DETECTION OF WATERLOGGING FLOODS IN BENGAL MEGA-DELTA FROM PEOPLE'S PERCEPTION UNDERPINNED BY HYDROMETEOROLOGICAL DATASET

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ABSTRACT

Bangladesh has a long history of sufferings from inundation and waterlogging due to monsoon rainfall. We tried to represent waterlogging flood from social and hydrometeorological science perspectives. Research aimed to highlight on people's sufferings from inundation and waterlogging at village Garaber in Bangladesh; to calculate local rainfall and its relation of waterlogging; to measure the patterns of inundation and waterlogging around the targeted location based on satellite and in-situ observation. We found two types of inundation at Garaber from Focus Group Discussion (FGD) and in-depth interview. Respondents identified the post monsoon waterlogging as a threat for their livelihood. It was found that waterlogging around Garaber started from June that stayed until October in every year for a decade. It also shortened crop rotation, disrupted food security, forced individuals to migrate, created problems on sanitation and diminished fodders at Garaber.
Monsoon inundation in monsoon season and waterlogging in October near Garaber was studied using MODIS surface reflectance data. It was shown that local inundation events like waterlogging near Garaber can be detected and analyzed using MODIS data. Monsoon inundation index and Garaber waterlogging index were defined as inundated area fraction. Garaber waterlogging was significantly associated with monsoon inundation, which was attributed to high river water discharge due to higher rainfall over the upper catchments. Prolonged monsoon floods like 2007 summer can explain some of waterlogging events. On the other hand, local and simultaneous post-monsoon rainfall impact was also clearly observed. These results overall support Garaber people's perception of floods. We have to prepare for the future Sea Level Risk (SLR) affecting both monsoon floods and waterlogging floods near Garaber.
Present study asserts to include rainfall measurement of upper catchment to Bangladesh and to measure water depthness and backwater effects of the Brahmaputra to see the clear inundation and waterlogging scenario in northwestern part of Bangladesh.

INTRODUCTION

Bangladesh is a low-lying riverine country. The delta plain of the Ganges (Padma), Brahmaputra (Jamuna), and Meghna Rivers and their tributaries occupy 79 percent of the country. Bangladesh consists a coastline of 580 km of the Bay of Bengal on the south and the Himalayas to the north. It has a tropical monsoon climate characterized by heavy seasonal rainfall from June to September that creates flash and fluvial floods in almost all parts of the country every year. Around 700 rivers containing branches run through the country that amount a channel of total length around 24,140 kilometers which are directly or indirectly related to the tide from the Bay of Bengal. The extent of these rivers-tide has a direct relation to the sea. Obviously, the particular geographical characteristics made Bangladesh a 'land of river' and it experiences flooding due to river water and heavy rainfall during monsoon.

The geographical position and socio-economic condition of Bangladesh combine a high-risk disaster-prone country in the world. The country ranked 7th in Climate Risk Index (CRI) for the year (1998–2017) with the loss of 0.64% average annual GDP during this period (Eckstein et al., 2018). Floods and future SLR are often considered as highly concerned natural hazard among policy makers. Flood often outweighs other existing natural hazards in Bangladesh. For example, in between 1954 and 1996, Bangladesh experienced 28 major floods, of which 11 were classified as "devastating" and five as "most devastating (Khan et al., 2011)." In addition to that, enormous researchers from around the globe are predicting that future SLR may inundate around one-third of the country. It will not only hamper the country's economic growth but also will be the biggest natural disaster for the people of Bangladesh.

Researchers frequently used various hydrological and mathematical simulation model to show the impact of rainfall on flooding in different time scales. Measures of rainfall data has been shown as a very useful tool to predict flash floods (Koralegedara et al., 2019; Yuan et al., 2019; Archer and Fowler, 2018). Flood forecasting based on rainfall data produced from remote sensing and in-situ observations is a frequent research theme. (Nanda et al., 2016; Emerton et al., 2016; Douinot et al., 2015; Tekeli & Fouli, 2016; Bajracharya et al., 2017; Coughlan de Perez et al., 2017; Quintero et al., 2016; Yoshimoto & Amarnath, 2017).

Rahman et al. (2012) proved that various rainfall data collected from satellite and from local raingauge stations might be an effective approach to forecast floods in Bangladesh. The image derived from Moderate Resolution Imaging Spectroradiometer (MODIS) satellite of NASA and RADARSAT (A Canadian remote sensing Earth observation satellite program overseen by the Canadian Space Agency) had been presented as significant tools to illustrate flood risk mapping in Bangladesh (Islam et al., 2010). A positive correlation exists between rainfall and flooding in Bangladesh based on the analysis of rainfall data between 2002 and 2011 (Guiteras et al., 2015). Shahid (2009) detected a significant increase of average annual rainfall of Bangladesh at a rate of 5.52 mm/year over the time period 1958–2007, which could also increase the possibility of floods in Bangladesh (Shahid, 2009). For instance, a small-scale research based on a single year rainfall data showed that the inundation in the north-eastern part of Bangladesh during 2017 resulted from heavy rainfall and it also predicted that this type of hazardous event might be redundant in the near future (Mahtab et al., 2018). Interestingly, Nowreen et al. (2014) presented that the effect of rainfall has shifted over time from North-east to further North in Bangladesh and flash floods with high magnitude occurred frequently in this area. However, rainfall research in Bangladesh has many diversities. Researchers are also interested in trend analysis of rainfall pattern especially monsoon rainfall in Bangladesh (Endo et al., 2015; Tanoue et al., 2018; Ahasan et al., 2010).

People of Bangladesh do not always consider flooding, waterlogging and heavy rainfall as a natural hazard. For example, post-flood bumper productions of crops, occupation of fishermen and fish migration are largely depended on inundation and flooding during monsoon every year. Hence, it might be crucial for researchers to know the perception of people when, why and for what circumstances they feel that *'yes. now flooding is a problem for us'*. On the other hand, the government of Bangladesh went for gigantic structural and hydrological solutions to control flood after experiencing heavy losses of human lives and properties in 1988 flood. Government's initial response to control flood ignored accessible societal resources that could be very useful for flood recovery. It is important to note that Paul and Sultana (1996) identified the failure of structural flood control projects, showing that four out of five projects got higher losses of flood damage compared to non-protected flooding areas.

There are regional variations also for inundation, flooding and waterlogging in Bangladesh. The pattern and dynamics of inundation through heavy rainfall during monsoon are much complicated as researchers have already analyzed. A huge low-lying area starts from coastal part of Bangladesh extends to the north-western part that may have a chance of inundation and waterlogging both from rainwater and SLR. Usually the north-western part faces lower monsoon rainfall than any other part of Bangladesh. But the areas near the bank of the Brahmaputra River always have a higher risk of inundation from river water during monsoon. Searching for patterns and dynamics of inundation and flooding, a semi-remote village named 'Garaber' has been selected for the present study purposively.

