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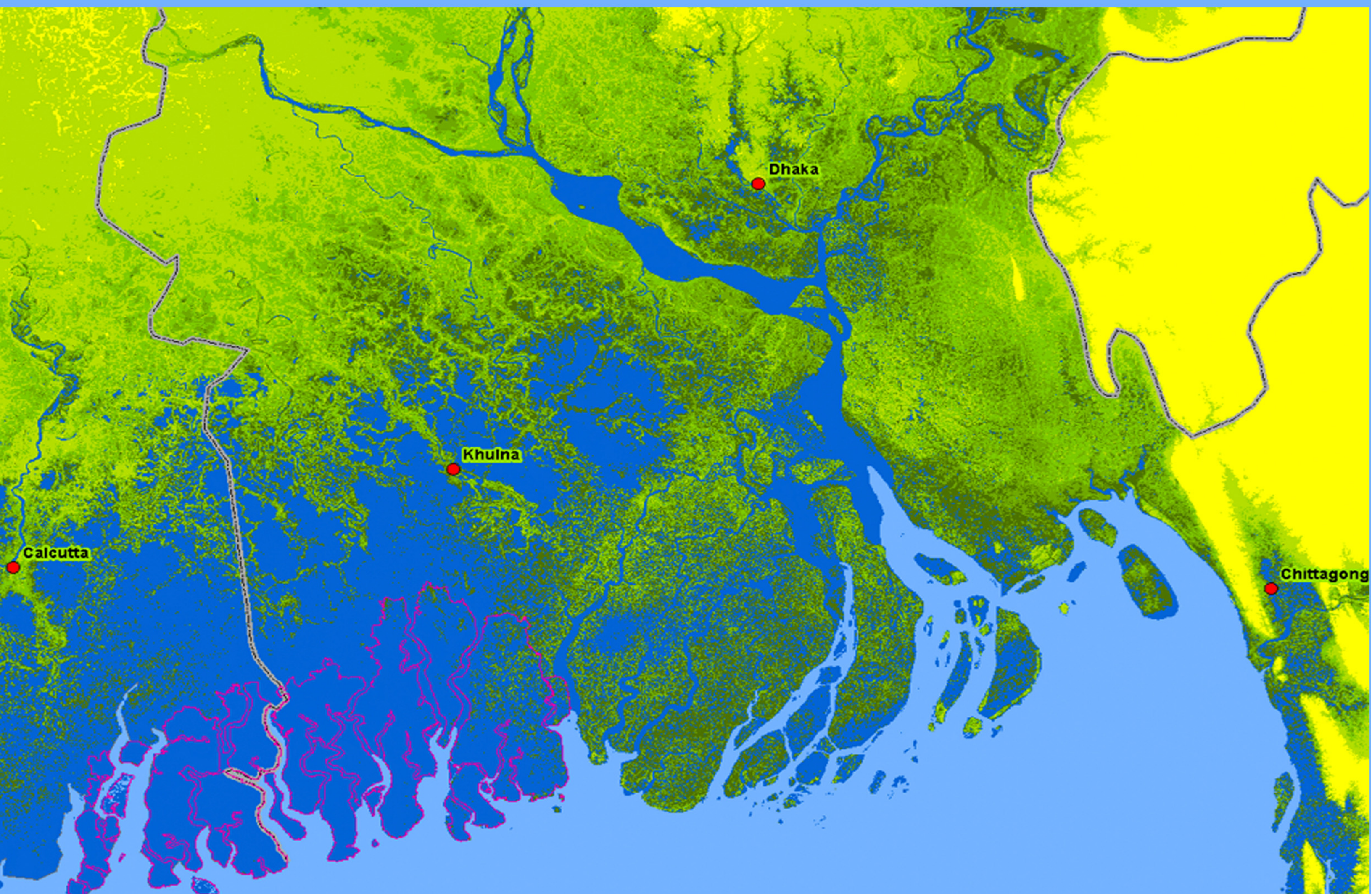

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Underlying Causes of Early Floods in the Haor Region

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Abstract

Four haor (vast wetlands) districts (Sunamganj, Sylhet, Netrokona, and Kishoreganj) in NE Bangladesh suffered an unprecedented flood in late March-early April of 2017. Though not as extensive, parts of the haor region was affected by hail storm and early flood in April of 2019.

