The Impact of Small Tributaries Flood in the Braided Plain of Large River

Md. Manjurul Hussain, Shampa, Juwel Islam, Md. Shibbir Ahmed, Md. Ashiqur Rahman, and Md. Munsur Rahman

Abstract Flooding of the braided Brahmaputra-Jamuna River causes significant economic losses in the northern region of Bangladesh every year. Presently, the intensity and timing of floods are mainly captured by the water level at a few selected stations of the river. Flood Forecasting and Warning Centre (FFWC) of the Bangladesh Water Development Board (BWDB) is officially mandated to regularly disseminate the water level for several rivers during the flood season. The water levels along the Brahmaputra-Jamuna at some strategic stations (such as Chilmari, Bahadurabad, Sirajganj etc.) are playing an important role for the above flood warning system in the North-Central part of Bangladesh. The right bank tributaries to the Brahmaputra-Jamuna River—the Teesta and the Dharla—are contributing rapid (flashy in nature) flow to the system, the effects of which are still unidentified. This study investigates the effects of the variations of flood flow of these tributaries on the flooding of the Brahmaputra-Jamuna basin at the local level by using the 2D hydrodynamic model. A 225 km long hydrodynamic model domain was set along the Brahmaputra-Jamuna, including the most vulnerable floodplain of Dharla and Teesta at Kurigram and Jamalpur districts, respectively. The results show that the variation of flow of the tributaries is trivial to the flood level at the stations where BWDB is capturing water-level data. However, the tributaries' flow has considerable effects on Charland flooding. In addition, the results demonstrate that the flood depth of some places in the char lands varies more than one metre for the variation of the contribution it receives from the tributaries. These observations indicate that the above fact for flood forecasting and warning systems will be important, especially for the Charland area in the Brahmaputra-Jamuna system.

Keywords Brahmaputra-Jamuna · Dharla · Teesta · Tributaries · Charland · Flooding

Md. M. Hussain (✉) · Shampa · J. Islam · Md. S. Ahmed · Md. A. Rahman · Md. M. Rahman
Institute of Water and Flood Management (IWFM), Bangladesh University of Engineering and Technology, Dhaka, Bangladesh

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1 Introduction

Bangladesh is one of the world's most natural disaster-prone country where floods, storm surges, cyclones, riverbank erosions and droughts are frequent occurrences (Nasreen 2004). Among these natural disasters, flood represents one of the most dominant ones. Flood is a regular feature in Bangladesh due to its geographical setting influenced by the overflow of major rivers and their tributaries and distributaries (Karim and Mimura 2008; Mamun et al. 2019; Younus et al. 2007). Catastrophic flooding events, for example, floods from the years 1988, 1998 and 2020, are a highly critical issue for the country which causes untold suffering to millions of people. The effect of catastrophic floods can be devastating and result in appreciable damage to crops and houses, severe riverbank erosion with consequent loss of homesteads, schools and land, as well as loss of human lives, livestock and fisheries (Pramanik 1991). If we consider basin-wise flooding, the mighty Brahmaputra-Jamuna has been the main contributor to most of the catastrophic flood cases in Bangladesh (NAWG 2020).

The Brahmaputra-Jamuna River, draining from the northern and eastern slopes of the Himalayas, is 2900 km long, wherein the reach length is 240 km in Bangladesh (Bhuiyan 2014). Geologically, it is one of the youngest rivers in the world (Archana et al. 2012). Because of abnormal flood and tectonic activity, the Brahmaputra River began to flow through a new course known as Jamuna from 1787 (Uddin et al. 2011). The right bank of the Jamuna was once a part of the Teesta floodplain, and now through the Dudhkumar and Dharala distributary of the Jamuna, is part of the bigger floodplain. Several distributaries of the Brahmaputra-Jamuna flow through the left bank floodplain which is later sub-classed as the Brahmaputra-Jamuna floodplain. The southern part of this sub-region was once a part of the Ganges floodplain (Paul 2011). The Brahmaputra-Jamuna River contributes ∼51% of the water discharge and 38% of the sediment yield to the Ganges–Brahmaputra-Meghna (GBM) system (Schumm and Winkley 1994). The river is braided in nature with a width of up to 15 km and average depths of 6 m to 7 m (Klaassen and Vermeer 1988; Shampa 2019a). It has three main tributaries in the left bank i.e. Dudhkumer, Dharla and Teesta, and three main distributaries in the right bank which are Old Brahmaputra, Jenai and Dhaleswari (see Fig. 1).

The transboundary Teesta River is one of the major contributors or tributaries of Brahmaputra-Jamuna. The river flows through five northern districts of Bangladesh, which are Gaibandha, Kurigram, Lalmonirhat, Nilphamari and Rangpur (Rangpur Division), comprising an area of 9667 sq.km, 35 thanas and 5427 villages with an estimated population of 9.15 million as of 2011. The river plays a key role in flushing silt and sediment deposited during the dry season is a lifeline for irrigation, agriculture, farming, fishing and navigation in the region. This transboundary river is encroached by many dams and barrages both in India and Bangladesh. In the rainy season, excessive flow is dispensed by these dams and barrages, causing floods in the downstream areas (Rahman and Ali 2016). The river Teesta experiences several peaks during the monsoon season causing local floods. For example, in the year 2017, the