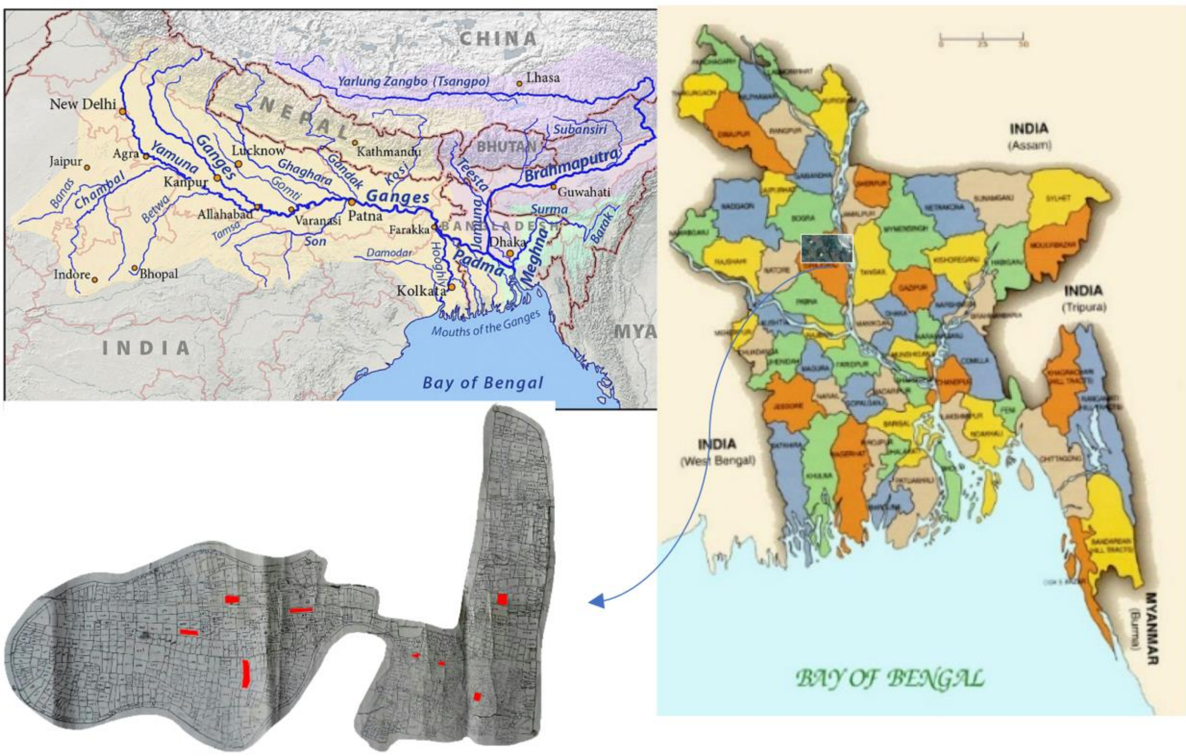

Figure 1. Garaber village map and geographical location.

The village is located nearly 3.5km from the bank of the Brahmaputra river. Center of the village's latitude and longitude are 24.678N and 89.607E respectively (GPS Coordinate, 2019). The village administrative location is under Sirajganj district of Rajshahi division in Bangladesh (Figure-1). Total population of the village is approximately 2300. There are 13 religious and educational institutions which are usually considered for shelter center during monsoon season. The village had a long history of flooding and inundation but now the villagers have been experiencing waterlogging flood.

Unusual flooding from waterlogging surrounding Garaber village during monsoon severely affects the villager's income earning activities. The effects were so serious that they had been forced to migrate seasonally for earning money at neighboring towns, districts and even in the capital, Dhaka. During monsoon, virtually they don't have any work to do. The major earning activities of women were tailoring (specially making Islamic cap), raising domestic cattle & poultry, working seasonally as a garment worker in the capital, assisting at health clinic etc. The adolescent girls who usually had little income earning activities as they were mostly student and also helped their parents earning activities. Very few of them earned money by their own from tailoring as part-time work. But during and after the monsoon season their income reduces dramatically compared to the winter or dry season. In contrast to women, the main occupations for men were farmer, agricultural labor, transport worker, carpenter, tailor, shop-keeper and petty-businessman. A very few of them were working as fishermen. Work in livestock farm and working as primary school teachers were also counted. The notable damages due to the seasonal inundation and waterlogging are crop losses, food crises, seasonal migration, loss of income earning activities, spread of water-borne disease, damage of private properties and houses in Garaber village. The impacts were usually similar to a normal flood happened at any other rural village in Bangladesh. Since the seasonal inundation and waterlogging affects the villager's livelihood, we would present scientific reasoning to policy makers for serious and effective measures.

Though the villagers have been suffering with waterlogging flood since 2000, the local government rarely concerns about it. The inundation and waterlogging are needed to be investigated to explore the extent and pattern of flooding at Garaber to represent the local people's inundation and waterlogging sufferings systematically.

Global mean sea level will rise at least 0.2 meters (8 inches) and no more than 2.0 meters (6.6 feet) by the year 2100 (Parris et al., 2012). And the years (1880 to 1935) recorded annual average SLR of only 1.1 _ 0.7 mm/year (0.043 _ 0.028 inches/year), whereas it accelerated from 1936 to 2009 (1.8 _ 0.3 mm/year or 0.071 _ 0.012 inches/year) (Paul and Rashid, 2016). Again, the increasing rates of SLR will increase extreme flooding by tropical cyclones which is common in the Bay of Bengal (Woodruff et al., 2013). They concluded that by 2100, a total of 5500 square kilometer will be inundated due to SLR. In Bangladesh, the government and policy makers much worry about the risk of SLR predicted by the researchers. But it is obvious that the geographical position, population density and average elevation from sea level might accelerate the impacts of SLR in Bangladesh. Researchers tried to predict huge losses based on tide-gauge data and satellite data of SLR over the years. In contrast, relative mean sea level data might not solely predict the future flood events in Bangladesh because floods in Bangladesh depends on so many factors like sediment of the river, tide and so on (Pethick and Orford, 2013). Islam et al. (2016) considered SLR as one of their physical parameters to present the vulnerability along coastal area and discussed SLR might promulgate flood in coastal areas in Bangladesh. Vital water graphics designed and presented the maps of the future impacts of SLR in Bangladesh. Around 18 million people will be affected and 22,000 km^2 of land will be submerged by flooding only if rise of 1.5meter SLR in the Bay of Bengal (UN Environment, 2019). Leatherman (2001) stated that "*Bangladesh is a classic case where major impacts from accelerated sea level rise will affect a large number of people …the country is regarded as the most vulnerable country in the world because of coastal impacts (sea level rise and cyclones)*".