This study analyzed underlying causes of these untimely floods using the rainfall data available in public domain for Cherapunji, West Garo Hills, West and East Khasi Hills, and Jaintia Hills in Meghalaya State of India, and Sunamganj in Bangladesh for the period of 1901–1917. Geomorphic analyses of stream cross sections in the haor region indicate that water carrying capacity of these streams are critically insufficient to effectively discharge the generated surface water run-off that results from major rainfall without causing flooding.

The results of data analysis reveal that the rainfall patterns during the months of April and May have changed during 1959–2017 period when compared to the rainfall patterns during 1901–1958 period. Analysis of monthly rainfall data indicates that flooding in early April is likely to become more common in the future, which is compatible with the concerns expressed in the IPCC reports. The study also concludes that the carrying capacity of rivers in the haor region has substantially declined over the last few decades due to siltation in riverbeds and landuse changes in the watershed area, which is likely to be responsible for an increase in flood inundation and duration in recent years. This study recommends to increase water carrying capacity of haor rivers through widening and deepening of river channels, especially at Bhairab Bridge outlet point, to accommodate expected surface run-off. Adopting an integrated water-sediment-landuse management plan at watershed scale involving all stakeholders and co-riparian nations is essential for successful solution of flooding problems in the haor region.

1 Introduction

The haors are saucer-shaped large freshwater wetlands in northeastern region of Bangladesh. The haor region in Bangladesh occupies 21,000,00 hectares of land in seven districts (Sylhet, Maulavibazar, Sunamganj, Habignj, Netrokona, Kishoreganj, and Brahmanbaria), out of which 950,000 hectares are cultivated for *boro* rice crop (MoWR 2012). The haor region in Bangladesh experiences flooding on a yearly basis (Figure 1). During most years, the flooding starts in late April to early May and lasts for several months.

Flooding is a natural process and it plays a vital role in maintaining continuous sedimentation process on floodplains, recharging groundwater in aquifer, supporting riverine and wetland ecosystems, fisheries, and is an integral part of haor culture and heritage. Bangladesh currently has two sites designated as Wetlands of International Importance (Ramsar Sites), one of which is Tanguar Haor located on the floodplain of the Surma River. Tanguar Haor is considered as Bangladesh's most important freshwater wetland (https://www.ramsar.org/wetland/bangladesh). Wetlands are considered the "kidney of landscapes" as they perform many ecological functions, including reducing flooding propensity, removing pollutants, improving water quality, and providing habitat to numerous plants and animals (Johnston 1991).

In late March and early April of 2017, four districts in the haor region (Sylhet, Sunamganj, Netrokona, and Kishoreganj) experienced an unprecedented and untimely flooding that caused severe damage to crop, livestock, property, human health, and fisheries (The Daily Star 2017, April 5, 16, 17, 18). Historically, annual flooding caused by monsoonal precipitation occurs during late April-early May of each year; however, excessive rainfall in upper reaches of the watersheds in Meghalaya, India, that replenish the haor region resulted in an untimely flood in 2017 that extended over approximately 7,000 km^2, ruined rice crops and damaged infrastructures, fisheries, and residential property.

As per newspaper reports, 80–90% of the *boro* rice crop was completely destroyed by this early flood. The target for *boro* rice crop was set at 1,300,000 tons amounting to a market price of TK. 13,000 crores. The haor region produces 18% of the rice crop for the nation (The Daily Kaler Kantha (Bangla) 2017, 8 July). Although not as extensive as was the case in 2017, about 195 km^2 of *boro* crop was affected by hail storm and early flood in 2019 (The Daily Kaler Kantha 2019, 5 April).

Since the damage was caused by an early flood, the two key questions that begs answer are: (i) why did the flood occur so early, and (ii) will similar floods recur in the future? This study attempts to analyze the underlying causes of the early flood and offered recommendations to mitigate future damage stemming out of such disasters.

The causes of floods in a watershed—the area that drains part of rainfall that produces surface run-off to a common river or stream—can be broadly grouped into three categories: (1) the amount and timing of rainfall; (2) the reduction in water carrying capacity of river network, streams, and wetlands; and (3) the reduction of relative elevations of floodplain with respect to riverbed and the mean sea level (Khalequzzaman 1994). The haor flood of 2017 has been explained in light of these three underlying causes.