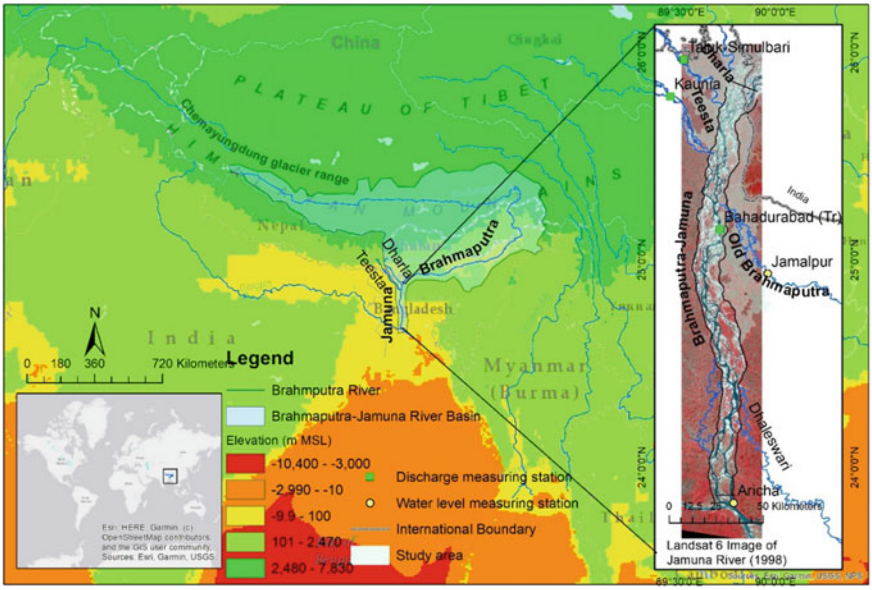

Fig. 1 The Brahmaputra-Jamuna River and its major tributaries and distributaries

water level crossed the danger level at Dhalia Point of Teesta for more than 6 days, a resulting in low-lying areas being submerged for several days (FFWC 2018). Among the other tributaries, Dharla is one of the major contributors to Brahmaputra-Jamuna. It originates in the Himalayas and enters Bangladesh through the Lalmonirhat district and flows as the Dharla River until it meets the Brahmaputra-Jamuna River near the Kurigram District (Fig. 1). Dharla River, along with the Brahmaputra River, has substantial influence on floods and riverbank erosion in different districts of Bangladesh (Pal et al. 2017). For example, the water level of the Dharla river at Kurigram point remained above the danger level for more than 30 days due to the 1998 floods, as a result of which the area was inundated for a long time (FFWC 2018). While the overall flooding situations of past events (i.e. 1987, 1988, 1998, 2007) are quite well documented, the contribution of these two major tributaries in the flooding of the Brahmaputra-Jamuna is yet to be known (Best et al. 2007; Dewan et al. 2003; Islam and Chowdhury 2002; Mosselman 2006).

Nevertheless, human activities such as land use and construction of infrastructure, such as dams, barrages, bridges, artificial levees, are continuously altering the river regime. Given the large-scale approach, it is important to understand the sub-regions scale details of the flooding characteristics. In recent decades, flood damage has been increasing all over the world, due to high population growth, economic activities in floodplain areas, and intensified precipitation due to climate change (Albano et al. 2017; Kvočka et al. 2016; Munich Re 2015). Bangladesh is no exception (Dewan 2015). Although the country has been able to significantly reduce the loss of lives due to floods, the economic loss and damage have increased over the decades (Ferdous et al. 2019; Mechler and Bouwer 2015). The recent monsoon floods of 2020 affected about 30 districts in Bangladesh, of which 15 districts were severely hit. The damage was comparatively higher in the Brahmaputra-Jamuna floodplain areas of the Kurigram and Jamalpur districts. More than 50% of the area in 59 unions of 7 Upazilas of Jamalpur district , and 59 unions of 9 Upazilas of Kurigram district, were flooded (NAWG 2020).

Against this backdrop, this study attempts to deduce the impact of flood flow of Teesta and Dharla tributaries on the river basin of Brahmaputra-Jamuna including its char areas. Specifically, the study attempts to identify the impacts of tributary flow on flood hazard parameters, such as flood depth, duration and velocity, of the major Brahmaputra-Jamuna River using 2D hydrodynamic simulations. The flooding condition of the year 1998 has been considered as the base, and three hypothetical conditions have been generated based on the flow of Dharla and Teesta. As a study area, the major flood-prone unions of Kurigram and Jamalpur districts were considered as shown in Fig. 1. The next section of the paper describes the methodology of this study. The impact of the tributary flood is illustrated in the last parts.

2 Methodology

For this research, we used a well-calibrated and validated 2D hydrodynamic model by Shampa (2019b) and Shampa et al. (2017). Delft3D (flow version 4.00.01.000000), an open-source software, was used to develop the numerical model (Lesser et al. 2004). In the hydrodynamic part, Navier–Stokes-based two-dimensional depth-averaged shallSow water (for incompressible free surface flow) equations with consideration of Boussinesq approximations were used to solve the model. A short description of the model is given below.

The continuity equation was used to calculate conservation of mass (1)

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \quad (1)$$

Conservation of momentum in the *x*-direction is shown by Eq. (2)

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \zeta}{\partial x} + \frac{gn^2}{\sqrt[3]{h}}\left(\frac{u\left(u^2 + v^2\right)}{h}\right) - v_h\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) = 0 \quad (2)$$

Conservation of momentum in the *y*-direction is shown by Eq. (3)

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial x} + g\frac{\partial \zeta}{\partial x} + \frac{gn^2}{\sqrt[3]{h}}\left(\frac{v\left(u^2 + v^2\right)}{h}\right) - v_h\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) = 0 \quad (3)$$

where ζ is water level elevation with respect to a datum (here in m); h represents water depth (m) u, v is depth average velocity in the x and y directions (m/s); g is the gravitational acceleration (m/s^2); v_h denotes kinetic eddy viscosity (m^2/s); n represents the Manning's coefficient (sm-1/3). The terms $v_h\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)$ and $v_h\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right)$ in Eqs. (2) and (3) represent the horizontal Reynold's stress under the eddy viscosity concept neglecting the shear stress along the closed boundaries. The model area consists of the whole Brahmaputra-Jamuna River and parts of Dudhkumar, Dharla, Teesra and Old Brahmaputra rivers encompassing a length of 246 km and an average width of 33 km. The total area has been divided into 127 × 893 cells curvilinear grids to perform the 2D hydrodynamic simulation. For the bathymetry data, the interpolated data from the measured bathymetry of BWDB for the year 1998 was considered. For the topographic data, Shuttle Radar Topography Mission data of the year 2014 was used. Figure 2 shows the model grid and bathymetry. The boundary data of discharge and the water level have been collected from BWDB. The observed/generated discharge data of Brahmaputra-Jamuna, Teesta, Dharla and Dudhkumar River are considered as the upstream boundary condition. At the same time, observed/generated water levels of Brahmaputra-Jamuna

