFAS versions 2.1 and 3.1 in terms of simulated discharge as well as flood forecast skill. Assessment of forecast skill can guide model developers' future improvements.

(h) the provision of a set of relevant recommendations for better understanding and improving flood early warning in Bangladesh.

6.4 Recommendations for improving flood forecasting for disaster management in Bangladesh

Synoptic situation: Currently in the FFWC in Bangladesh the synoptic situation is not fully considered in flood forecasting. Certain weather conditions are associated with heavy rainfall events in the basin (Section 2.3.1). Analysis of the synoptic situation over the lower sub-basins (Assam, Meghalaya and sub-Himalaya West Bengal region) could play an important role in anticipating timing of extreme rainfall events and their potential contribution to flooding. This could include analysis of weather charts to locate the position of the monsoon trough and monitoring of wind flow direction.

Tropical Intra-Seasonal Oscillation (ISO) and large-scale climate modes: The Boreal Summer Intra-Seasonal Oscillation (BSISO) mode needs to be carefully monitored during the monsoon period in order to consider its prominent northward propagation carefully and the associated active and break rainfall events. It is also important to consider the influence of teleconnections with ocean and atmospheric drivers, such as ENSO on basin scale rainfall. Strong La Niña development years are found to be linked with larger seasonal total rainfall; long duration floods are more likely in this scenario (50% of La Niña development years flood duration was >25 days). Therefore, a forecast of a La Niña issued at the beginning of the monsoon season (June–July) after the spring predictability barrier (when predictions of ENSO are more skilful) (Chen et al., 2020; Clarke, 2014) could provide a plausible early indication of long duration floods in Bangladesh.

Hydrological sweet spots and spatial distribution of monsoon rainfall: The spatial distribution of the monsoon rainfall varies significantly from more localized to basin-wide, and flood responses vary accordingly in the basin inside Bangladesh. Floods can occur from two sets of rainfall distributions; basin-wide and more localized rainfall at lower sub-basins. These distributions of rainfall events give an essential scenario to forecasters about the possible rate of rise in water level. Heavy rainfall event "sweet spots" in the lower sub-basins of the Brahmaputra (near the Bangladesh border) can create hydrological "sweet spots", where heavy rainfall events contribute to a more rapid rise of river water levels. The location of the rainfall events may also contribute to determine the flood timing and magnitude, with a possible synergistic effect for increased flood hazard produced by a synchronised flood wave from the tributaries. Therefore, the spatial distribution of rainfall at this sub-basin scale is essential for flood forecasting in the Brahmaputra. For instance, a medium-range forecast (5-10 day lead time) of a localised rainfall event over the "sweet spot" area would indicate to forecasters that a rapid rise flood event is likely.

Application for improving forecast lead-time in Bangladesh: Increasing the lead-time of skillful forecasts is a challenge in a transboundary basin where major flows come from upstream catchments and, where there may be limited access to upstream hydro-meteorological information. Skillful global models provide a source of forecast information for such transboundary river basins. GloFAS is able to predict normal floods (90th percentile) at short to medium range (1 to 10 days) and extended range (11 to 30 days) time scale with acceptable FAR. Deterministic style short-range forecast of the FFWC can anticipate floods around 3 days before on set of floods and is not able to tell anything about the duration of floods. Therefore, in addition to current GloFAS forecast skill evaluation, it is also necessary to evaluate the FFWC's short range deterministic forecast to find how many days it could effectively provide skill for decision perspectives. Similarly, skill assessment of the RIMES's medium range forecast is also necessary from decision perspectives. These all together can be used to develop seamless forecasting system cost effective way for a flood prone country like Bangladesh. The seamless forecasts can support a wide range of early actions for decision makers at different timescales starting from short range to extended range e.g., around 3 weeks. National hydrodynamic model simulation in Bangladesh largely depends on the model upstream boundary estimation, in future the GloFAS skillful forecast could be used as a source of upstream hydrological information for the national model. Thus, the GloFAS skillful forecast can support national flood forecasting by increasing forecast lead time.

Probability forecast dissemination for flood preparedness: The FFWC disseminates medium range water level forecasts in the form of forecast hydrographs with maximum, mean and minimum values. This information is not quite understandable to all users, particularly community people. Probability based forecast can provide essential information for early actions and forecast needs to provide in easy and understandable way for all decision makers. For example, consider the 50% probability to exceed danger level in the next 48 hours at Bahadurabad stream gauging station of the Brahmaputra River. This type of information clearly conveys potential forecast uncertainty for decision makers whether to take flood preparedness decisions or not. The FFWC should provide forecast messages including probability information in daily forecast bulletin for decision makers. Different early action decisions require different lead times and forecast skill, both of which change for different probabilities at different lead times. Therefore, decision makers need to understand the value of forecast across lead times– short, medium, and extended ranges.

Impact based forecast: The FFWC provides forecasts based on the river water level and whether the danger level at each particular river gauging station will be crossed. An example of a typical forecast message is:

> “The river water level is in rising trend. The Brahmaputra River Bahadurabad may cross danger level in next 24 hours.”
>
> “Flood situation in Kurigram, Jamalpur districts may deteriorate in next 24 hours.”

But this information itself does not convey enough meaning to take action. Therefore, a translation of the forecast information is necessary for the community to take action. Location specific forecast information based on flood inundation is of utmost important for better flood preparedness. Disaster managers also request such information for their emergency operation. This indicates instead of only river gauged based forecast inundation forecast is required to anticipate potential impact of floods. It is recommended that the FFWC, together with local partners and communities, develop location specific inundation forecasts so that the community can be informed when floods are likely to impact them.

Climate change and disaster management perspectives: Flood events with different characteristics have different challenges and impacts, and climate change is likely to influence these flood characteristics in future, possibly to different extents. Stronger interannual variability in the monsoon is expected in a warming climate (Kitoh et al., 1997; Sharmila et al., 2015), therefore for informed climate adaptation and long-term management of disaster risk, further investigation is needed in order to understand how the two scenarios which drive interannual variability in flood characteristics might change under different climate change scenarios. It is expected that frequency of ENSO events may increase in the future under climate change conditions (Cai et al., 2014; McPhaden et al., 2020). Spatial and temporal variations of the monsoon rainfall due to climate change are important aspects that influence flood characteristics. Climate change may cause frequent extreme monsoon rainfall events by increasing the number of short-duration rainfall events (Christensen et al., 2013; Sharmila et al., 2015; Turner & Annamalai, 2012) or changing in spatial variation of rainfall (Bhowmick et al., 2019; Christensen et al., 2013) which might lead to more frequent flood pulses with rapid rise or high water level in a monsoon.

Recommendation for decision makers: Decision makers must find a balance between the acceptable number of missed events and false alarms. For a global forecasting system, a new model version poses a challenge because overall improvements in skill do not necessarily mean that the same skill changes are seen in individual river catchments. In this case, the update from v2.1 to v3.1 limits the number of decisions that can be made from GloFAS in the Brahmaputra basin, especially at shorter lead times. While FFWC forecasts are available at these lead-times, working closer with GloFAS developers would allow issues with the model to be dealt with more efficiently.

6.5 Recommendations for future studies

- **Recent positive trend in water level and floods in the Brahmaputra basin**

The Brahmaputra is a braided river and morphological changes are common due to sedimentation. It is recommended that future studies should incorporate the influences of upstream dams and other human interventions, and natural changes which are the potential factors contributing to sedimentation, to understand and quantify how morphological changes are changing flood risk. Further work could also analyse the spatial extent of inundated areas and the role of river morphological changes of the

Brahmaputra and its tributaries, as a possible important driver of flood characteristics. Also, backwater effects of the main river and its influence on the flooding of the tributaries need further investigation.

- **Intraseasonal scale oscillation and floods**

A detailed study is also needed to investigate the influence of intra-seasonal modes such as the BSISO, MJO and their relationship with Brahmaputra basin floods in the long-term record. Also, a relationship between sub-seasonal variations of river flows and corresponding temporal variability of precipitation events is recommended for further research.