The major objective of this study was to decipher the trends in rainfall patterns in watersheds that encompass the haor region in Sunamganj, Sylhet, Netrokona, and Kishoreganj districts. The daily rainfall data for a weather station located at Cherapunji (https://www.cherrapunjee.com/daily-weather-data/) revealed that a total of 1262 mm of rain fell during March 28-April 4, 2017, which was 5.5 times greater than the amount of rainfall for the same period in 2016. Based on correlation between rainfall data at Cherapunji and all other weather stations mentioned above, this study concludes that an average of 542 mm of rain fell over an 8-day period, which must have resulted in 3.8 billion m^3 of rainfall. Since the ground was already saturated from previous rainfall event, most of this rainfall must have ended up in low lying areas and rivers in the haor region. The calculated amount of rainfall must have generated an average of 5,497 cumec (cubic meters per second) or 194,000 cusec (cubic feet per second) of surface water flow that must have rolled through the low-lying areas and rivers in the haor region.

2 Analysis Methodology, Results and Discussion

The amount and timing of rainfall: most of the major rivers and streams (Rakti, Wah Umngi, Jadukata, Piyan Gang, Gowain-Dawki, Sari-Goyain, Surma, Lubachara, and Kushiyara Rivers) that drain the flood-affected region in the haor originate in different parts of Meghalaya and Assam states of India. To calculate the amount, timing, and duration of rainfall within the haor watersheds during the flood event is very important for an accurate calculation of run-off. The hourly and daily rainfall data are scarce in the haor watersheds. The monthly rainfall data for five locations (West Garo Hills, West and East Khasi Hills, Cherapunji, and Jaintia Hills) were downloaded from the Indian Meteorological Department (http://www.indiawaterportal.org/met_data/) for the period between 1901–2017. The daily rainfall data for the period of the flood (March 28-April 4, 2017) were downloaded from a private rain gauge station in Cherapunji, Meghalaya (https://www.cherrapunjee.com/daily-weather-data/). The monthly average rainfall data for Sunamganj was downloaded from University of Columbia's public domain for the period of 1951–2007 (https://iridl.ldeo.columbia.edu/maproom/Agriculture/Historical_Monitoring/Bangladesh_Precip.html). Monthly rainfall data were used to establish a correlation between the rainfall in Cherapunji and other five locations mentioned above.

Based on the relationships between monthly rainfall at Cherapunjee and all other five locations established through regression equations, the amount of daily rainfall for those five locations were calculated for the duration of the flood (Figure 2). From Figure 2 we note that the daily rainfall data at Cherapunji revealed that a total of 461.2 mm of rain fell during the last week of March in 2017, which was 5.5 times more for the same time period in 2016. In addition, the rainfall during the period of the flood in 2017 fell continuously, most of which resulted in direct run-off and overwhelmed the carrying capacity of rivers and wetlands in the haor region. The timing and distribution patterns of rainfall are also important. The total amount of rainfall during the month of April in 2016 was greater than that in 2017; yet there was no major floods in 2016 that damaged the crop, because the rainfall pattern in 2016 was different when compared to the rainfall in 2017. In 2016, most of the rain fell during the later part of the month and was not continuous for an extended period as was the case in 2017.

The analysis of rainfall data showed that a total of 3.84 billion m^3 of rain fell over the haor region (approximately 7,000 km^2) in 8 days, which would have resulted in a flow of about 5,497 cumec (194,000 cusec) that must have discharged through the downstream outlet point in the Upper Meghna River at Bhairab Bazar. For comparison, the average maximum discharge of the Kushiyara River at Sheola was recorded at 3,000 cumec in 1983 (Sarkar, Nair, Akter and Hossain 2014). The maximum extent of the flood was confined within the Sylhet Basin that has an aerial extent of 8700 km^2 (Sincavage 2017). The flooded area is comparable in size of the haor region (8238 km^2) that gets flooded on a yearly basis (Sarkar