Thus, it is obvious that future SLR damage made Bangladesh one of the top vulnerable countries in the world. Bhuiyan and Dutta (2012) simulated a hydrodynamic model in south central and south-western region of Bangladesh to explore the impacts of SLR and rainfall. They concluded that these areas flooded up to 3.5m depth which had a relationship with SLR. Exclusively, Ikeuchi et al. (2015) developed a numerical model for dynamics of fluvial flood at Ganges-Brahmaputra-Meghna (GBM) delta in Bangladesh using a state-of-the-art river routing model that can include channel bifurcation and backwater effect. They found that these effects accelerate the inundation depth of fluvial flood in Bangladesh even in locations far from the river mouth. Thus, the real effect of the SLR on floods in the mega-delta regions such as Bengal Plain has not been considered enough. We should regard wide mega-delta regions as coastal regions in the context of SLR impact through the mighty rivers like the Ganges and Brahmaputra.

We will focus on the people's adaptation measures for current status of changing impact of the Ganges and Brahmaputra. In the near future, it is highly expected that SLR might affect riverside areas. Thus, it is indispensable to see the flood mechanisms at riverside areas in Bangladesh, considering the potential impact of SLR. It is also important to know how floods are characterizing differently at different locations in Bangladesh after structural management of flood by the government. Furthermore, changing nature of flooding and inundation during monsoon due to rainfall, types of losses and sufferings of people and future risks may also be very momentous in flood research. Hence, the location and the selection of Garaber was very important in present research. Garaber is situated on the bank of the Brahmaputra in northwest of Bangladesh. We illustrated details of inundation and flooding around villager and its effects on inhabitants. Preparing a concrete depiction of flooding pattern first which will enhance future study of flood research on localities by including SLR effects was one of our main motivations. Reasonably, study concentrates on to go beyond local people's perception regarding flooding and inundation experiences and sufferings. It also encompasses the relationship of daily local rainfall variability and flooding. Finally, the research focuses attention on patterns of inundation and waterlogging around the targeted location based on satellite and in-situ observations.

DATA AND METHOD

To understand people's perception regarding inundation and flooding experiences and sufferings in localities, we have selected an ideal location that had a long flooding history. In total 12 FGDs and 6 in-depth interviews have been carried out from Garaber village during February 2019. Objectives of these FGDs and in-depth interviews were (1) to know the detail history of flooding and inundation situation inside and around the village from 2000 to 2017; (2) sufferings and damages caused by flooding and (3) coping mechanisms if they had faced problems in earning due to flooding. In addition, we visited the surrounding areas of the village to observe the low-lying areas, man-made constructions and a dying canal around north-east side of the village.

Bangladesh Meteorological Department (BMD) owns 35 synoptic stations. We considered only the daily rainfall data from 2001 to 2016 at Bogra station, the closest BMD raingauge station at about 30 km to the northwest of Garaber village.

To detect inundation and flooding patterns, we utilized 8-day composite MODIS reflectance data, with pixel size at about 500 m. We followed inundation detection method given in Xiao et al. (2005, 2006), Sakamoto et al. (2007), and Islam et al. (2010). The temporal resolution of MODIS image was 8 days.

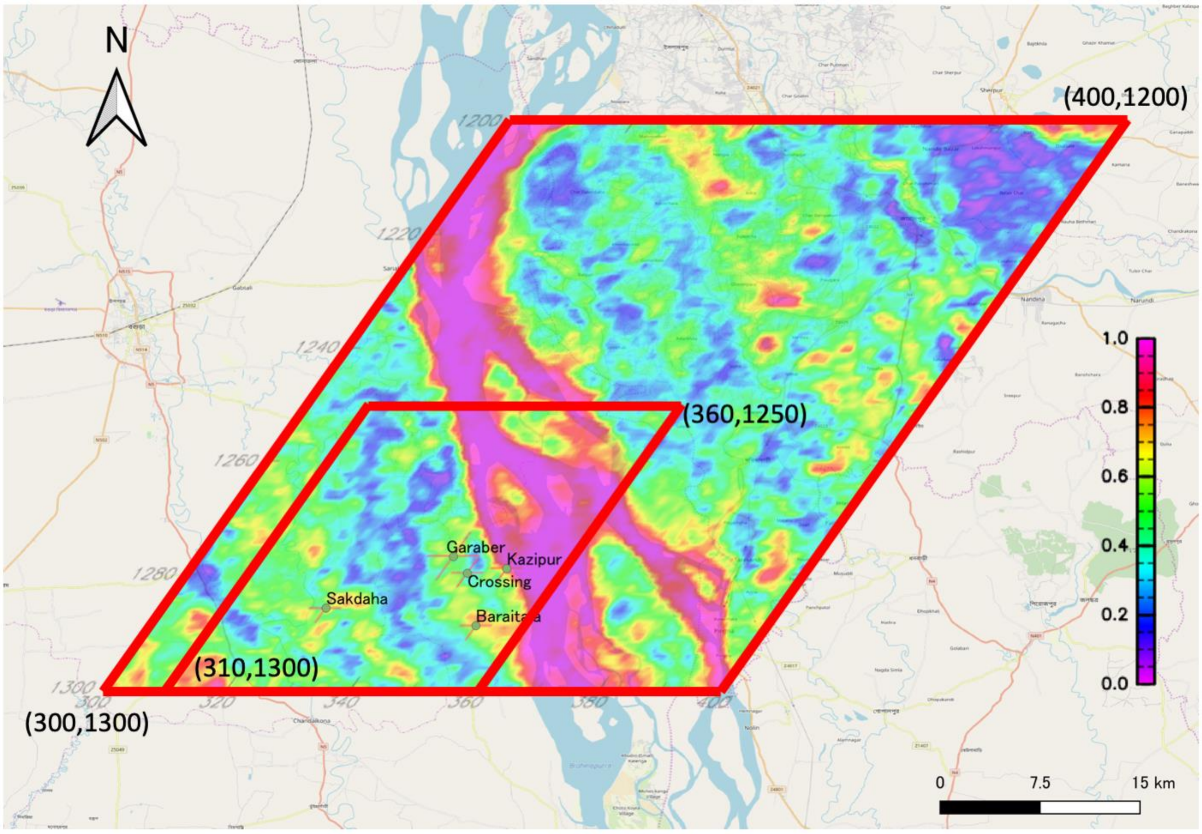

Figure 2. Map of MODIS analysis area. We analyzed MODIS surface reflectance 8-day L3 pixels in the area inside the large red rectangular. To see a closer look, we will show the smaller rectangular area.