- **GloFAS forecast skill under large scale climatic drivers**

In this study, GloFAS flood forecast skill has been evaluated from a flood preparedness decision perspective for flood behaviour of the Brahmaputra basin. Flood characteristics change with the variation of different climatic drivers. It is suggested that future studies consider how forecast skill changes under different climatic conditions. For example, model performance during a El Niño or La Niña year or how it might change with BSISO events. This can help to guide modellers for further improvement of models.

- **Evaluation of extended range rainfall forecast skills**

The monsoon rainfall is the main driving force of floods in the Brahmaputra basin. Forecasts of the evolution of monsoon rainfall events is also essential to anticipate flood events. World leading meteorological centres such as ECMWF, Japan Meteorological Agency (JMA), Korea Meteorological Administration (KMA), Météo France, United Kingdom Met Office (UKMO) provide sub-seasonal to seasonal scale rainfall forecasts. It is recommended to evaluate rainfall forecast skill at basin level of those models at lead-times of 1-4 weeks. This will help to understand evolution of rainfall events during the monsoon and model skill to predict rainfall events that are linked with floods in the basin.

- **Community level dissemination extended forecast**

Decision makers need extended lead-time (10 days and above) information for certain decisions. The GloFAS extended range forecast has skill in providing forecasts of the onset of floods which is useful for decisions such as crop planning. It is therefore recommended to undertake research to examine whether disseminating extended range forecasts to farmers at the community level is useful for decision making such as crop planning.

6.6 Personal reflection

I am an operational forecaster at the Bangladesh Flood Forecasting and Warning Centre (FFWC), and this PhD gave me the opportunity to learn various aspects of the flood driving mechanisms of the Brahmaputra basin. For example, how flood characteristics vary with weather and climate dynamics. As a flood forecaster, this information is essential to predict rightly a flood event. During the monsoon when a flood event is evident in the basin, I need to answer several questions such as timing of floods, how long flood will continue (flood duration) to policymakers, journalists, district disaster and flood managers. With the short-range forecast, it is not possible to predict the onset of floods and probable flood durations. GloFAS provides 30 days lead time forecast, which can tell about the onset of floods and probable flood durations. However, the modelling approaches and forecast skill were not familiar with us for the river basins in Bangladesh. Through this research program and participating different research workshops at the ECMWF, makes me confident about the GloFAS extended range forecasts. There are also important changes in model version during my PhD research and learning the relative changes of forecast skill between the two model versions was essential for me from an operational forecaster point of view. Before starting PhD research, I had very little understanding about the community people who suffer the most from floods. Now, we are in close collaboration with community people for capacity building to apply probabilistic forecasts for early action decisions. From the capacity development point of view, the research findings are being communicated with the forecasters of the FFWC. Thus, I am taking forward into my job for improve flood early warning and better flood preparedness in Bangladesh.

Chapter 7 Conclusions

This chapter concludes the thesis by summarizing the key research findings with respect to the research objectives and questions, as well as discussing the practical implications of the research findings. This research aimed to improve flood early warning by understanding the key flood drivers based on the assessment of hydroclimatological characteristics of floods, understanding the users' perspectives of flood early warnings in Bangladesh and assessing the forecast skill of the extended-range flood forecast of a global model. Based on long-term hydrological and meteorological data analysis, it can be concluded that the basin can experience floods with different characteristics, for example with long duration, rapid rise in water levels and high water level floods. The results indicate that key meteorological drivers are associated with certain flood characteristics. The key findings are summarised below:

- Hydrological behaviour shows shifting of flood behaviour from the 2016 monsoon when the river first exceeded historical annual maximum water levels. The river also exceeded annual maximum water levels during the 2017 and 2019 monsoons. Analysis of long records of annual maximum water levels shows a positive trend in high water levels floods while the annual maximum river flow trend is not significant. This indicates that the basin can experience such high water levels floods in future.
- The Brahmaputra is a massive river which is expected to respond slowly due to monsoon rainfall in the downstream section of the basin located in Bangladesh. However, localised extreme rainfall in the lower sub-basins that covers Bangladesh and adjacent areas upstream of Bangladesh can lead to a sharp rise in water level. Decomposing of discharge and water levels time series shows a high frequency component to the rapid rise floods. This suggests that the extreme rainfall that fell over a hydrological "sweet spot" (3 adjacent tributaries– the Teesta, the Dharla and the Dudkumar) can lead to such floods.
- Analysis of long record flood data shows that the basin can receive short (less than 3 days) to long duration (above 2 months) floods in a monsoon. Longer duration floods, which lead to very high impacts, are driven by basin-wide precipitation anomalies over the whole monsoon season (such as in 1998), with some evidence that this is linked to La Nina onset years.

- Spatio-temporal analysis of monsoon rainfall shows a dipole relationship with respect to the monsoon core zone (central Indian region). Less rainfall in central India can indicate more rainfall in the Brahmaputra basin.
- The two GloFAS hydrological models show differences in forecast skill which demonstrate that changes in model structure can affect user's decisions even though meteorological forcings are the same.
- Being a global model, the GloFAS two model versions are skillful in simulating hydrological characteristics such as peak flow, rising and falling stage of the annual cycle of river flows. This indicates that the model is capable of simulating floods on a transboundary river with limited access to observation data.
- The GloFAS forecast shows skill for medium to low threshold floods for uses including crop planning and national level preparedness plans before floods. However, it does not show enough skill for decisions being taken at short lead times, such as evacuation.
- The community are not fully aware of official forecasts available from the Flood Forecasting and Warning Centre, though high level users can pull forecast information from the sources. Still, the community uses their local knowledge and nature to anticipate floods on a shorter time scale. The results demonstrate community needs to be aware of the available forecast information for preparedness and response activities.
- Communication of medium to extended range forecasts to the community level is necessary for early actions. Community capacity development is required to understand forecast uncertainty and overcome barriers for applying to flood preparedness decisions.

This work can be further replicated for other river basins in Bangladesh to understand variations of flood drivers and the associated characteristics of floods. Further investigation of drivers other than hydro-meteorological aspects on the recent trend in high water level floods is also recommended. In addition, climate projections and attribution need to consider how hydrological and meteorological drivers will change in the future to adequately assess future flood hazard in the basin. This study has developed a research framework on hydrometeorological drivers for the application of flood forecasting in the Brahmaputra basin in Bangladesh, which will motivate forecasters to collaborate with decision makers to communicate forecast information and uncertainties and develop a user oriented early warning in Bangladesh.

Appendix 1 Discussion papers

Abstract: Hydrometeorological drivers of the 2017 flood in the Brahmaputra basin in Bangladesh

Two papers, based on Chapter 3 of the current thesis, are available as discussion papers in Hydrology and Earth System Sciences (HESS).

Paper 1: Hydrometeorological drivers of the 2017 flood in the Brahmaputra basin in Bangladesh

Sazzad Hossain, Hannah L. Cloke, Andrea Ficchì, Andrew G. Turner, and Elisabeth Stephens

https://hess.copernicus.org/preprints/hess-2019-286/

Hossain, S., Cloke, H. L., Ficchì, A., Turner, A. G., and Stephens, E.: Hydrometeorological drivers of the 2017 flood in the Brahmaputra basin in Bangladesh, Hydrol. Earth Syst. Sci. Discuss. [preprint], https://doi.org/10.5194/hess-2019-286, 2019.

Abstract. Flooding is a frequent natural hazard in the Brahmaputra basin during the South Asian summer monsoon. Understanding the causes of flood severity is essential for flood management decisions, but to date there has been little attempt to identify sub-seasonal variability of flood characteristics and drivers for the Brahmaputra in Bangladesh. In the 2017 summer monsoon, there was severe flooding in Bangladesh, but the Brahmaputra River, as well as its tributaries, behaved unusually compared to previous major flood events. This study analyses different hydrometeorological drivers of these floods, providing valuable information for the assessment and forecasting of future flood events. Water level and river flow time series have been decomposed using wavelet analysis to study the temporal variability within the hydrological cycle. During the 2017 monsoon, the extreme rainfall in August caused the water level of the Brahmaputra river and its tributaries to rise rapidly and exceed their previous historical record. This heavy rainfall was associated with a northward shift of the monsoon trough, creating active monsoon conditions in the Brahmaputra basin. The rainfall was localised over the lower sub-basins adjacent to the northern border of Bangladesh. The estimated river discharge in 2017 was slightly lower than the two previous major flood events in 1998 and 1988. The wavelet analysis of both daily water level and discharge shows that a high frequency component drove the severe flooding in 2017, compared to the low frequency component in 1998, where widespread basin accumulated rainfall acted as main driver of the flooding. The study concludes that the location and magnitude of extreme rainfall are key drivers controlling on the characteristics of the Brahmaputra floods. Understanding these drivers is essential for flood forecasting, in order to predict the timing, magnitude and duration of flooding, and also for understanding future climate change impacts on

flooding. The study recommendations include analysing the synoptic situation along with different intra-seasonal oscillations as well as considering the spatial location of rainfall events for flood forecasting.