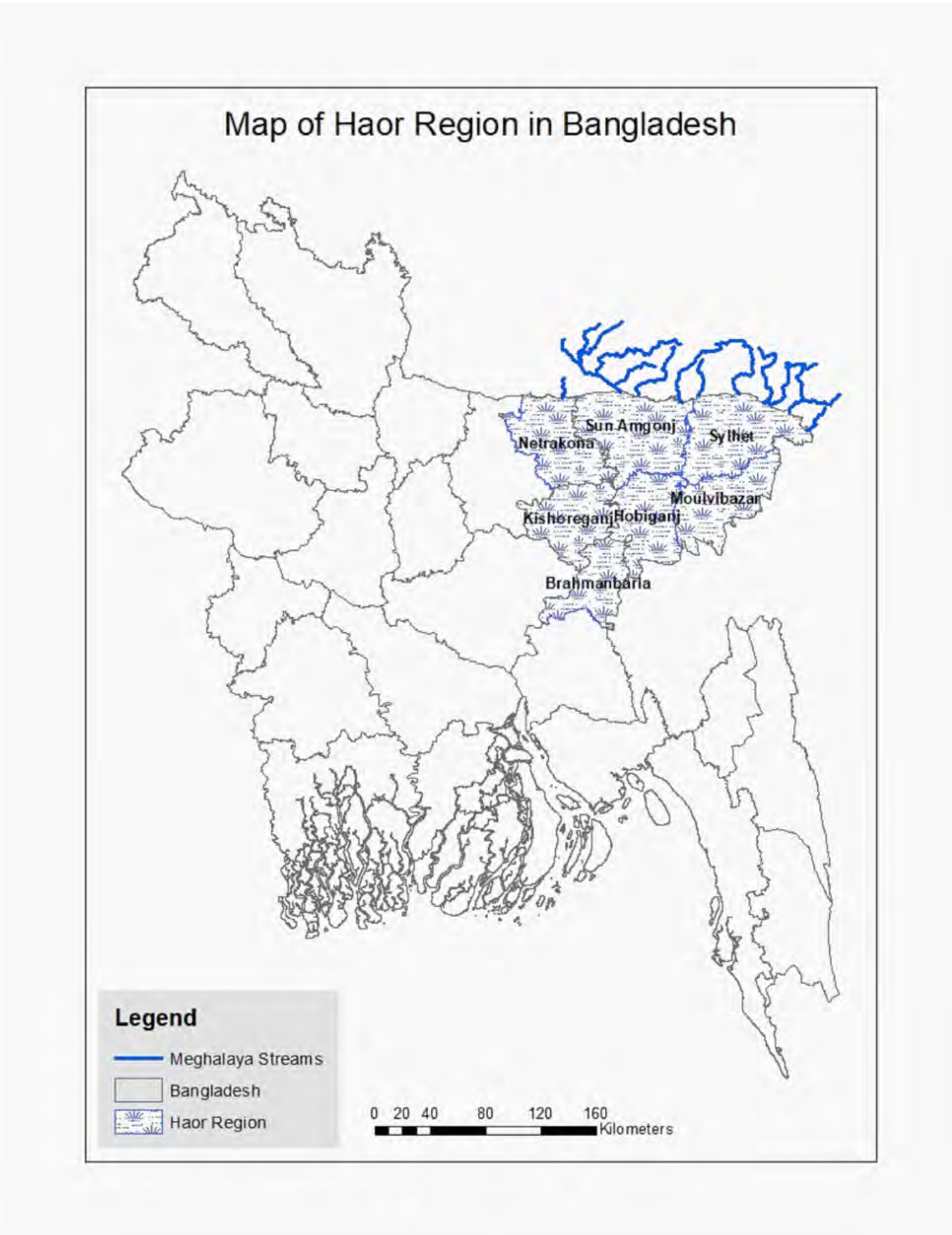


Figure 1: Map showing the haor region and the rivers originating form Meghalaya that drain in the haor region Watersheds of the rivers originating from Meghalaya (India) predominantly experienced flood in 2017.

Inferring Amount of Rainfall for Various Locations during March 28-April 4, 2017 Using the Known Rainfall Data at Cherapunji