Bangladesh corresponds with the h26v6 tile in zonal and meridional direction in the MODIS sinusoidal grid system. Each tile has 2400 by 2400 grids, and Garaber coincides with the pixel at 1277th line and 341st sample grid point in that tile. We put big red cross mark at the location of Garaber (24.679N, 89.607E). Small red cross marks are placed at four locations at 24.669N-89.647E, 24.666N-89.618E, 24.640N-89.513E, and 24.627N-89.624E.

RESULT OF FGDs STUDIES AND IN-DEPTH INTERVIEWS ON IMPACTS OF FLOODING

Here, we describe the impact of flooding in the perception of people at Garaber based on FGDs and in-depth interviews conducted by the authors.

The villagers had gone through long experiences of flooding. Respondents can recall flood history from 1988 to present. But special focus has been given on history, damages and coping strategies of flooding and inundation they had faced from the year 2000 to 2017. The respondents reported that last severe flooding attacked at their village in June, 2017. But they have experienced monsoon floods almost every year. It is important to note that the villagers reported that no flooding had occurred due to overflow of the Brahmaputra River since 2007. Villagers of Garaber reported two types of flood experiences; (1) flooding caused by overflow of the bank of river Brahmaputra (last attacked in 2007) and (2) waterlogging and flooding stimulated by upstream rainwater that logged around the village up to October every year. Notable that respondents clearly distinguished the extents and damages from these two types of flooding. First one damages their properties, crops, livestock and even human lives.

The second one (waterlogging flood) happened during 2003, 2004, 2005, 2007, 2008, 2011, 2014, 2016 and 2017. People around the Garaber village have been suffering severely from this prolonged waterlogging. The most devastating damage of waterlogging was to shorten the crop rotation that has been disrupting food security over the years. Even though it produces a lot of weeds in the field that raises the cost of cultivation. The respondents reported waterlogging forced individual to migrate nearby districts and towns for earning activities, also created problems in sanitation and finding fodders. In comparison to flood, waterlogging flood affects mostly on livelihood, food and fodder (Table 1).

Table 1. Differences between the two types of flooding impacts at Garaber from 2000 to 2017

Flooding from river water	**Waterlogging and flooding from rain water**
Occurred in the year 2003, 2004 and 2007 but never happened after 2007.	Occurred almost in every year from 2000 to 2017 (2003, 2004, 2005, 2007, 2008, 2011, 2014, 2016, 2017).
Shifting family members at nearby villages and even in other districts temporarily for shelter.	Shifting family members at high ground within the village for temporary.
Total loss of crops.	Partial loss of crops.
Deaths of human lives and cattle	No deaths of human lives and cattle
Huge damage of infrastructures like roads, schools and houses.	Sometimes damage infrastructures.
Changing modes of transportation.	Sometimes changing modes of transportation.
Went to flood shelter.	Did not go to flood shelter.
Major crises – income and earnings, food insecurity, sanitation, cooking, finding fodder, relief, transportation, education and temporary migration of families.	Major crises – food shortages, income and earnings, sanitation, finding fodder and temporary migration of individuals.

During Key Informant Interview (KII), a male respondent aged 72 recalled the history of flooding at village. He quoted *"Oh! flood had damaged severely in the past; I saw the real sufferings of my village people during 1988 when the Brahmaputra River overflowed our village. I saw many floating dead bodies during that time. But after 2000, major flooding events were in 2003 and in 2004, 2007 and 2017. We stuck in our home for at least three days. Then, we moved for shelter in neighboring village which was relatively less-flooded area. There is no big flood in 2018 and 2019 but we have been suffering from water logging due to monsoon rain for long time. Sometimes, the water logging is so serious that overflow roads and houses in my locality. Yes, it is obvious that the water coming from upstream area logged around my village and it never passes to downstream that creates flood in my village area until October in each year"*.

We summarized the major destructions of flooding and waterlogging at Garaber based on our FGDs, in-depth interviews and observations. The villagers are losing crops especially *amon rice* (popularly cultivated rice from April to June), jute, corn, green chili, papaya etc. Respondents reported that the monsoon flood inundated considerable number of houses, village roads, educational institutions, courtyards, playgrounds and culverts. During this monsoon flood toilets and tube-wells were also drowned. Besides, the flood interrupts food security, fish farming, education, cooking, mobility among communities and maintaining healthy behavior. The flood creates spread of infectious animals like snake, shortening fuel, raising the prices of basic subsistence, tendency of NGOs to provide loan, changing income earning activities, moving livestock. Sometimes most affected community members migrated to relative's house or to higher ground within the village. Spreading rubbish around yards and weed on cultivable land were also reported as problems by the villagers. Monsoon flooding also changed the patterns of transportation among communities. The main mode of transportation during that time is boat and *vela* (boat made from banana tree and bamboo stick). Besides, it shifted place of local markets.

The severity of flood is much less destructive in Garaber after 2007. Even though, during this seasonal flooding and waterlogging, a considerable number of people still have to take shelter on higher ground or to go to relatives. It was observed that there are flood shelters in nearby village areas and generally villagers took shelter there during flood. However, local people usually feel shy to disclose the information of staying flood shelters and taking reliefs during disaster in front of strangers. It is one kind of local cultural view that people feel that taking reliefs and staying flood shelters are considered as a type of disrespectful tasks. One of the respondents from FGD noted that she migrates Dhaka during monsoon flood only for searching work regularly. She illustrated like "*I have been going to Dhaka every year as a garments worker to support my family during monsoon season because that time there are no earning opportunities for both men and women in our areas. After staying four months, I used to return home because I love to stay with my family members. This four-months income helped me and my family a lot during that crisis time".*