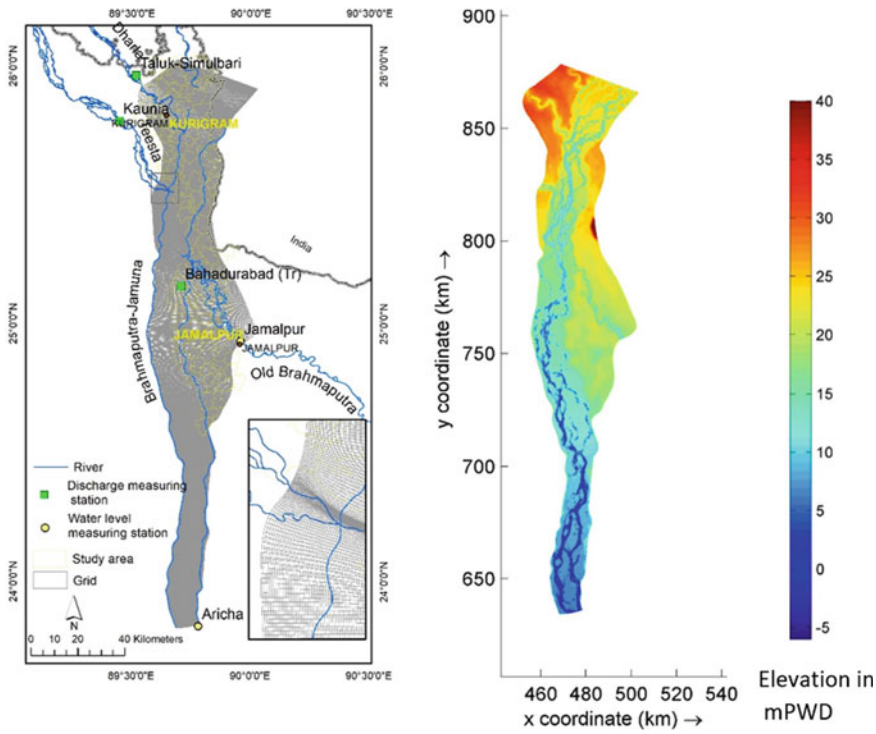

Fig. 2 Model grid and bathymetry

(Aricha), Old Brahmaputra (Jamalpur), are considered as the downstream boundary condition.

For this research, two types of conditions have been considered which are base and hypothetical conditions as shown in Table 1. Three types of scenarios were set up for the hypothetical conditions—(i) the discharge value of the Teesta-Dharla River is Zero (Both Zero); (ii) the discharge value of Dharla is Zero (Dharla Zero) and (iii) the discharge value of Teesta is Zero (Teesta Zero). All models run at the 100-year return periods condition reflecting the flood of 1998. The boundary condition of the base condition, $BJ_a D_a T_a$ is shown in Fig. 3.

From the simulation results, flood information such as the area of inundation, depth of inundation, duration of inundation and flow velocity has been extracted for three temporal conditions (pre-flood, post-flood and peak flood). Depth of inundation and

Table 1 Scenario considered in this study

Scenarios	Criteria
Base condition, $BJ_a D_a T_a$	Flood of 1998
Hypothetical condition	
Both Zero $BJ_a D_0 T_0$	Discharge of Dharla and Teesta is zero But Brahmaputra-Jamuna has the same discharge of the flood 1998
Dharla Zero, $BJ_a D_0 T_a$	Discharge of Dharla is zero But Brahmaputra-Jamuna and Teesta have the same discharge of the flood 1998
Teesta zero $BJ_a D_a T_0$	Discharge of Teesta is zero But Brahmaputra-Jamuna and Dharla have the same discharge of the flood 1998

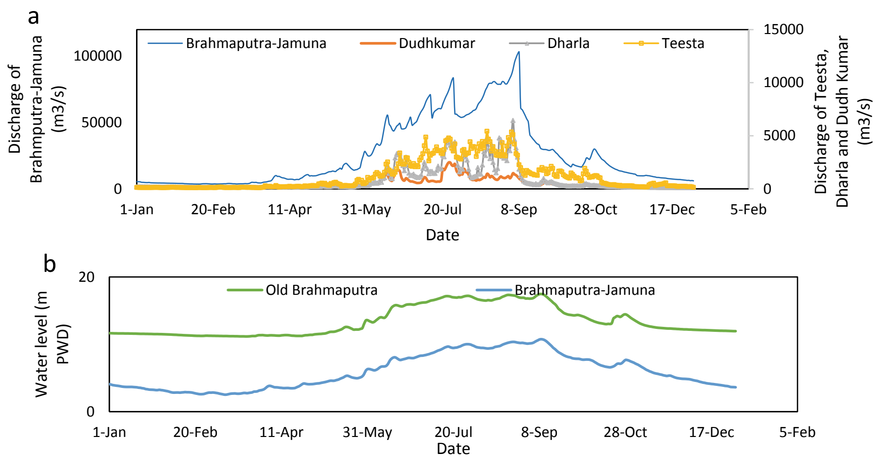

Fig. 3 Boundary conditions of the model for Base condition, $BJ_a D_a T_a$. **a** Upstream discharge boundary. **b** Downstream water-level boundary

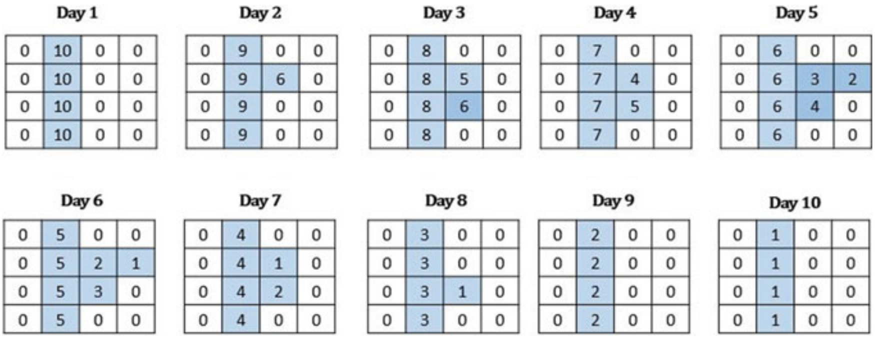

Fig. 4 Flood duration calculation process, where blue indicates water in that cell

flow velocity were directly extracted from model results, and duration was calculated from the depth of inundation. Calculations were done separately for every individual cell. If one cell contains water continuously for several days, then it was counted backwards to find the duration for every day in that cell (Fig. 4). After extracting all the results, a comparison was made between actual and hypothetical conditions to determine the influence of tributary rivers.