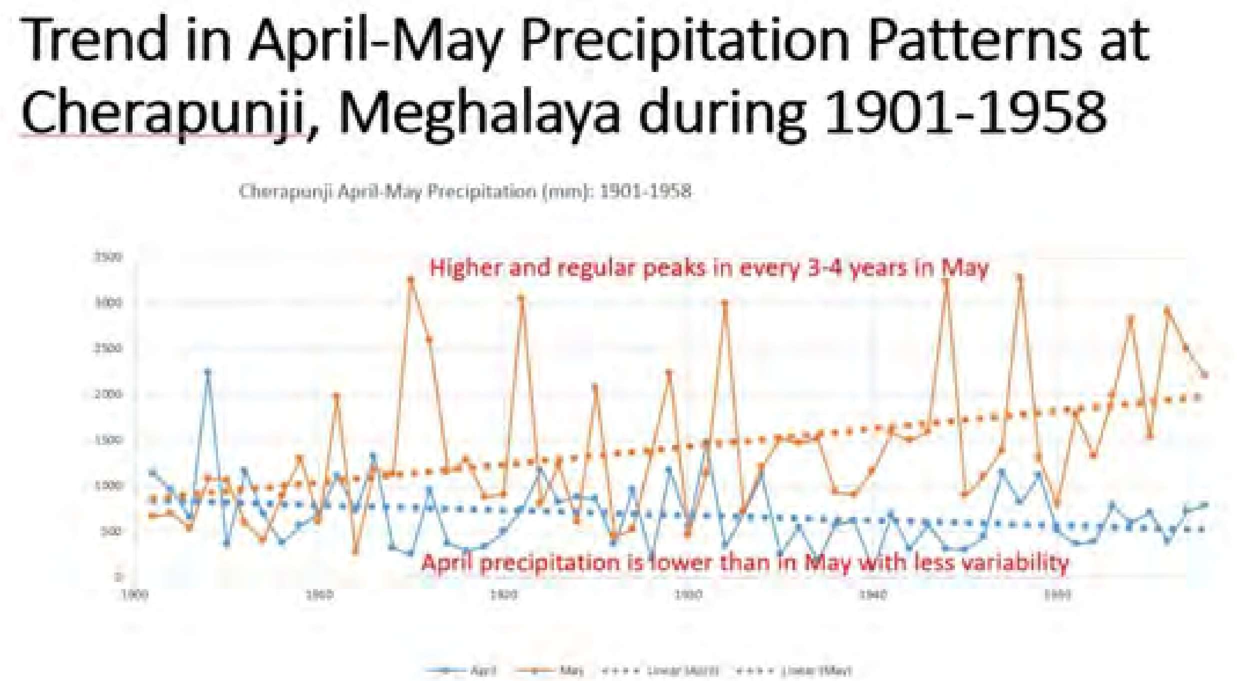
Location	Rainfall (mm)	Relationship to Cherapunji	R^2	Rainfall (inch)
Cherapunji	1262.4	1	1	49.7
West Garo	210.0	Y=0.0908X+95.34	0.28	8.3
West Khasi	341.4	Y=0.2222X+60.85	0.79	13.4
East Khasi	448.1	Y=0.3104X+56.27	0.85	17.6
Jaintia	452.1	Y=0.2937X+81.30	0.72	17.8
Sunamganj	370.7	Y=0.1756X+149.54	0.46	14.6
Average	542.8			21.4
Avg. per day	67.85			2.67
Avg. per hour	2.83			0.33

Figure 2: Relationship between the amount of rainfall at Cherapunji and other five locations within the haor watersheds during the period of flood in 2017. Note that, while Cherapunji received 1262.4 mm of rainfall during the flood period, West Garo, West Khasi, East Khasi, Jaintia, and Sunamganj received 210, 341.4, 448.1, 452.1, and 370.7 mm, respectively.