It is evident that a huge embankment had been built on the banks of the Brahmaputra around Garaber. The embankment had been built by the government after realizing the severe damages caused by 1988's flood on the western part of the Brahmaputra River. Later on, earthworks (construction of roads, local dams and houses on low lying areas) construction on downstream may have prevented rain water flows towards further south of the Brahmaputra River. Besides, there was a live canal in this village which was very helpful to pass upstream monsoon rainwater towards downstream which was a link with the Brahmaputra. Now the river is going to be dead because of absence of water tide. These overall change of hydrological environment around Garaber may partly explain the reason why such waterlogging is severe problem now. Village head of Garaber illustrated "*look, only 25 to 30 years ago, people who were somehow educated and got a little job, they thought to shift their family to the nearest towns. There were no roads, electricity, hospitals and even proper schools for children. Most of the people's major occupation was a fisherman. Before 30 years ago, we had flooding all around the village but construction of river dams (Brahmhaputra river westside dam) prevented us from such flooding. That type of flood did not stay longer than 30 to 40 days. Even before, there were distances and large yards between houses. But now all are occupied. From the year 2000, people were building their homes even in the rice fields. The story of the surrounding villages of Garaber are same. Things have been changed rapidly after 2000. Our minister changed the area rapidly by constructing colleges, hospitals, roads and schools which are mostly southern side of Garaber. The canal is important, I saw rapid tide in it but now, you can find only water hyacinth in it. I suppose, dredging the canal to runoff water from north towards south might be a good solution to our waterlogging flooding problem".*

Villagers now mentioned this waterlogging as flood that damages crop and shortening fodder for livestock. It harms their livelihood nearly a similar way of flooding from river water. It might be an interesting part of further investigation of villagers' perception regarding differentiation between waterlogging and flooding.

INUNDATION PATTERNS BASED ON HYDROMETEOROLOGICAL OBSERVATION

To further confirm the flood patterns in the perception of local community in Garaber area, we performed satellite image analysis over surrounding area (Figure 2), and rainfall data analysis. People in this area told about two different types of floods. One is the monsoon flood in monsoon season associated with the Brahmaputra River. The other is the flood due to the waterlogging near the village. People felt that the impact of former flood reduced because no overflow of the Brahmaputra is not observed after 2007. The waterlogging tends to be recognized as the effect of local rainwater.

To detect temporal evolution of inundations causing these floods, we utilized 8-day composite MODIS reflectance data with 500 m spatial resolution. We associate each MODIS pixel with 'cloud', ‘flood’, ‘mixture’, or ‘non-flood’ pixel, following the criteria utilized in Islam et al. (2010). Firstly, we determined if the pixel was covered by cloud or not using MODIS reflectance of band 3 (459-479nm). If the reflectance is equal to or greater than 0.2, it was classified as a 'cloud' pixel. To further classify the pixel, we calculated several MODIS-derived indices, Enhanced Vegetation Index (EVI), Land Surface Water Index (LSWI), and difference value between EVI and LSWI (DEVL) from MODIS reflectance of band 1, 2, 3, and 6. If $\mathrm{EVI} > 0.3$ it is classified as non-flood pixel. Pixels with $\mathrm{DVEL} < 0.05$ are defined as water-related pixels. However, these criteria sometimes misclassify some open water surface because of low reflectance of near infrared band (Sakamoto et al. 2007). Therefore, we put another criterion, $\mathrm{EVI} \leq 0.05$ and $\mathrm{LSWI} \leq 0$, which also classifies them as water related pixels. Water related pixels were further classified as 'flood' or 'mixture'. It was defined as 'flood' pixel if $\mathrm{EVI} \leq 0.1$, otherwise as 'mixture'.

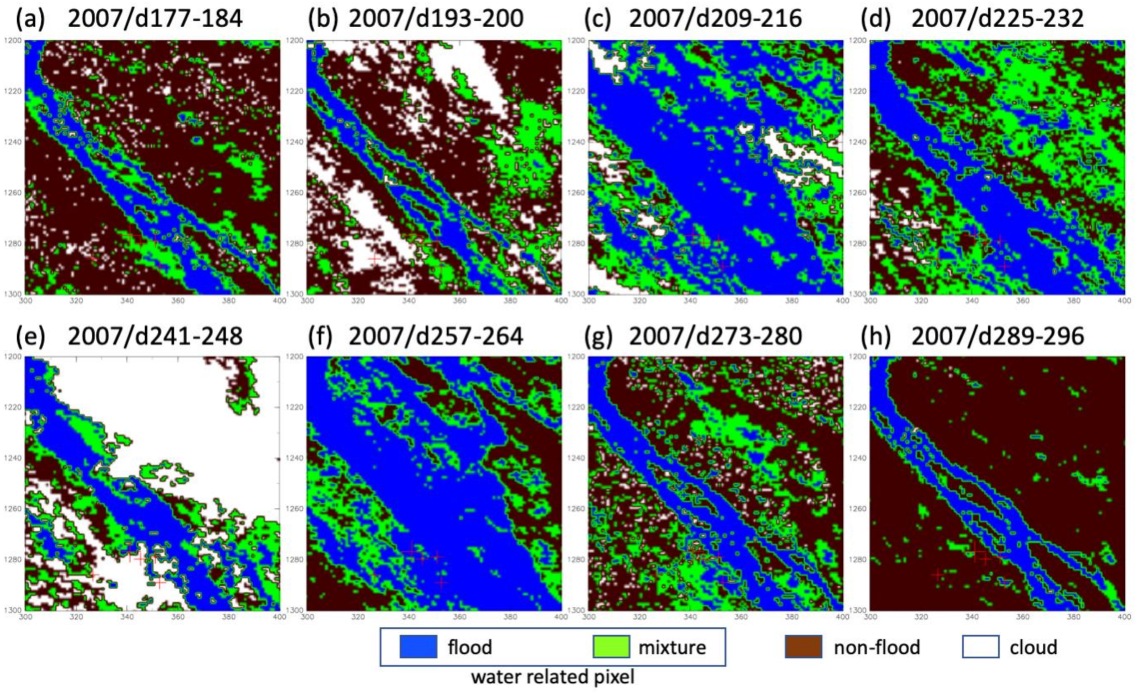

Figure 3. Seasonal inundation map for June to October, from 177th to 296th day of the year (d177-296 hereafter), in 2007, one of the severest flood cases in recent years. Colors indicate the classification of pixels as shown in the legend below. Panels (a) to (h) are spatial distributions of inundation for 16-day interval from the d177-184 to the d289-296. Horizontal and vertical axis shows the sample and line of MODIS sinusoidal grid in the tile-h26v6.