3 Results

3.1 The Flood Characteristics

Before discussing the hypothetical condition results, it is important to examine the character of the actual flooding (base) condition. Figure 5 shows the flood-hydrograph characteristics of the considered rivers at the base or actual condition $BJ_a D_a T_a$. It is evident from this figure that the Brahmaputra-Jamuna carried more than 90% (annual average) of flow during the considered year (Fig. 5a). However, during the peak monsoon, the sharing of Dharla (6.25%) and Teesta (5.26%) increased slightly (around 1% to 2%). But this slight increase had an impact on local water levels. Figure 5b shows the 7-day moving average of the rate of rising of water-level hydrograph of the Bahadurabad at Brahmaputra-Jamuna, Teesta at Kaunia and Dharla at Taluk-Simulbari. It is evident from this figure that the rise of Dharla and Teesta caused an increase of the hydrograph of the Brahmaputra-Jamuna each time. This phenomenon contributes to the local flooding.

Figure 6 shows the flooding depth and extent for different conditions at peak monsoon. It confirms that when the river discharge is nil either in Dharla ($BJ_a D_0 T_a$), or Teesta ($BJ_a D_a T_0$) or both ($BJ_a D_0 T_0$, c), the flooding depth is 0 m to 0.30 m lower than the base condition. Though the areal extent was almost similar in all conditions (Kurigram 55% and Jamalpur 43%).

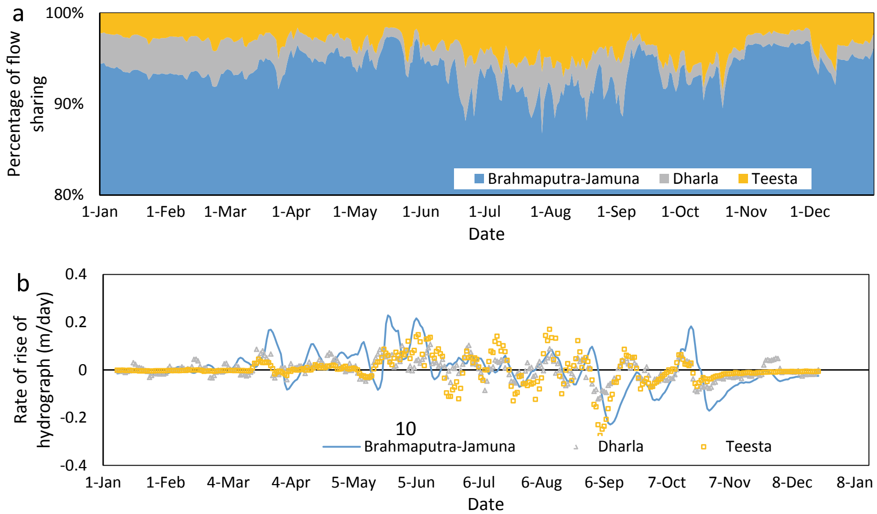

Fig. 5 The flood-hydrograph characteristics of the considered rivers at the base condition $\mathrm{BJ}_a D_a T_a$. **a**. The percentage of flow sharing in actual condition, **b**. 7-days moving average of rate of rising of water-level hydrograph of the considered rivers

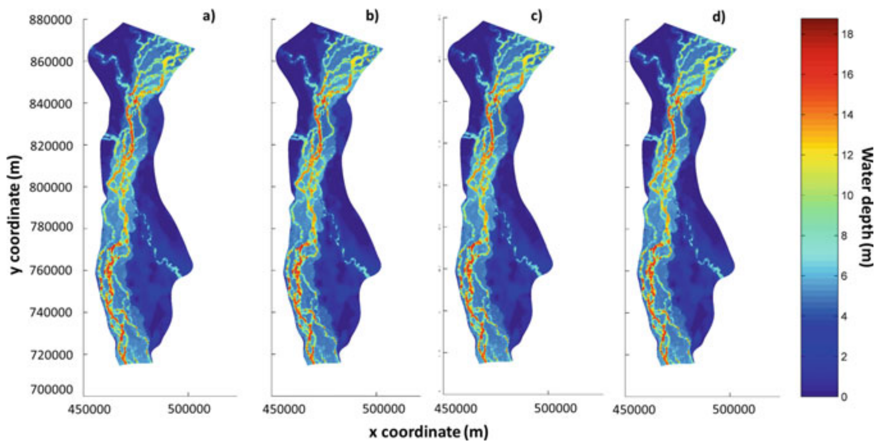

Fig. 6 Water depth (in m) of **a** base $\mathrm{BJ}_a D_a T_a$, **b** both zero $\mathrm{BJ}_a D_0 T_0$, **c** Dharla zero $\mathrm{BJ}_a D_0 T_a$, **d** Teesta zero $\mathrm{BJ}_a D_a T_0$ condition at peak-flooding time

3.2 *Flood Depth*

The simulation results showed that at base condition, $\mathrm{BJ}_a D_a T_a$, the average flooding depth varies between 2.06 m and 3.37 m in the study domain as shown in Table 2. However, at Both Zero condition, the depth was lowered by 3.8% and 3.6% in