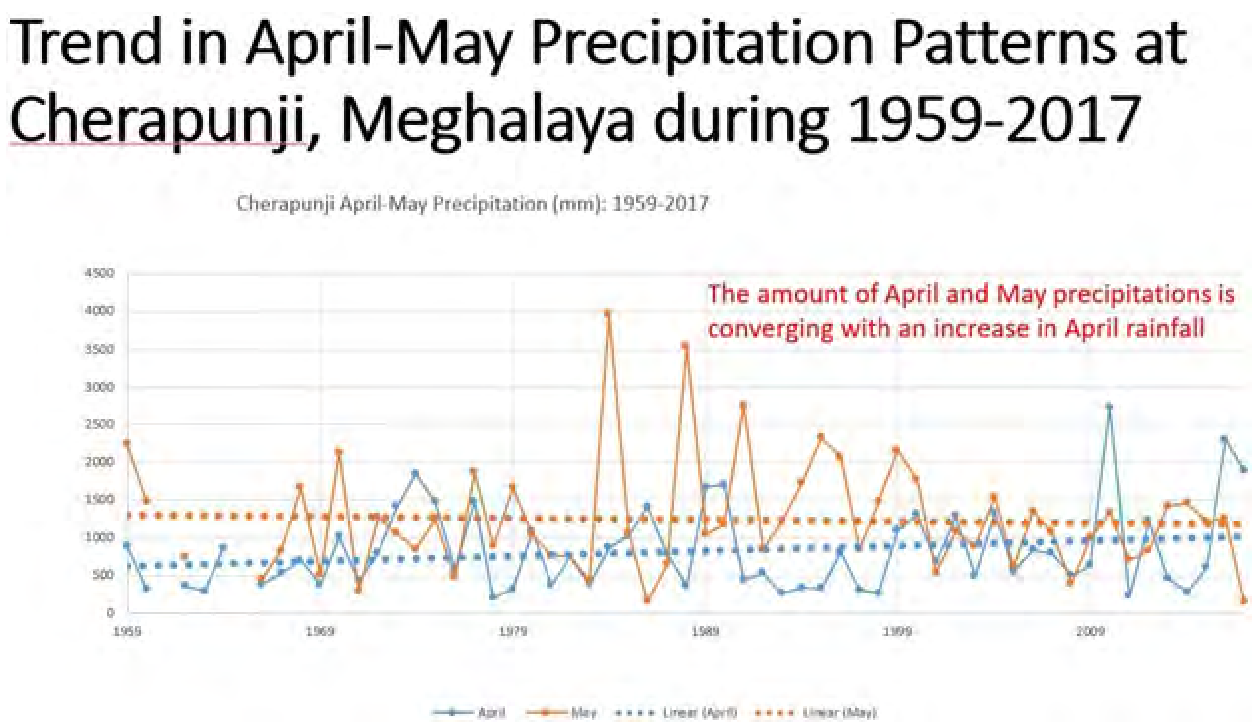
et al. 2014). However, the flood in 2017 occurred earlier than usual. The flood water most likely did not stagnate over the entire haor region with equal depth; part of the flood water must have accumulated over low-lying areas and rivers (10–20% of the flood affected areas), and the other part was discharged through the Meghna River at Bhairab Bazar.

In calculating the amount of surface run-off and river discharge from rainfall, it is important to have hourly data from different parts of a watershed. Rainfall within particular sub-watersheds can influence the run-off and river discharge in the relevant sub-watersheds and in areas downstream of the sub-watersheds. For example, the rainfall at Cherapunji can affect areas near Sunamganj, but will not affect the areas near Chatak or Dowarbazar, or Companyganj, which are located upstream of Sunamganj on the Surma River. On the other hand, the flood water in Sunamganj can affect areas located downstream, such as Bajitpur and Bhairab Bazar. In modeling and predicting occurrences of flood from rainfall at various parts of the haor watersheds, it is important to have detailed rainfall information, as well as soil type, landuse, and slope of each sub-watershed.

Analysis of long-term (1901–2007) monthly averages of rainfall data for the haor watersheds indicated that the rainfall pattern has changed during the last several decades (1950–2017) at East Garo Hills, West and East Khasi, and Cherapunji (which is located within East Khasi Hills watershed). For example, during the earlier decades (1901–1958), the month of May used to receive greater amount of rainfall than the rainfall in April. Also, higher amount of rainfall during the month of May used to have a periodicity of 3–4 years. The total amount of rainfall during May and April was showing an opposite trend with the total amount increasing during May and was decreasing during April during this time period. This trend in rainfall amount and pattern for the months of May and April have reversed during the last several decades (1959–2017) at Cherapunji (Figure 3). A similar trend can also be observed at other locations, except at Jaintia Hills, where the amount of rainfall is on a rise for both April and May over the last 50 years (1952–2002). This means that the amount of rainfall in April is on the rise during recent decades, which indicates that early floods in April may increase in the future. Another study by Mahtab and Convenor (1991) identified an increase in the average annual rainfall in Sylhet region during the period of 1948–1988.



(a)



(b)

Figure 3: The average monthly rainfall data and trend for the month of April and May at Cherapunji during (a) 1901–1958 period and (b) 1959–2017 period. Note that the amount of rainfall is higher for May compared to April for both the periods. During the period 1901–1958, the amount of rainfall in May shows an increase while the amount in April shows a decrease over time. Whereas during the period 1959–2017, the amount of rainfall in May shows a decline while the amount of rainfall for April shows an increase over time.