Figure 3 shows time series of MODIS image describing the classification of pixels including Garaber for June to October 2007. We drew the area of large red rectangle of Figure 2. The left-bottom, left-top, right-bottom and right-top corners of each panel correspond with 24.581N-89.350E, 24.998N-89.650E, 24.581N-89.909E and 24.998N-90.110E, respectively. We put big red cross at the location of Garaber (24.679N, 89.607E). Small red crosses are placed at four locations at 24.669N-89.647E, 24.666N-89.618E, 24.640N-89.513E, and 24.627N-89.624E. The cloud, non-flood, mixture, and flood pixels are indicated by white, brown, green and blue colors, respectively. On from 241^{st} to 248^{th} day of the year (d241-248, hereafter, Figure 3e), almost half of pixels are covered by clouds. In other figures, most of pixels were classified as either water related or non-flood pixels. By d193-200, water related pixels were seen only in some limited areas over some eastern region. However, in d209-216 (Fig. 3c), areas of water related pixels significantly extended to both sides of the Brahmaputra River, showing a massive monsoon inundation. Though the inundation was somewhat moderated by d241-248 (Fig. 3d-e), in d257-264 (Fig. 3f), it again spread large surrounding areas. By d273-280, the massive inundation finished. However, we can find several water related pixels just to the southwest of Garaber continuously. In 2007, a massive monsoon inundation continued for more than two months periods due to double peaks of river water discharge of the Brahmaputra in July and September (Hopson and Webster, 2010). Furthermore, a small area with several km^2 in area size was seen just to the southwest of Garaber, and was continued to be inundated by the end of October. Such time evolution of the inundation deduced from MODIS images was consistent with Garaber people's perception.

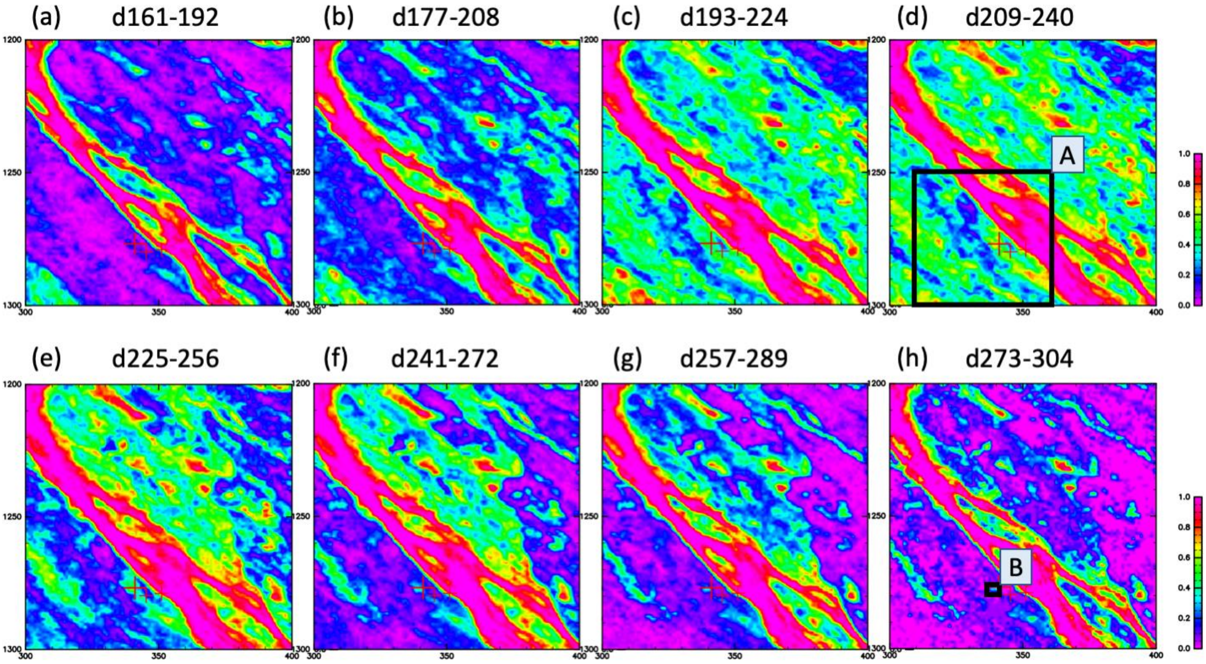

Figure 4. Climatological occurrence frequency of water related pixels calculated from MODIS data for 2001 to 2017. Area is same as Fig. 2. Areas A and B indicated by large and small black rectangles in (d) and (h) are used for calculation of monsoon inundation index and water logging inundation index, respectively

Climatological temporal evolution of inundation over this area averaged for 2001 to 2017 is shown in Fig. 4. This shows the spatial distribution of water related pixel occurrence frequency for the same area as Fig. 3. Each panel shows the average of 32-day period indicated at the top of the panel. The monsoon inundation in this area gradually develops from day 177-208 (Fig. 4b). It matured around day 209-240 (Fig. 4d), and retreats after that. However, in some areas, the inundation continues up to October as shown in Fig. 4h. Pixels just southwest of Garaber is one of typical areas at which we can observe long lasting water logging at least up to late October.

Two different types of inundation processes; one is the monsoon inundation which matures in the middle of monsoon season especially in August (Fig. 4d), and the other is waterlogging inundation near Garaber which continues up to October (Fig. 4g and h). To define representative indices for the extent of these inundation patterns, we calculated fractions of inundation pixels excluding cloud pixels for two different areas and durations. For the index of the large scale monsoon inundation, we calculated that for the rectangular area A indicated in Fig. 3d, which is defined as monsoon inundation index. Fraction of the water related pixels in the area B indicated by the rectangular in Fig. 3h represents the water logging near Garaber, which is indicated as the water logging index. We selected the period of day 209 to 240 and day 265-296 for monsoon flood index and water logging index, respectively.

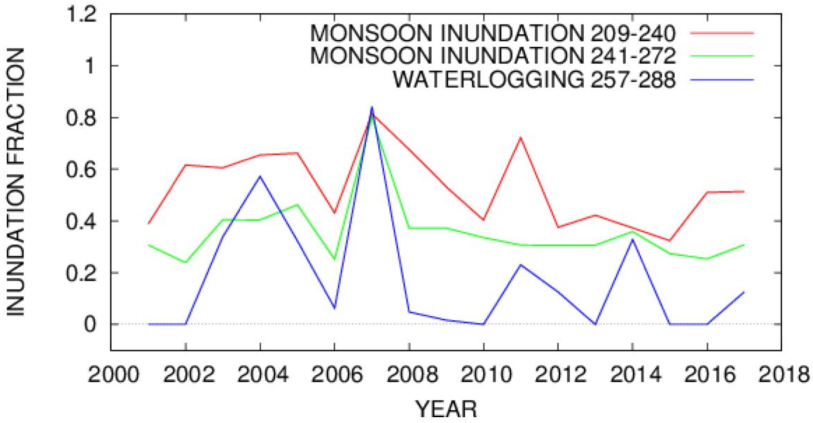

Figure 5. Interannual variability of monsoon inundation index for d209-240 (around August) and d241-272 (around September), and water logging index for d273-304 (around October), which are the fractions of water related pixels excluding cloud pixels for the areas A and B, respectively.