Abstract: Hydrometeorological drivers of flood characteristics in the Brahmaputra River basin in Bangladesh

Paper 2: Hydrometeorological drivers of flood characteristics in the Brahmaputra river basin in Bangladesh

Sazzad Hossain, Hannah L. Cloke, Andrea Ficchì, Andrew G. Turner, and Elisabeth M. Stephens

Hossain, S., Cloke, H. L., Ficchì, A., Turner, A. G., and Stephens, E. M.: Hydrometeorological drivers of flood characteristics in the Brahmaputra river basin in Bangladesh, Hydrol. Earth Syst. Sci. Discuss. [preprint], https://doi.org/10.5194/hess-2021-97, 2021.

https://hess.copernicus.org/preprints/hess-2021-97/

Abstract. While flooding is an annual occurrence in the Brahmaputra basin during the South Asian summer monsoon, there is large variability in the flood characteristics that drive risk: flood duration, rate of water level rise and peak water level. The aim of this study is to understand the key hydrometeorological drivers influencing these flood characteristics. We analyse hydrometeorological time series of the last 33 years to understand flood dynamics focusing on three extraordinary floods in 1998 (long duration), 2017 (rapid rise) and 2019 (high water level). We find that long duration floods in the basin have been driven by basin-wide seasonal rainfall extremes associated with the development phase of strong La Niña events, whereas floods with a rapid rate of rise have been driven by more localized rainfall falling in a hydrological ‘sweet spot’ that leads to a concurrent contribution from the tributaries into the main stem of the river. We find that recent record high water levels are not coincident with extreme river flows, hinting that sedimentation and morphological changes are also important drivers of flood risk that should be further investigated. Understanding these drivers is essential for flood forecasting and early warning and also to study the impact of future climate change on flood.

Appendix 2 Paper on decision led evaluation GloFAS flood forecasting model

The Chapter 5 of this thesis has been published in the special issue of the Journal of Flood Risk Management.

Title: A decision-led evaluation approach for flood forecasting system developments: An application to the Global Flood Awareness System in Bangladesh

Hossain, S., Cloke, H. L., Ficchì, A., Gupta, H., Speight, L., Hassan, A., & Stephens, E. M. (2023). A decision-led evaluation approach for flood forecasting system developments: An application to the Global Flood Awareness System in Bangladesh. *Journal of Flood Risk Management*, e12959. https://doi.org/10.1111/jfr3.12959

Abstract. Scientific and technical changes to flood forecasting models are implemented to improve forecasts. However, responses to such changes are complex, particularly in global models, and evaluation of improvements remains focussed on generalised skill assessments and not on the most relevant outcomes for those taking decisions. Recently, the Global Flood Awareness System (GloFAS) flood forecasting model has been upgraded from version 2.1 to 3.1 with a significant change to its hydrological model structure. In the updated version 3.1, a single fully configured hydrological model (LISFLOOD) has been adopted, including ground water and river routing processes, instead of two coupled models, a land surface and a simplified hydrological model, of the previous version 2.1. This study aims to evaluate changes in the simulated behaviour of floods and the forecast skill of the two GloFAS versions based on different decision criteria for early action.

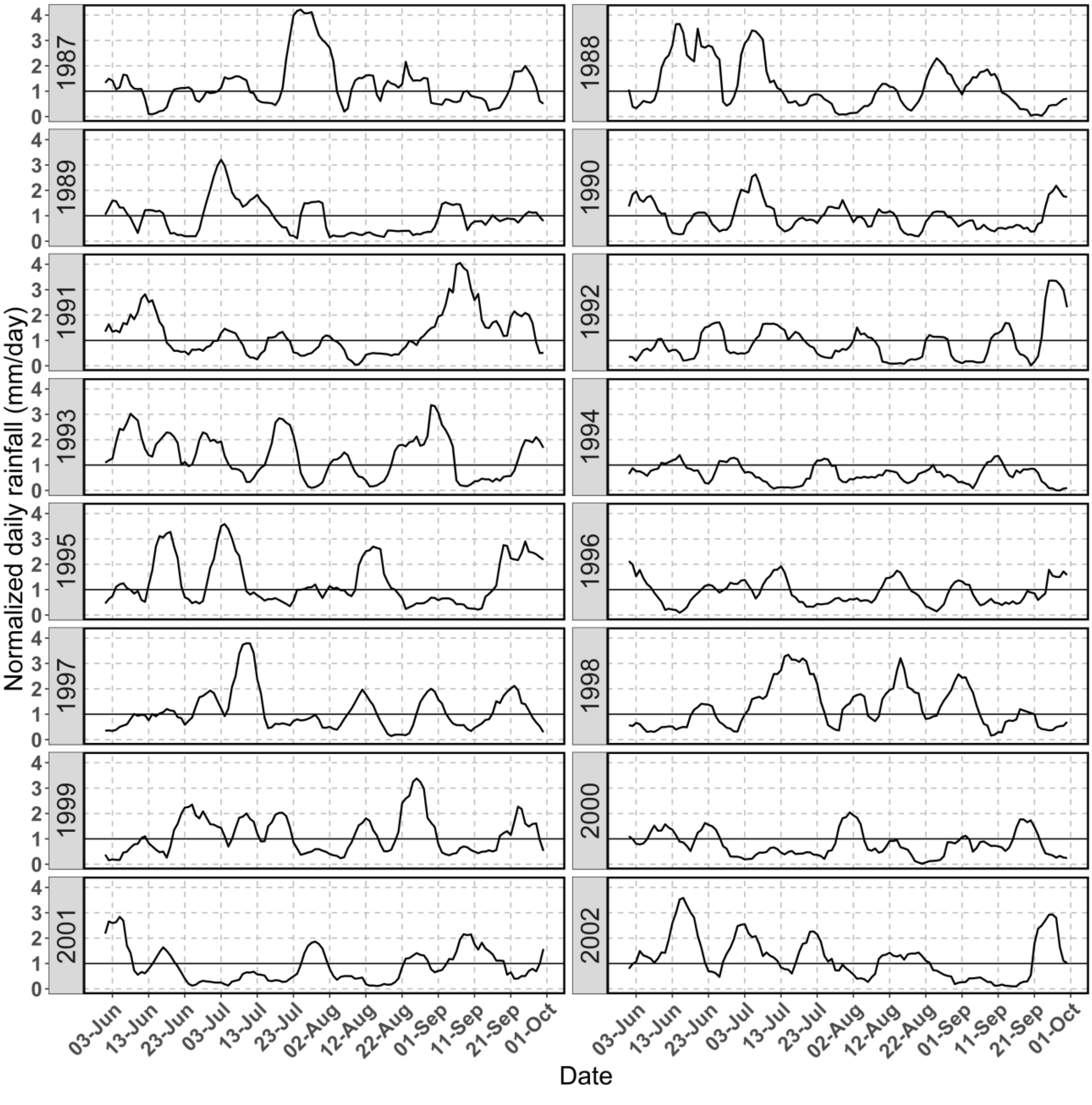
We evaluate GloFAS reforecasts for the Brahmaputra and the Ganges Rivers in Bangladesh for the period 1999–2018. For the Brahmaputra River, the old GloFAS 2.1 version performs better than the 3.1 version, especially in predicting low-(90th percentile) and medium-level (95th percentile) floods. For the Ganges, GloFAS 3.1 shows improved probability of detection of low to medium-level floods compared to version 2.1, especially for lead times longer than 10 days. Both versions show limited skill for more extreme floods (99th percentile) but results are less robust for these less frequent floods given the lower number of events. Using lead-time dependent thresholds improves the false alarm ratio while reducing the probability of detection. The changes in model structures influence the model performance in a complex and varied way and forecast skill needs further investigation across regions and decision-making criteria.