Table 2 Flooding depth of the considered cases the study domain

Scenarios	Average flooding depth (in m)		
	Pre-monsoon	Monsoon	Post-monsoon
Base condition, $BJ_a D_a T_a$	2.06	3.37	2.15
Hypothetical condition			
Both zero $BJ_a D_0 T_0$	1.98	3.25	2.11
Dharla zero, $BJ_a D_0 T_a$	2.03	3.30	2.14
Teesta zero $BJ_a D_a T_0$	2.02	3.32	2.12

pre-monsoon and monsoon periods correspondingly. In the post-monsoon season, the depth was similar to that of the base condition (1.86%). The impact of flooding depth in $BJ_a D_0 T_a$ and $BJ_a D_a T_0$ conditions was prominent in monsoon time. In Dharla Zero condition $BJ_a D_0 T_a$, the depth was decreased by 2.07% whereas in Teesta Zero condition $BJ_a D_a T_0$, it was found to be 1.48% less than that of the base condition. The special comparison of flood depth among the base, $BJ_a D_a T_a$ and hypothetical scenarios (Both Zero $BJ_a D_0 T_0$, Dharla Zero $BJ_a D_0 T_a$, Teesta zero $BJ_a D_a T_0$) is shown in Fig. 7. It indicates that the floodwater depth increases 0 m to 0.3 m due to both Dharla and Teesta River discharge. Whereas, the contribution to Jamuna flood depth for only Dharla or Teesta is 0 to 0.15 m (Fig. 7). The maximum variation found in peak flood conditions and the variation in post-flood conditions are negligible.

Here, the area-specific analysis was done by differentiating the flooding of inland and char areas in the two districts. At base condition, the average depth of flooding during the monsoon season was 5.44 m and 0.30 m in Kurigram district's char land and inland area, respectively. In pre-monsoon and post-monsoon seasons, the flooding depth was 67% and 59% lower in char areas, whereas the depth was 0.07 m in both pre and post-monsoon seasons for inland areas. In Jamalpur, the flooding depth was higher in inland areas (0.34 m) but lower in char areas (5.22 m) in comparison to the Kurigram district during monsoon season. In the char areas of Jamalpur, the depth was 70% and 57% lower than the monsoon season in pre and post-monsoon seasons, respectively. In inland areas of Jamalpur, the depth was 0.10 m in both pre and post-monsoon periods. Figure 8 shows the flood depth difference between the base condition and all hypothetical conditions. It is evident from this figure that the alteration of tributary discharge affects the flooding depth of char areas in both districts mostly. The maximum difference (0.22 m) was found in the chars of Jamalpur district in Both Zero $BJ_a D_0 T_0$ conditions during monsoon time. In the case of the chars of Kurigram, it was 0.12 m. The influence of Teesta was greater (0.07 m in char and 0.1 m in inland) in flooding depth than Dharla compared to the base condition.