Interannual variation of these indices are shown in Fig. 5. We can find significant correlation between waterlogging index in October (d257-288) and preceding monsoon inundation indices at correlation coefficients of 0.63 and 0.85 for August (d209-240) and September (d241-272) monsoon inundation, respectively. It indicates that the waterlogging at a part can be explained by the influence of the preceding monsoon inundation. In 2004 and 2007, severe floods attacked wide area along the Brahmaputra (Hopson and Webster, 2010; Islam et al., 2010). Especially in 2007, flood events attacked not only in July but also in September (Hopson and Webster, 2010), which caused prolonged monsoon flood, affecting waterlogging in October. However, at the same time, we can find several important years with waterlogging but without high monsoon inundation in August to September, like 2012 and 2014. On the other hand, in 2002, we found no water logging after relatively high monsoon inundation August (d209-240). It is observed that the monsoon inundation prevailed before 2008 and it decreased after that, which supports people's perception that the monsoon flood impact reduced after 2007.

Figure 6 is the temporal variation of spatial extent of waterlogging near Garaber for selected years from end of September to October (d265-296). For recent two cases in 2012 and 2014, it was found that the waterlogging did not continue from previous monsoon inundation (d265-272, Figure 6i and m) but redeveloped after October (d273-280 and later, Figure 6j-l and n-p). The inundation pattern on d265-272 in 2014 (Figure 6m) shows an inundation area several kms to the north of Garaber. The logged water after d273 may flew down from upstream inundated area. For the cases in 2004 and 2007, the area B was covered by water related pixels from September (d265-272, Figure 6a and e). It is continued from the monsoon inundation. Similar waterlogging flood near Garaber can be observed for 2003 and 2011 also (figures are not shown).

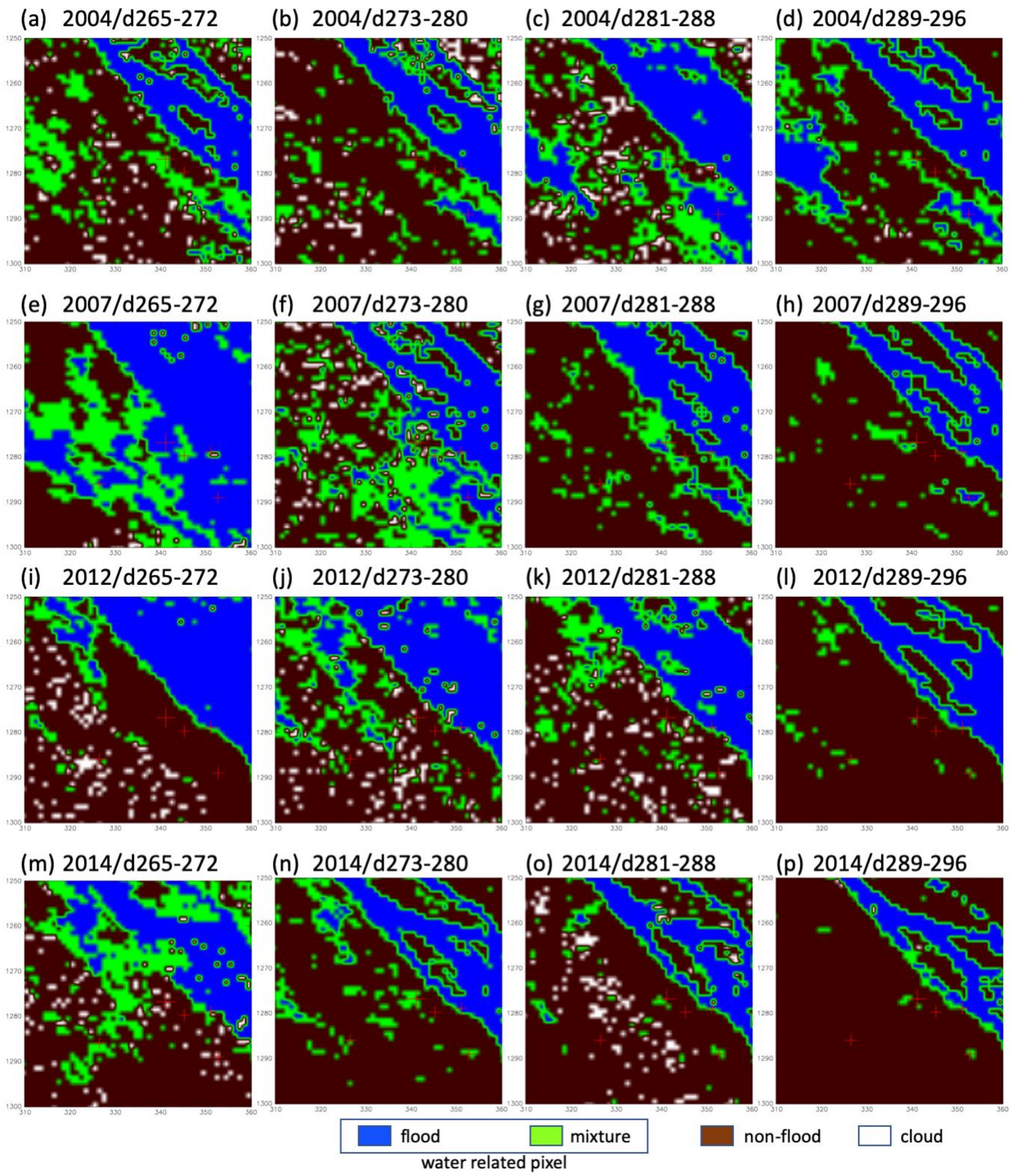

Figure 6. Temporal evolution of water logging near Garaber. We showed patterns of the area indicated by area A defined in Fig. 2. Four selected waterlogging cases were plotted in (a-d) 2004, (e-h) 2007, (i-l) 2012 and (m-p) 2014.

Now, we focus on the mechanism of waterlogging near Garaber related with rainfall. Figure 5 and high correlation between monsoon inundation index and waterlogging index suggest that the waterlogging is partly related with monsoon inundation in August and September. Upper catchment rainfall impact on the monsoon inundation in 2007 along the Brahmaputra was well documented in Hopson and Webster (2010) and Webster et al. (2010). These monsoon floods were attributed to the larger monsoon rainfall spell in upper catchment. In this regard, the impact of large rivers such as the Ganges and the Brahmaputra can not be ignored. The

effect of SLR comes through the backwater effect of these rivers. Therefore, the future impact of SLR on the waterlogging must be clarified in future work.
However, as is shown in Fig. 5 and 6, there are waterlogging events that cannot be attributed to the monsoon inundation. So, we investigated local rainfall utilizing daily rainfall data observed by Bangladesh Meteorological Department (BMD) in Bogra, which is at about 30 km northwest of Garaber.