Understanding the skill changes between different model versions is important for decision-makers, however, focused case studies such as this should also be used by model developers to guide future changes to the system to ensure that they lead to improvements in decision-making ability

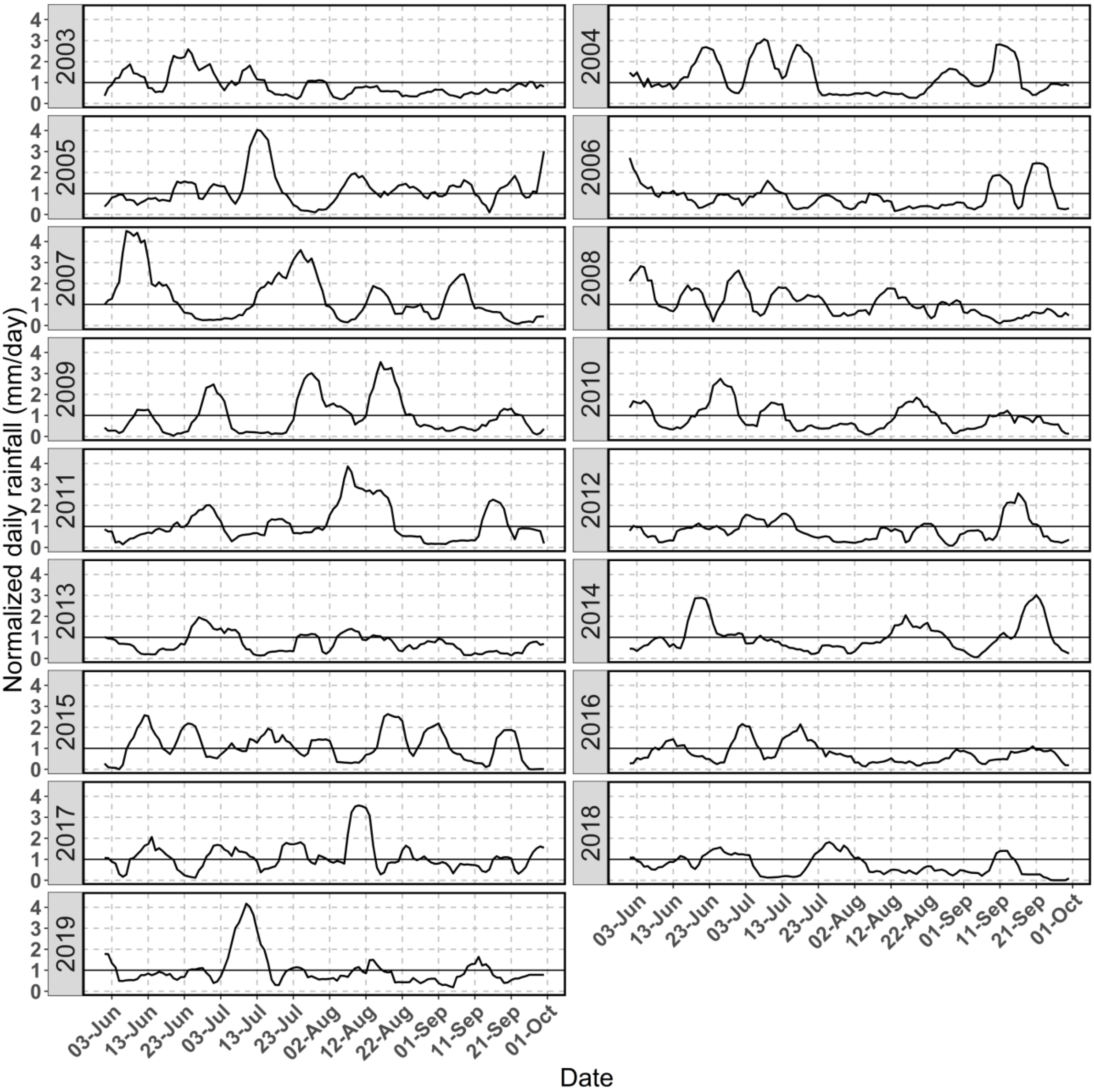
Appendix 3 Monsoon rainfall events

Historical monsoon rainfall events

(a) year: 1987-2002



(b) year: 2003 -2019



Appendix 4 Questionnaire for qualitative research work

Questionnaire for household survey, Key informant interviews (KII) and Focus group discussion on

"Users' perspectives on and needs for flood early warning in Bangladesh"

1. Name of respondent:

2. Age:

3. Address:

4. Occupation (household main income source):

(i) Farmer (ii)Fisherman (iii) Businessman (iv) Service holder (v) Daily wagelabour (vi) Housewife (viii) Other (specify)
5. From where does the flood come to your home or agricultural land?
(i) Heavy rainfall (ii) From river

6. Which type of property is affected during flooding?

Answer: (i) Agricultural crops (ii) Houses (iii) Pond fisheries (iv) Poultry (vi) Cattle (v) Tube well (vi) Sanitation system (v) Human life (vi) others (Please specify)

7. Have you received flood early warning message during floods?

Yes/ No / I have no idea

If yes, then how early and what is the format of warning message?

Answer: How early (How many days before):

8. How do you receive flood early warning message?

(i) TV/radio (iii) Mike (iv) Newspaper (v) Mobile SMS (iv) from people/neighbours-union/chairman/ member/village police/ volunteer/NGO worker, (v) website (vi) 1090 calling (vii) others.

9. What are the preparedness/response actions for response during the floods?

(list of actions)

Answer:

10. Is this early warning message is sufficient for your action?

Yes/No

11. Which information in flood early warning you need for your flood preparedness?

- (i) Duration of Flood and timing
- (ii) Flood Extent
- (iii) Flood depth
- (iv) All

12. What is their expected lead-time for flood preparedness activities?

Example: 24 hours/ 48 hours / 72 hours/ 5 days / 7 days/ 10 days/12/ 15 days /any other …….

Your answer:

13. What are the preparedness activities you like to take based on the flood early warning lead-time?

List of activities

14. Do you like to get early warning if you are given forecast in the probability format (In bangla call it is *somvabana*) want probability you like to use probability based early warning in your preparedness decisions. Example: The probability of flood after x days will be y%

Answer:

Key informant interviews (KII) for national and district level stakeholders

(i) Could you tell me about flood early warning in terms of accessibilty and understanding warning message? How do these forecast help to prepare for flooding? What are the limitations of the current early warning?

(ii) How would extended range (probabilistic) forecast improve your decision?

(iii) What are the potential challenges in using extended range forecast? How these challenges could be overcome? What are the useful format of extended range forecast information for your decesion making?

(iv) What other information do you need for better flood preparedness?

(v) Is there anything else you would like to say or ask?

Community level focus group discussion

(Number of participants: 8 to 10)

Target audience:

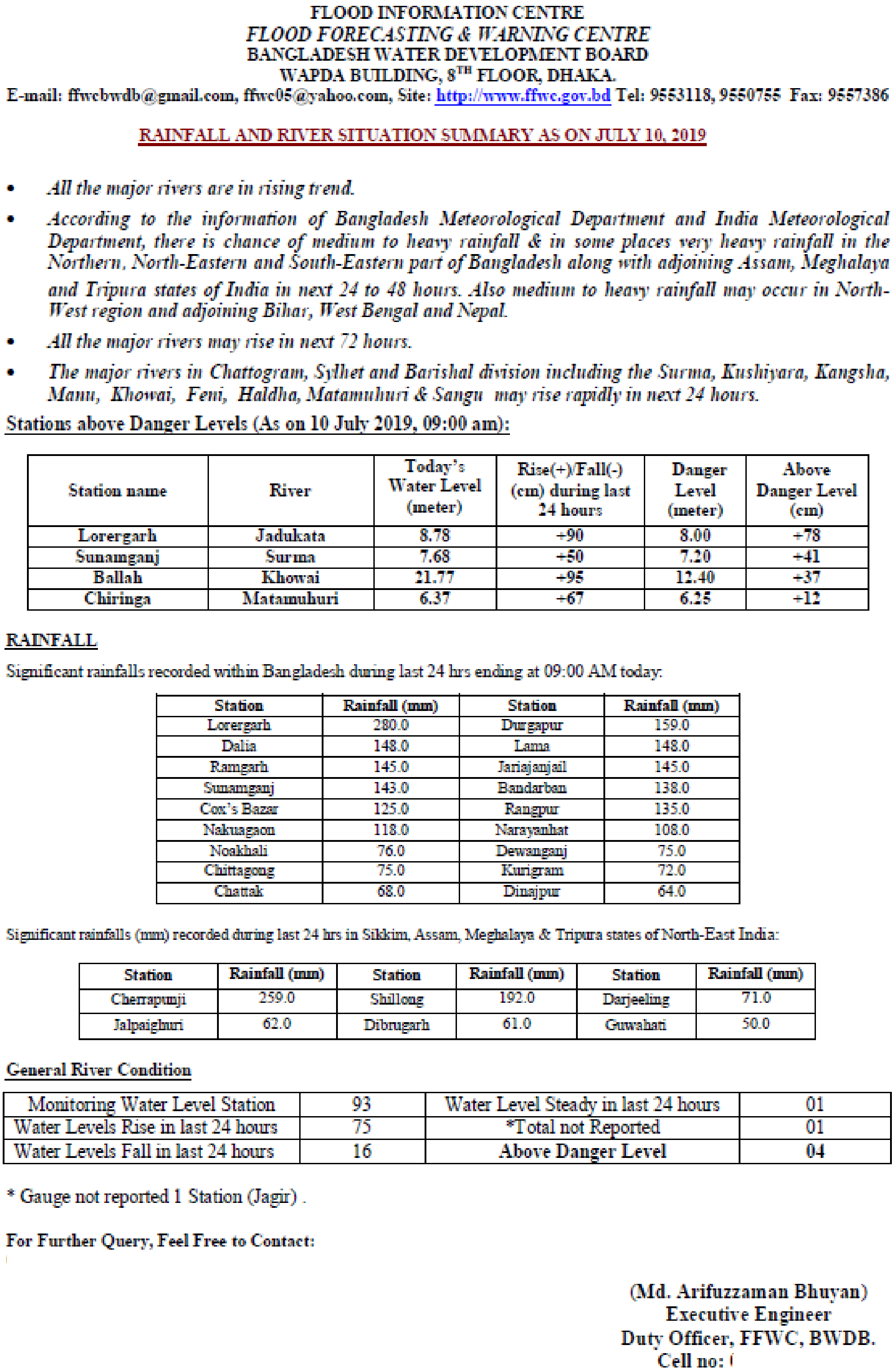
- Farmers (Both landless farmer/share cropper and land owner)
- Fisherman
- Cattle farming people
- Day labour
- Business man
- School teacher at community level
- Service holder
- Public representaive

Agenda for Focus group discussion:

1. What are the common decisions taken for flood preparedness/response during floods? How to you take major your agriculture decesions such as do you keep plantation time same for every year or you change timing e.g. early or late?
2. If you get forecsat, how do you get forecast? What type flood warning message you get and use it?
3. What are the major limitations of the early warning that you received in flood preparedness and response activities?
4. What forecast information you need such timing duration, peak flood level, inundation depth?
5. What is the expected forecast lead-time you need for your flood preparedness activities?
6. If forecast is given in the probabilistic format how do you use it for your decision? (How do you take decision if you get forecast probabilistic forecast -like 50% chance or 75 % of flood?) Say, 80% probability indicates more likely of flood, and 10-20 % probability has less likely. Is this carry value to in making decesions?
7. What would be the challenges or difficultties in understaing the extended range probability forecast for your flood preparedness?
8. How do you want to get forecast for your flood preparedness?
9. Any comments you want to add with this regard

Appendix 5 Sample Flood Bulletin of Bangladesh

(i) Flood Summary



FLOOD INFORMATION CENTRE
FLOOD FORECASTING & WARNING CENTRE
BANGLADESH WATER DEVELOPMENT BOARD
WAPDA BUILDING, 8TH FLOOR, DHAKA.
E-mail: ffwcbwdb@gmail.com, ffwc05@yahoo.com, Site: http://www.ffwc.gov.bd Tel: 9553118, 9550755 Fax: 9557386

RAINFALL AND RIVER SITUATION SUMMARY AS ON JULY 10, 2019

- *All the major rivers are in rising trend.*
- *According to the information of Bangladesh Meteorological Department and India Meteorological Department, there is chance of medium to heavy rainfall & in some places very heavy rainfall in the Northern, North-Eastern and South-Eastern part of Bangladesh along with adjoining Assam, Meghalaya and Tripura states of India in next 24 to 48 hours. Also medium to heavy rainfall may occur in North-West region and adjoining Bihar, West Bengal and Nepal.*
- *All the major rivers may rise in next 72 hours.*
- *The major rivers in Chattogram, Sylhet and Barishal division including the Surma, Kushiyara, Kangsha, Manu, Khowai, Feni, Haldha, Matamuhuri & Sangu may rise rapidly in next 24 hours.*

Stations above Danger Levels (As on 10 July 2019, 09:00 am):

Station name	River	Today's Water Level (meter)	Rise(+)/Fall(-) (cm) during last 24 hours	Danger Level (meter)	Above Danger Level (cm)
Lorergarh	Jadukata	8.78	+90	8.00	+78
Sunamganj	Surma	7.68	+50	7.20	+41
Ballah	Khowai	21.77	+95	12.40	+37
Chiringa	Matamuhuri	6.37	+67	6.25	+12

RAINFALL

Significant rainfalls recorded within Bangladesh during last 24 hrs ending at 09:00 AM today:

Station	Rainfall (mm)	Station	Rainfall (mm)
Lorergarh	280.0	Durgapur	159.0
Dalia	148.0	Lama	148.0
Ramgarh	145.0	Jariajanjail	145.0
Sunamganj	143.0	Bandarban	138.0
Cox's Bazar	125.0	Rangpur	135.0
Nakuagaon	118.0	Narayanhat	108.0
Noakhali	76.0	Dewanganj	75.0
Chittagong	75.0	Kurigram	72.0
Chattak	68.0	Dinajpur	64.0

Significant rainfalls (mm) recorded during last 24 hrs in Sikkim, Assam, Meghalaya & Tripura states of North-East India:

Station	Rainfall (mm)	Station	Rainfall (mm)	Station	Rainfall (mm)
Cherrapunji	259.0	Shillong	192.0	Darjeeling	71.0
Jalpaiguri	62.0	Dibrugarh	61.0	Guwahati	50.0