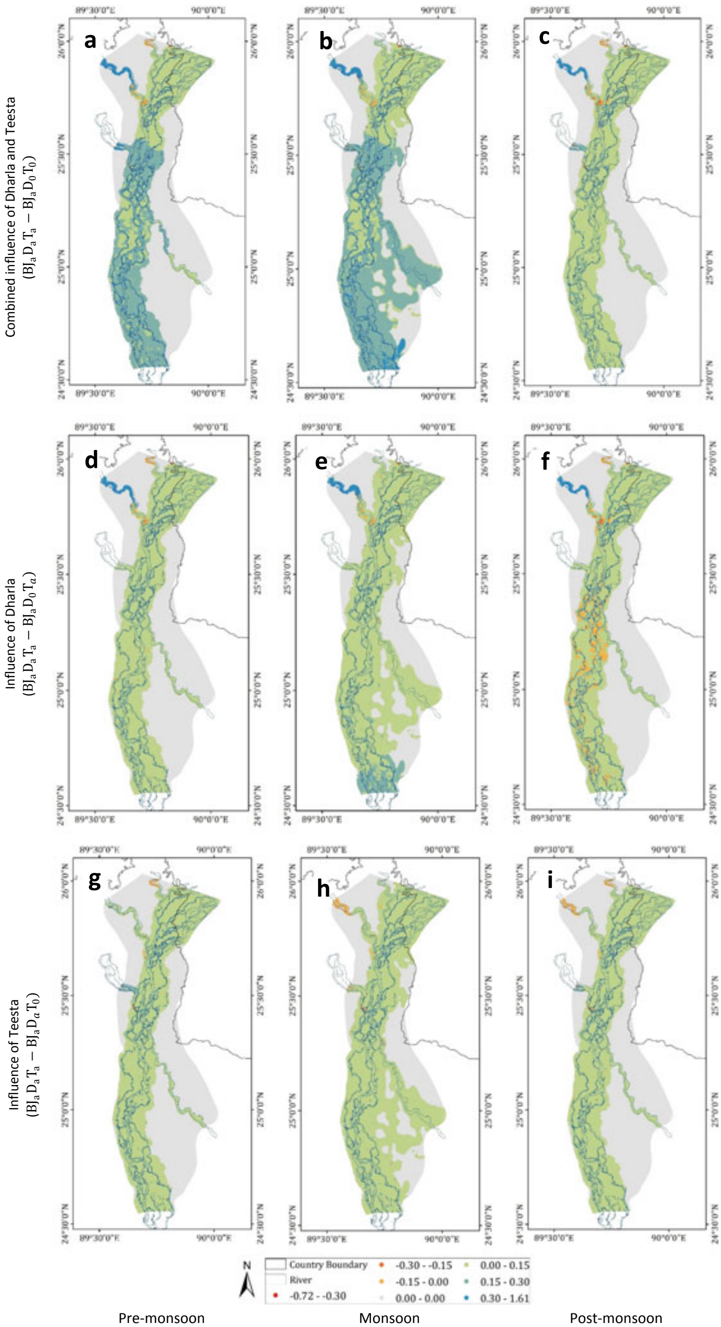

Fig. 7 Difference of flood depth between base and hypothetical condition

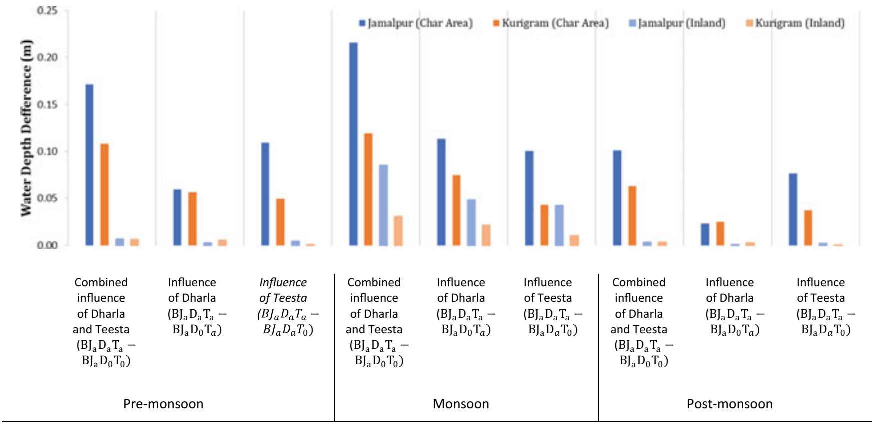

Fig. 8 Flood depth difference between base and hypothetical condition

3.3 Flood Duration

Duration is one of the major hazard parameters for floods. The study area consists of inland and char areas. The flood duration was found to be relatively low for inland areas, whereas the chars experienced very high duration flood. The results show that in the base condition, the flood duration varies from 0 to 115 days. But in Both Zero condition $\mathrm{BJ}_a D_0 T_0$, the duration was only 1% less. The influence of Dharla (0 days) was greater than Teesta (1 day) on flood duration. Figure 9 shows the difference map of flood duration among the considered scenarios in pre-monsoon, monsoon and post-monsoon periods. It is evident from this figure that the influence of the tributary discharge was similar during these three timelines. When considering the discharge of both tributaries to be nil ($\mathrm{BJ}_a D_a T_a - \mathrm{BJ}_a D_0 T_0$), the flooding duration reduced to two days compared to the base condition (Fig. 9a–c). The effect of the Dharla on flood duration was insignificant (nearly 1 day) due to its flashy nature of the hydrograph. But it resulted in local flood in the Kurigram district (Fig. 9d–f). Due to the influence of Teesta, the flood duration may increase by nearly three days (Fig. 9g–i). Figure 10 shows the difference in flood duration in char and inland areas in both districts. This figure depicts that due to the influence of tributary discharge, the highest flood duration altered around 4 days in char areas and 1 day in inland areas. The chars of Jamalpur areas are more susceptible to long-duration flooding compared to Kurigram district's flood. The influence of tributary discharge inland flood duration is insignificant (about one day).