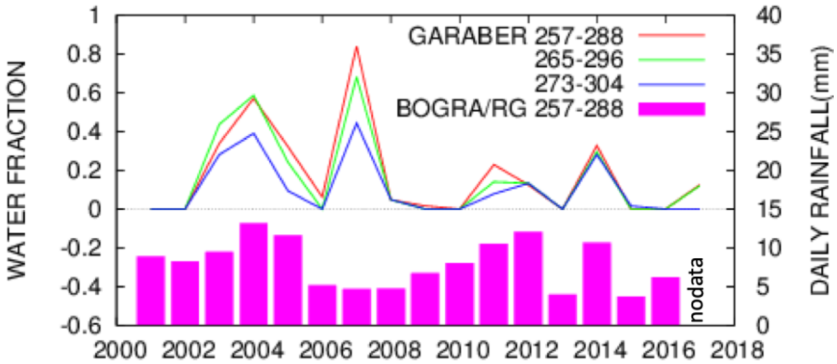

Figure 7. Line plots for interannual variability of waterlogging index for the period after the middle of September (d257-304), and bar graph for the rainfall intensity at Bogra for d257-288. Values of waterlogging index and rainfall intensity (mm day^{-1}) are indicated by left side and right side axes, respectively.

In Figure 7, we plotted the area of waterlogging after the mid-September by line plots, and rainfall intensity averaged for 32 days from mid-September to mid-October. Larger waterlogging events can be seen in 2003, 2004, 2005, 2007, 2011, 2012 and 2014. Six highest rainfall intensities can be observed in 2003, 2004, 2005, 2011, 2012 and 2014 which covers all larger waterlogging events except 2007. Though rainfall at Bogra in 2007 was exceptionally small, waterlogging in 2007 was associated with well known monsoon inundation event.

CONCLUSION

Flooding caused by rainwater have been identified at Garaber which is neither a flash flood nor a fluvial flood. The inundation has already been mentioned as waterlogging from June to October in present research. The dependency on daily income and an immense dependency on produced crops at their own land the villagers are highly related with their sufferings from ongoing after-monsoon waterlogging. Present study revealed loss of earning opportunity, food insecurity, unhygienic environment, damaging infrastructures, hampering education, temporary individual migration as the major impacts of waterlogging floods near Garaber, even though the area is not huge. Similarly, significant impacts of water logging on settlement, agriculture, health and education in the south-western coastal areas of Bangladesh have been identified by Moniruzzaman (2011). In contrast households rarely affected crop production by waterlogging in Bangladesh (Alam et al., 2017). Besides, villagers also experienced worst impacts of flooding ever they can imagine due to overflow of Brahmaputra River. Present research identified human deaths, severe food shortages, changing modes of transportation, total loss of rice crops, spread of diseases, destruction of roads and houses as major impacts of this type of flood. The impacts are similar with a study of detail impacts of flooding of 1998 in Bangladesh (Ninno et al., 2001). Respondents also informed that the severity of monsoon flood is much less destructive in Garaber after 2007, possibly due to the construction of a huge embankment on the banks of the Brahmaputra around Garaber. However, waterlogging flood is continuing to have severe impact on people in Garaber still now. Respondents confirmed that the northwest-side canal of Garaber had high tide that helped rainwater runoff from the north to the south of the village. It is observed that the canal is now full of water hyacinth and rarely has its tide. Moreover, people are occupying the canal for cultivation and building infrastructures. A huge river dam has been found on the bank of the Brahmaputra which is only 3.5km away from Garaber. But the villagers never claimed that this river dam causes waterlogging around their villages rather they reported this dam protects them from river-water flooding during the monsoon season. Huge earthworks on downstream regions around Garaber village have been found and villagers informed these earthworks may cause waterlogging around Garaber. Because the earthworks prevent the runoff during monsoon season. Correspondingly, lack of silt removal or dredging in canals, reduction of water flow in canals and encroachment of canals were the main causes of waterlogging in southwester coastal regions in Bangladesh (Alam et al., 2017).

Field research on perception of local people in Garaber described above suggested that there are two different types of floods that have severe impacts on their life. The satellite observation of inundation pattern using MODIS reflectance data clearly detected not only monsoon devastating flood in July to September, but also waterlogging flood affecting southwestern side of Garaber village up to October. As has been described in narrative of people, this long-lasting inundation affects daily life, though the area may not be so large. Such waterlogging flood near Garaber can be observed in MODIS analysis for 2003, 2004, 2007, 2011, 2012, and 2014, almost consistently with people's observation (Table 1). This result confirmed the high reliability of inundation pattern analysis using MODIS reflectance, even for local inundation such as the waterlogging near Garaber. The waterlogging in October was clearly associated with monsoon floods in August and September. Especially in 2007, waterlogging was connected with one of the most devastating monsoon floods along the Brahmaputra in recent decades after the 1998 flood. Thus, the waterlogging was partly explained by monsoon floods. However, some of waterlogging cases are not associated with monsoon floods. Furthermore, in some cases, the waterlogging begins after the recession of monsoon flood water, as shown in 2012 and 2014 cases (Figure 6i, m), suggesting the importance of local simultaneous source of inundation water. We obtained most reliable monthly scale rainfall intensity observation from BMD Bogra station, which is at about 30 km northwest of Garabar. We found that all larger waterlogging cases near Garaber except for 2007 were associated with high rainfall intensity at Bogra station. Waterlogging near Garaber is likely to be explained by prolonged monsoon inundation or the local post-monsoon rainfall from mid-September to mid-October.

FGDs and in-depth interview resulted one of the main sufferings during flooding and waterlogging was food crisis at Garaber. If geographical and meteorological methods include social science method to explore the food security situation during waterlogging, it will be an applicable way to go beyond the human geography. Present research shows a significant relationship between daily local rainfall and waterlogging at Garaber in Bangladesh which is explorative. It also directs to explore the inundation pattern at northwestern part of Bangladesh including much upper catchment's regional rainfall data like Nepal, Bhutan, Assam, Meghalaya and Bihar. Because river runoff of northern part of Bangladesh is mostly related to these regional rainfalls that have already confirmed by previous researchers. Interview and MODIS image analysis confirmed that even in October there were waterlogging at southwest part of the study location. But the temporal variation of water depthness of the nearest river of Garaber as well as the depthness of southwestern part of Garaber would be included for further study. Finally, we will try to include SLR and backwater effect to see the waterlogging in northwestern part in Bangladesh.

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