General River Condition

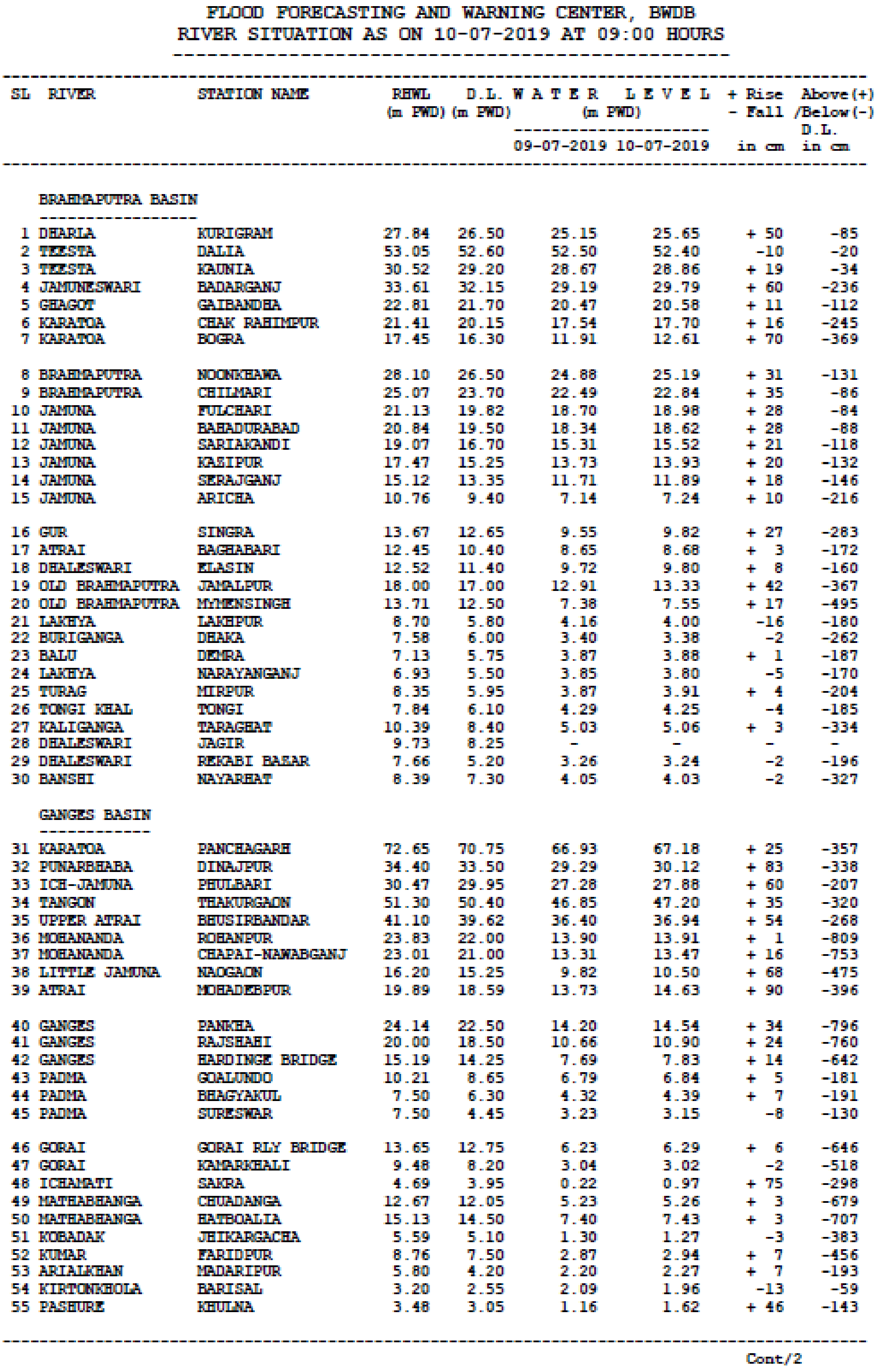
Monitoring Water Level Station	93	Water Level Steady in last 24 hours	01
Water Levels Rise in last 24 hours	75	*Total not Reported	01
Water Levels Fall in last 24 hours	16	**Above Danger Level**	**04**

* Gauge not reported 1 Station (Jagir) .

For Further Query, Feel Free to Contact:

(Md. Arifuzzaman Bhuyan)
Executive Engineer
Duty Officer, FFWC, BWDB.
Cell no:

(ii) Observed flood bulletin (Water level)



```
                  FLOOD FORECASTING AND WARNING CENTER, BWDB
                 RIVER SITUATION AS ON 10-07-2019 AT 09:00 HOURS
                 -----------------------------------------------

---------------------------------------------------------------------------------------------
SL  RIVER              STATION NAME          RHWL    D.L.  W A T E R   L E V E L  + Rise Above(+)
                                           (m PWD) (m PWD)       (m PWD)          - Fall /Below(-)
                                                          ---------------------          D.L.
                                                          09-07-2019 10-07-2019  in cm  in cm
---------------------------------------------------------------------------------------------

   BRAHMAPUTRA BASIN
   -----------------
 1 DHARLA             KURIGRAM             27.84   26.50     25.15      25.65    + 50     -85
 2 TEESTA             DALIA                53.05   52.60     52.50      52.40     -10     -20
 3 TEESTA             KAUNIA               30.52   29.20     28.67      28.86    + 19     -34
 4 JAMUNESWARI        BADARGANJ            33.61   32.15     29.19      29.79    + 60    -236
 5 GHAGOT             GAIBANDHA            22.81   21.70     20.47      20.58    + 11    -112
 6 KARATOA            CHAK RAHIMPUR        21.41   20.15     17.54      17.70    + 16    -245
 7 KARATOA            BOGRA                17.45   16.30     11.91      12.61    + 70    -369

 8 BRAHMAPUTRA        NOONKHAWA            28.10   26.50     24.88      25.19    + 31    -131
 9 BRAHMAPUTRA        CHILMARI             25.07   23.70     22.49      22.84    + 35     -86
10 JAMUNA             FULCHARI             21.13   19.82     18.70      18.98    + 28     -84
11 JAMUNA             BAHADURABAD          20.84   19.50     18.34      18.62    + 28     -88
12 JAMUNA             SARIAKANDI           19.07   16.70     15.31      15.52    + 21    -118
13 JAMUNA             KASIPUR              17.47   15.25     13.73      13.93    + 20    -132
14 JAMUNA             SERAJGANJ            15.12   13.35     11.71      11.89    + 18    -146
15 JAMUNA             ARICHA               10.76    9.40      7.14       7.24    + 10    -216

16 GUR                SINGRA               13.67   12.65      9.55       9.82    + 27    -283
17 ATRAI              BAGHABARI            12.45   10.40      8.65       8.68    +  3    -172
18 DHALESWARI         ELASIN               12.52   11.40      9.72       9.80    +  8    -160
19 OLD BRAHMAPUTRA    JAMALPUR             18.00   17.00     12.91      13.33    + 42    -367
20 OLD BRAHMAPUTRA    MYMENSINGH           13.71   12.50      7.38       7.55    + 17    -495
21 LAKHYA             LAKHPUR               8.70    5.80      4.16       4.00     -16    -180
22 BURIGANGA          DHAKA                 7.58    6.00      3.40       3.38      -2    -262
23 BALU               DEMRA                 7.13    5.75      3.87       3.88    +  1    -187
24 LAKHYA             NARAYANGANJ           6.93    5.50      3.85       3.80      -5    -170
25 TURAG              MIRPUR                8.35    5.95      3.87       3.91    +  4    -204
26 TONGI KHAL         TONGI                 7.84    6.10      4.29       4.25      -4    -185
27 KALIGANGA          TARAGHAT             10.39    8.40      5.03       5.06    +  3    -334
28 DHALESWARI         JAGIR                 9.73    8.25       -          -        -       -
29 DHALESWARI         REKABI BASAR          7.66    5.20      3.26       3.24      -2    -196
30 BANSHI             NAYARHAT              8.39    7.30      4.05       4.03      -2    -327

   GANGES BASIN
   ------------
31 KARATOA            PANCHAGARH           72.65   70.75     66.93      67.18    + 25    -357
32 PUNARBHABA         DINAJPUR             34.40   33.50     29.29      30.12    + 83    -338
33 ICH-JAMUNA         PHULBARI             30.47   29.95     27.28      27.88    + 60    -207
34 TANGON             THAKURGAON           51.30   50.40     46.85      47.20    + 35    -320
35 UPPER ATRAI        BHUSIRBANDAR         41.10   39.62     36.40      36.94    + 54    -268
36 MOHANANDA          ROHANPUR             23.83   22.00     13.90      13.91    +  1    -809
37 MOHANANDA          CHAPAI-NAWABGANJ     23.01   21.00     13.31      13.47    + 16    -753
38 LITTLE JAMUNA      NAOGAON              16.20   15.25      9.82      10.50    + 68    -475
39 ATRAI              MOHADEBPUR           19.89   18.59     13.73      14.63    + 90    -396

40 GANGES             PANKHA               24.14   22.50     14.20      14.54    + 34    -796
41 GANGES             RAJSHAHI             20.00   18.50     10.66      10.90    + 24    -760
42 GANGES             HARDINGE BRIDGE      15.19   14.25      7.69       7.83    + 14    -642
43 PADMA              GOALUNDO             10.21    8.65      6.79       6.84    +  5    -181
44 PADMA              BHAGYAKUL             7.50    6.30      4.32       4.39    +  7    -191
45 PADMA              SURESWAR              7.50    4.45      3.23       3.15      -8    -130

46 GORAI              GORAI RLY BRIDGE     13.65   12.75      6.23       6.29    +  6    -646
47 GORAI              KAMARKHALI            9.48    8.20      3.04       3.02      -2    -518
48 ICHAMATI           SAKRA                 4.69    3.95      0.22       0.97    + 75    -298
49 MATHABHANGA        CHUADANGA            12.67   12.05      5.23       5.26    +  3    -679
50 MATHABHANGA        HATBOALIA            15.13   14.50      7.40       7.43    +  3    -707
51 KOBADAK            JHIKARGACHA           5.59    5.10      1.30       1.27      -3    -383