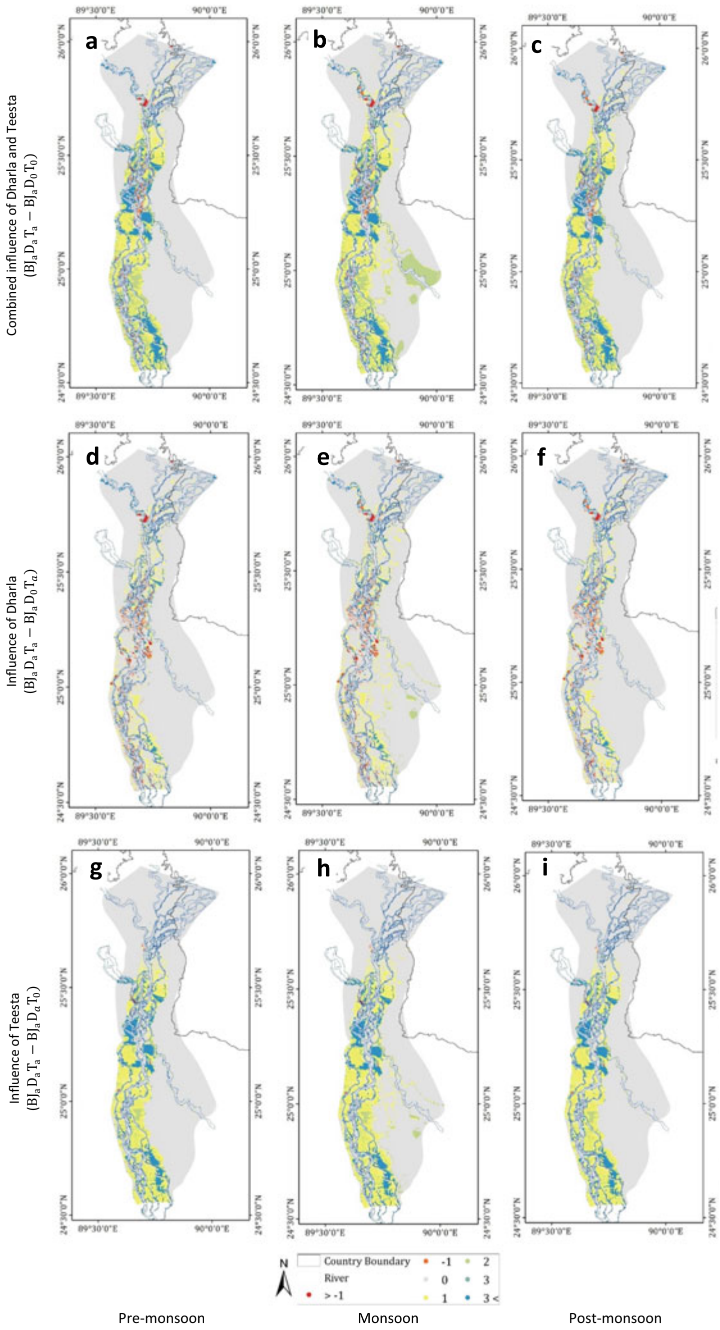

Fig. 9 Difference map of flood duration among the considered scenarios

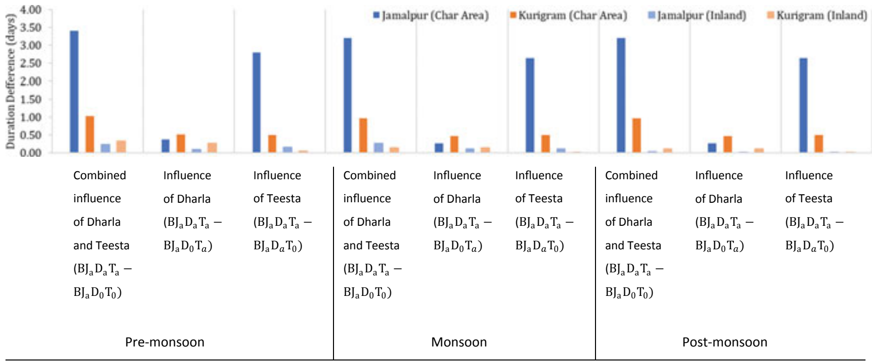

Fig. 10 Flood duration difference between base and hypothetical condition

3.4 Flood Velocity

Figure 11 shows the histogram plot of velocity magnitude in different scenarios. The *x*-axis showed the velocity magnitude class while the *y*-axis shows the number of grid cells containing that velocity in the model domain. As the study domain contains the land of various elevations, the range of velocity distribution is quite large. For example, the near channel area of chars has very low elevation compared to the floodplain or mid-char areas. Therefore, we consider the histogram plot for comparing the velocity of different cases. All the subfigures of Fig. 11 show two peaks due to the variation of velocity in low-lying and higher elevated areas. It depicts that unlike the flood duration, the flooding velocity shows seasonal variation. In base condition ($\mathrm{BJ_a}D_aT_a$), during the pre-monsoon period, the velocity magnitude varies from 0 m/s to 2.26 m/s. In the inland areas, the velocity varies between 0 and 0.22 m/s, and when near the channel, it ranges between 0.44 m/s and 0.89 m/s, maintaining an average velocity of 0.40 m/s. During the monsoon period, the maximum velocity was found to be 2.51 m/s, wherein the average velocity increases by 1.5 times. In the post-monsoon season, the velocity distribution was quite similar to the pre-monsoon season (Fig. 11a–c). The distribution pattern of the hypothetical cases was similar to that of the base condition (Fig. 11d–l). In the pre-monsoon period, the velocity magnitude ranges from 0 m/s to 2.3 m/s with the average value of 0.38 m/s in all hypothetical conditions. In the monsoon season, the maximum velocity was found to be 2.53 m/s ($\mathrm{BJ}_aD_0T_0$) with an average value of 0.60 m/s. In the post-monsoon season, a maximum velocity of 2.3 m/s ($\mathrm{BJ}_aD_\mathrm{a}T_0$) was noted, wherein the average velocity was 0.40 m/s. Figure 12 shows the spatial distribution of the difference of flood velocity magnitude among the considered scenarios. It illustrates that the contribution in velocity magnitude of Dharla and Teesta varies between − 0.015 m/s and 0.030 m/s. The main variation was observed at the lower left bank of Brahmaputra-Jamuna in peak-flooding conditions as this section has better floodplain connectivity (the right bank of the study domain was partially embanked).

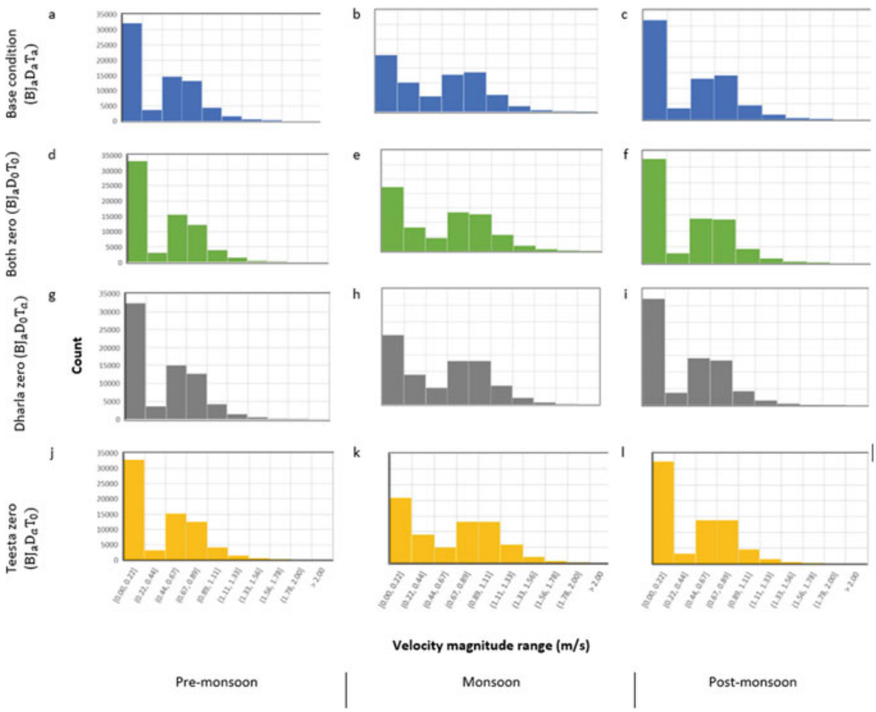

Fig. 11 Distribution of velocity magnitude of the considered cases

At base condition, the average velocity was 0.97 m/s in Kurigram district's char areas, whereas in Jamalpur it was 0.93 m/s as the valley slope is higher in Kurigram. But for the inland areas, the flooding velocity was 0.15 m/s in Kurigram and 0.25 m/s in Jamalpur. As the inland area of Kurigam contains partial embankment, it hampered the drainage path of the floodwater. The contribution of the tributary in velocity increment or decrement in char and inland areas was very small (0.01 m/s).

4 Discussion

Brahmaputra-Jamuna River is one of the major rivers in Bangladesh, and a lot of studies have been conducted on the Brahmaputra-Jamuna River floods (Best et al. 2007; Dewan et al. 2003; Islam and Chowdhury 2002; Mosselman 2006). But no previous study has been done to investigate the contribution of its tributaries. In this study, we tried to find the impact of tributaries by comparing different flood parameters (inundation depth, flood duration, flow velocity) in different conditions (base, $\mathrm{BJ}_a D_a T_a$, Both Zero $\mathrm{BJ}_a D_0 T_0$, Dharla Zero $\mathrm{BJ}_a D_0 T_a$, Teesta Zero $\mathrm{BJ}_a D_a T_0$). The results show that the inundation depth varies up to 3.8% due to contribution of Teesta

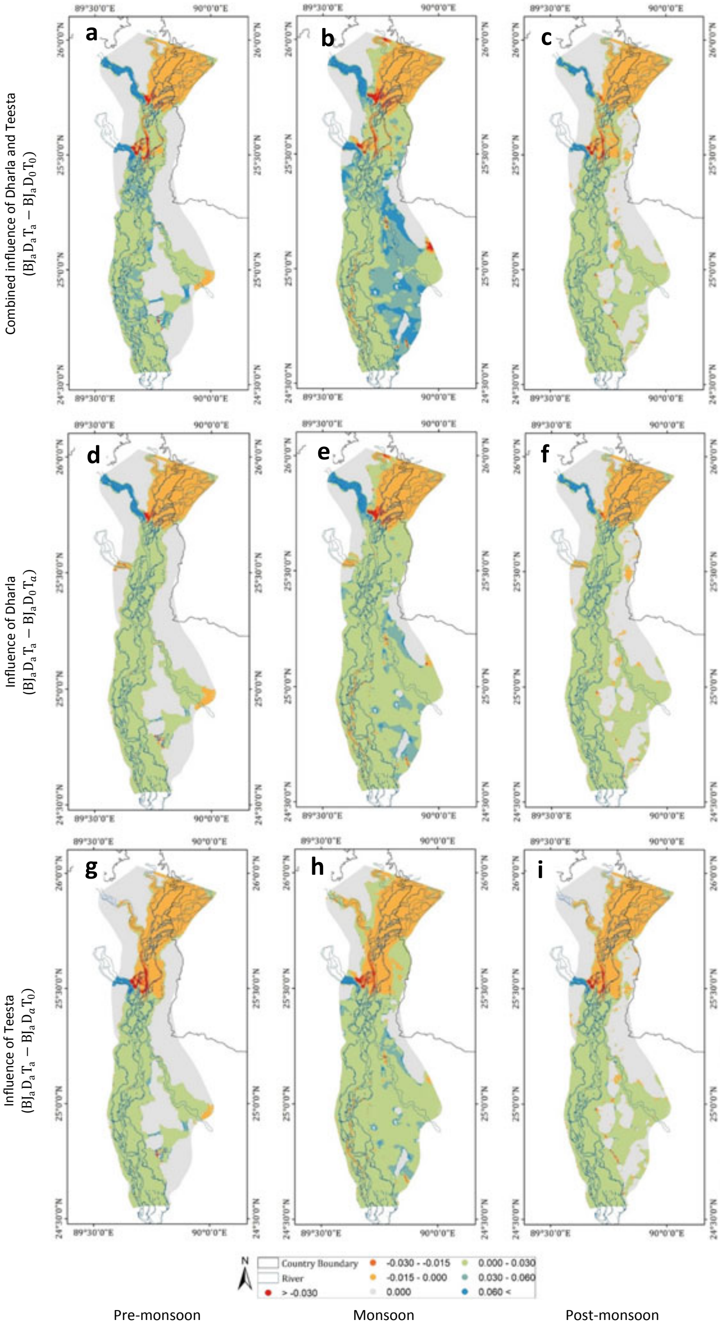

Fig. 12 Spatial distribution of flood velocity magnitude change among the considered scenarios

and Dharla river water. Islam and Chowdhury (2002) claims that, continuous inflow of high discharge for more than two and half months occurred in the Brahmaputra-Jamuna in 1998, which is consistent with the base condition $BJ_a D_a T_a$ results. The contribution in velocity magnitude of Dharla and Teesta varies between -0.015 m/s and 0.030 m/s. The study also found that Teesta and Dharla only contribute to 10% of discharge water in Brahmaputra-Jamuna River. The large difference between the river discharge of Brahmaputra-Jamuna and Teesta and Dharla is the probable reason for this small impact in Brahmaputra-Jamuna floods.

Although the aerial extent of flooding is largely dependent on the flooding pattern of the Brahmaputra-Jamuna, tributary flooding affects local flood conditions especially in the char areas. The flooding depth increase by up to 0.20 m due to the flooding conditions of the tributaries. The flooding duration can increase by up to three days due to the influence of the Teesta and Dharla. The flooding velocity was influenced by the presence of the local infrastructure (e.g. embankments). The downstream district Jamalpur was found to be more susceptible to flooding. The recent flood of the year 2020 has also shown a similar damage trend in Jamalpur (NAWG 2020).

This study aimed to gather new insights into the impact of tributaries on the Brahmaputra-Jamuna floods, by undertaking analyses that have not been conducted before. However, this study only accounted for Brahmaputra-Jamuna high flood (100-year return periods) condition. For a comprehensive understanding of the nature of Brahmaputra-Jamuna's tributaries, other types of scenarios (such as the high flood in Dharla-Teesta, normal flood in Jamuna etc.) can be investigated.

5 Conclusion

In this study, we investigate the influence of the flow of Teesta and Dharla river tributaries on flooding of the Brahmaputra-Jamuna. The study found that the rise of water level in the Dharla and Teesta rivers cause an increase in the water level of the Brahmaputra-Jamuna each time, which results in local floods, especially in char areas. The impact of Teesta is higher in terms of flood depth, duration and velocity compared to Dharla River. The downstream reach (i.e. Jamalpur district in this case) is more susceptible to tributary flooding. The char and inland flooding characteristics are significantly different. The flooding depth increases almost 25 times in char lands relative to inland flooding. The flood duration increases nearly 18 times in char lands and velocity may increase ninefold in char areas compared to inland areas. Therefore, similar flood adaptation techniques in inland and char areas may be inappropriate. It is expected that the results of this study will contribute to Brahmaputra-Jamuna's long-term flood risk management planning.

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