52 KUMAR              FARIDPUR              8.76    7.50      2.87       2.94    +  7    -456
53 ARIALKHAN          MADARIPUR             5.80    4.20      2.20       2.27    +  7    -193
54 KIRTONKHOLA        BARISAL               3.20    2.55      2.09       1.96     -13     -59
55 PASHURE            KHULNA                3.48    3.05      1.16       1.62    + 46    -143

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                                                                                 Cont/2
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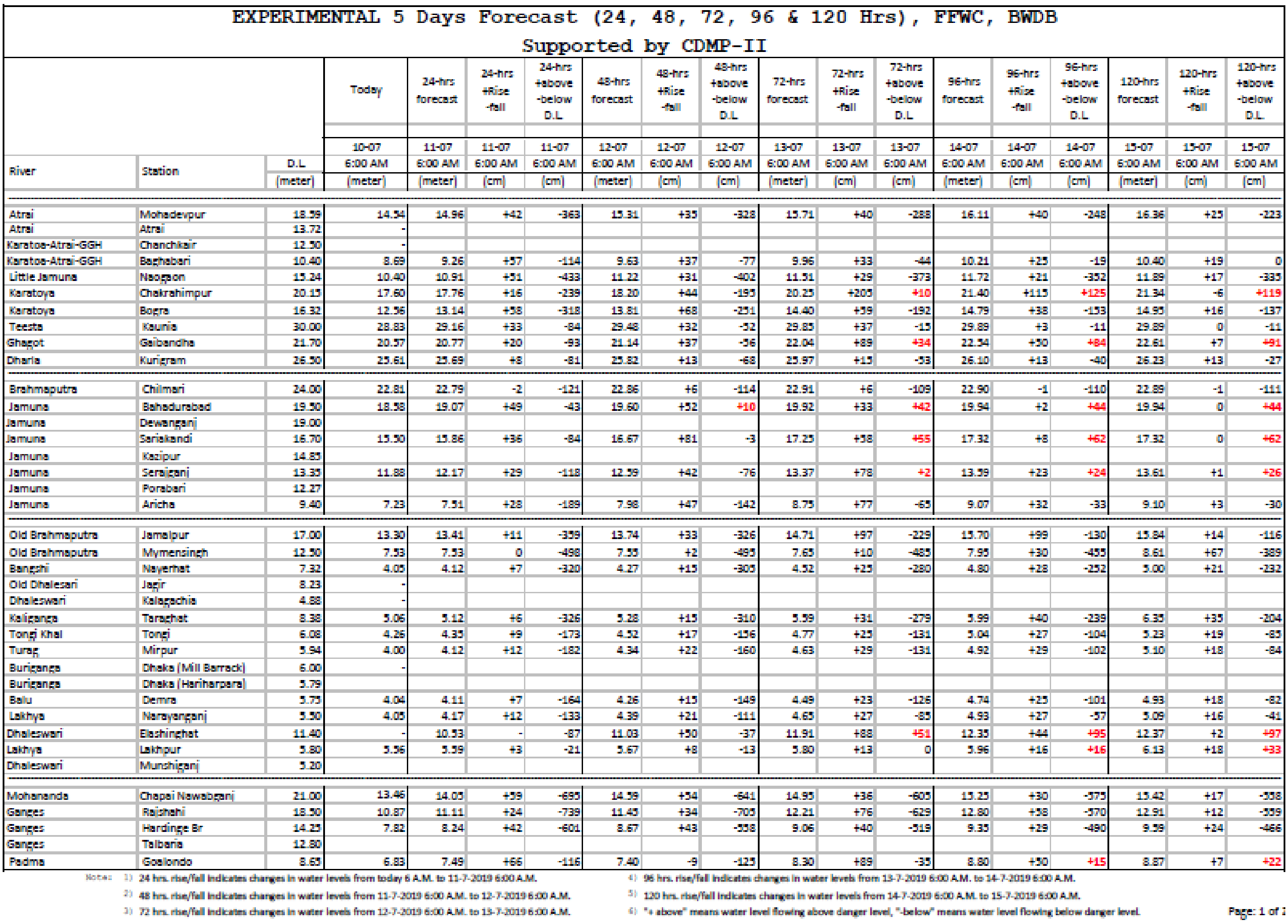
(iii) Forecast bulletin



EXPERIMENTAL 5 Days Forecast (24, 48, 72, 96 & 120 Hrs), FFWC, BWDB
Supported by CDMP-II

River	Station	D.L	Today	24-hrs forecast	24-hrs +Rise -fall	24-hrs +above -below D.L	48-hrs forecast	48-hrs +Rise -fall	48-hrs +above -below D.L	72-hrs forecast	72-hrs +Rise -fall	72-hrs +above -below D.L	96-hrs forecast	96-hrs +Rise -fall	96-hrs +above -below D.L	120-hrs forecast	120-hrs +Rise -fall	120-hrs +above -below D.L
			10-07 6:00 AM	11-07 6:00 AM	11-07 6:00 AM	11-07 6:00 AM	12-07 6:00 AM	12-07 6:00 AM	12-07 6:00 AM	13-07 6:00 AM	13-07 6:00 AM	13-07 6:00 AM	14-07 6:00 AM	14-07 6:00 AM	14-07 6:00 AM	15-07 6:00 AM	15-07 6:00 AM	15-07 6:00 AM
		(meter)	(meter)	(meter)	(cm)	(cm)	(meter)	(cm)	(cm)	(meter)	(cm)	(cm)	(meter)	(cm)	(cm)	(meter)	(cm)	(cm)
Atrai	Mohadevpur	18.59	14.54	14.96	+42	-363	15.31	+35	-328	15.71	+40	-288	16.11	+40	-248	16.36	+25	-223
Atrai	Atrai	13.72	-															
Karatoa-Atrai-GGH	Chanchkair	12.50	-															
Karatoa-Atrai-GGH	Baghabari	10.40	8.69	9.26	+57	-114	9.63	+37	-77	9.96	+33	-44	10.21	+25	-19	10.40	+19	0
Little Jamuna	Naogaon	15.24	10.40	10.91	+51	-433	11.22	+31	-402	11.51	+29	-373	11.72	+21	-352	11.89	+17	-335
Karatoya	Chakrahimpur	20.15	17.60	17.76	+16	-239	18.20	+44	-195	20.25	+205	+10	21.40	+115	+125	21.34	-6	+119
Karatoya	Bogra	16.32	12.56	13.14	+58	-318	13.81	+68	-251	14.40	+59	-192	14.79	+38	-153	14.95	+16	-137
Teesta	Kaunia	30.00	28.83	29.16	+33	-84	29.48	+32	-52	29.85	+37	-15	29.89	+3	-11	29.89	0	-11
Ghagot	Gaibandha	21.70	20.57	20.77	+20	-93	21.14	+37	-56	22.04	+89	+34	22.54	+50	+84	22.61	+7	+91
Dharla	Kurigram	26.50	25.61	25.69	+8	-81	25.82	+13	-68	25.97	+15	-53	26.10	+13	-40	26.23	+13	-27
Brahmaputra	Chilmari	24.00	22.81	22.79	-2	-121	22.86	+6	-114	22.91	+6	-109	22.90	-1	-110	22.89	-1	-111
Jamuna	Bahadurabad	19.50	18.58	19.07	+49	-43	19.60	+52	+10	19.92	+33	+42	19.94	+2	+44	19.94	0	+44
Jamuna	Dewanganj	19.00																
Jamuna	Sariakandi	16.70	15.50	15.86	+36	-84	16.67	+81	-3	17.25	+58	+55	17.32	+8	+62	17.32	0	+62
Jamuna	Kazipur	14.85																
Jamuna	Serajganj	13.35	11.88	12.17	+29	-118	12.59	+42	-76	13.37	+78	+2	13.59	+23	+24	13.61	+1	+26
Jamuna	Porabari	12.27																
Jamuna	Aricha	9.40	7.23	7.51	+28	-189	7.98	+47	-142	8.75	+77	-65	9.07	+32	-33	9.10	+3	-30
Old Brahmaputra	Jamalpur	17.00	13.30	13.41	+11	-359	13.74	+33	-326	14.71	+97	-229	15.70	+99	-130	15.84	+14	-116
Old Brahmaputra	Mymensingh	12.50	7.53	7.53	0	-498	7.55	+2	-495	7.65	+10	-485	7.95	+30	-455	8.61	+67	-389
Bangshi	Nayerhat	7.32	4.05	4.12	+7	-320	4.27	+15	-305	4.52	+25	-280	4.80	+28	-252	5.00	+21	-232
Old Dhalesari	Jagir	8.23	-															
Dhaleswari	Kalagachia	4.88	-															
Kaliganga	Taraghat	8.38	5.06	5.12	+6	-326	5.28	+15	-310	5.59	+31	-279	5.99	+40	-239	6.35	+35	-204
Tongi Khal	Tongi	6.08	4.26	4.35	+9	-173	4.52	+17	-156	4.77	+25	-131	5.04	+27	-104	5.23	+19	-85
Turag	Mirpur	5.94	4.00	4.12	+12	-182	4.34	+22	-160	4.63	+29	-131	4.92	+29	-102	5.10	+18	-84
Buriganga	Dhaka (Mill Barrack)	6.00	-															
Buriganga	Dhaka (Hariharpara)	5.79																
Balu	Demra	5.75	4.04	4.11	+7	-164	4.26	+15	-149	4.49	+23	-126	4.74	+25	-101	4.93	+18	-82
Lakhya	Narayanganj	5.50	4.05	4.17	+12	-133	4.39	+21	-111	4.65	+27	-85	4.93	+27	-57	5.09	+16	-41
Dhaleswari	Elashinghat	11.40	-	10.53	-	-87	11.03	+50	-37	11.91	+88	+51	12.35	+44	+95	12.37	+2	+97
Lakhya	Lakhpur	5.80	5.56	5.59	+3	-21	5.67	+8	-13	5.80	+13	0	5.96	+16	+16	6.13	+18	+33
Dhaleswari	Munshiganj	5.20																
Mohananda	Chapai Nawabganj	21.00	13.46	14.05	+59	-695	14.59	+54	-641	14.95	+36	-605	15.25	+30	-575	15.42	+17	-558
Ganges	Rajshahi	18.50	10.87	11.11	+24	-739	11.45	+34	-705	12.21	+76	-629	12.80	+58	-570	12.91	+12	-559
Ganges	Hardinge Br	14.25	7.82	8.24	+42	-601	8.67	+43	-558	9.06	+40	-519	9.35	+29	-490	9.59	+24	-466
Ganges	Talbaria	12.80																
Padma	Goalondo	8.65	6.83	7.49	+66	-116	7.40	-9	-125	8.30	+89	-35	8.80	+50	+15	8.87	+7	+22

Notes:
1) 24 hrs. rise/fall indicates changes in water levels from today 6 A.M. to 11-7-2019 6:00 A.M.
2) 48 hrs. rise/fall indicates changes in water levels from 11-7-2019 6:00 A.M. to 12-7-2019 6:00 A.M.
3) 72 hrs. rise/fall indicates changes in water levels from 12-7-2019 6:00 A.M. to 13-7-2019 6:00 A.M.
4) 96 hrs. rise/fall indicates changes in water levels from 13-7-2019 6:00 A.M. to 14-7-2019 6:00 A.M.
5) 120 hrs. rise/fall indicates changes in water levels from 14-7-2019 6:00 A.M. to 15-7-2019 6:00 A.M.
6) "+ above" means water level flowing above danger level, "-below" means water level flowing below danger level.

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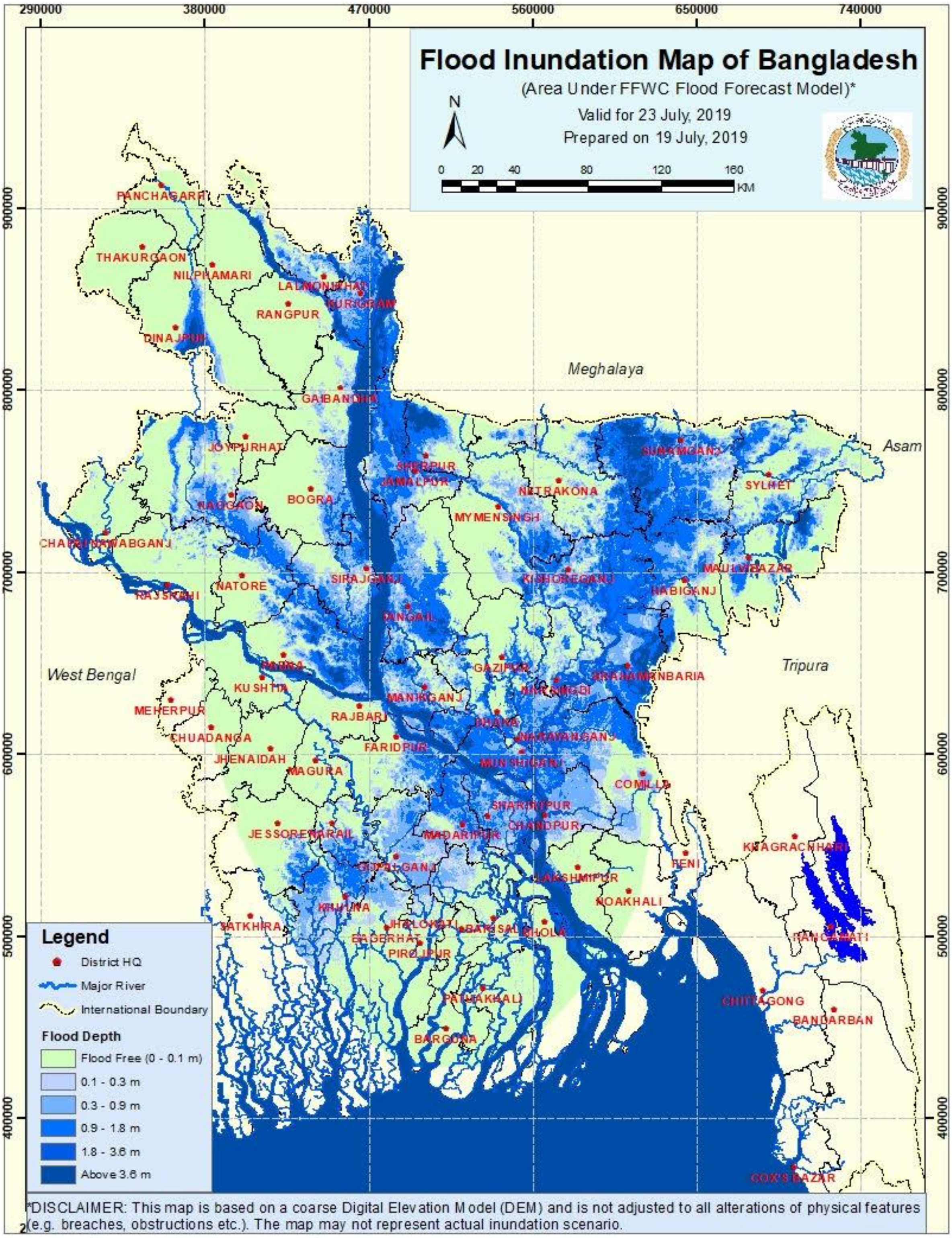
(iv) FFWC's forecasted inundation map



Flood Inundation Map of Bangladesh

(Area Under FFWC Flood Forecast Model)*

Valid for 23 July, 2019

Prepared on 19 July, 2019

*DISCLAIMER: This map is based on a coarse Digital Elevation Model (DEM) and is not adjusted to all alterations of physical features (e.g. breaches, obstructions etc.). The map may not represent actual inundation scenario.

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