3 Decline in Water Carrying Capacity and Increase in Flood

Flood is a natural phenomenon by which excess run-off resulting from rainfall is spread on floodplain. As a part of natural variations in the amount of rainfall, most all rivers in the world reach the bankful stage every 2–3 years. As the rainfall data shows, (Figure 3) and has been discussed above, the amount of rainfall used to increase every 3–4 years in the month of April-May in a cyclic manner. Such an increase in rainfall results in higher run-off and river flow in haor region, which causes floods. The rivers in haor region experience normal flood every year, because the amount of rainfall is more than what the rivers in haor watersheds can carry.

However, high velocity in a river during flood can increase its carrying capacity by deepening riverbed or widening its banks through sediment erosion. There exist a natural equilibrium between the amount of flow in a river and its carrying capacity, which is manifested by cross-sectional area of a river. Sauer, Thomas Jr., Stricker and Wilson (1983) formulated the following relationship between the cross-sectional area of a river and its watershed area for North American rivers in mid-Atlantic region where annual rainfall is about 1,000 mm:

Cross-sectional area of a river (ft^2) $=$ 24.8*Area of watershed (mi^2)$^{0.657}$.

Since the haor region receives between 2,500 and 5,500 mm of rainfall annually, it is likely that the average cross-sectional area of a river in the haor region for an equivalent watershed in North America will be 2.5 to 5 times greater. As per this relationship, cross-sectional area, depth, and velocity of a river will increase as it flows downstream to accommodate additional flow resulting from larger watershed area (Figure 4).

Cross-sectional width of all major rivers in the haor region was assessed using Google images for this study. Analysis of satellite images showed that width of the Rakti, Wah Umngi, Jadukata, Piyain Gang, Goyain-Dawki, Sari-Goyain, Surma, Lubachara, and Surma-Kushiyara Rivers narrow as they flow downstream, which is not conducive to carrying flood water as they flow downstream. As a consequence, most all rivers spread on floodplain in haor region during flood season. Flood water carries sediments, which is deposited on floodplain. It is through this sedimentation process that floodplains gain elevations over time and the soil on floodplain is rejuvenated by organic-rich sediments during such flood. In this sense, annual flood cycle is an integral part of haor ecosystem. However, an untimely flood that persists for an extended period of time can cause damage to crop, property, and human well-being.

As a general rule of thumb, the carrying capacity of streams and rivers increases as they flow downstream to accommodate additional surface run-off from tributaries and baseflow fed by groundwater. However, the carrying capacity of the Upper Meghna River—the major conduit of surface water flow in the haor region—is characterized by a decrease in cross-sectional area at the most downstream location at Bhairab Bridge, which is likely to cause drainage congestion in upper reaches of the haor region, resulting in a prolonged waterlogging conditions that prevailed long after the rainfall ended on April 4, 2017.

Analysis of river morphology using Google satellite images indicate that most of the rivers in the haor region have become narrower and shallower over the last few decades. For example, the width of the Jadukata River has decreased by 77% between 2004 and 2017 (Figure 5).

As a general rule of thumb, the carrying capacity of streams and rivers increases as they flow downstream to accommodate additional surface run-off from tributaries and baseflow fed by groundwater. However, the carrying capacity of the Upper Meghna River—the major conduit of surface water flow in the haor region- is characterized by a decrease in cross-sectional area at the most downstream location at Bhairab Bridge, which is likely to cause drainage congestion in upper reaches of the haor region, resulting in a prolonged waterlogging conditions that prevailed long after the rainfall ended on April 4, 2017.

The reduction in river width and depth results in reduced carrying capacity of rivers, which in turn, increases flooding propensity in a watershed. The reduction in cross-sectional area of rivers can be attributed to siltation of riverbeds caused by increase in soil erosion in the watershed due to changes in landuse practices. Human interference has changed the natural flow patterns in the haor region by constructing embankments along the riverbanks and by building roads across the haor region, which create impediment to natural surface water flow across the haor region. Embankments also constrict flood flow within the rivers and streams, which cause flooding to intensify at downstream region. As a part of implementation of the Master Plan of Haor Area, new roads are being constructed in the haor region from Itna to Austagram in Kishoreganj district, which is likely to interfere with natural flow in the haor region during flood (MoWR 2012). This study recommends to carry out flow simulation model before such roads and embankments are built to assess potential impact of such infrastructures on the natural flow of rivers.

Additionally, unregulated mining in upper reaches of the watersheds, increase in urbanization and agricultural practices are likely to have contributed to an increase in run-off and sediment erosion in watershed areas. Part of the eroded sediments from watershed areas are deposited in riverbeds, resulting in reduction of water carrying ca-

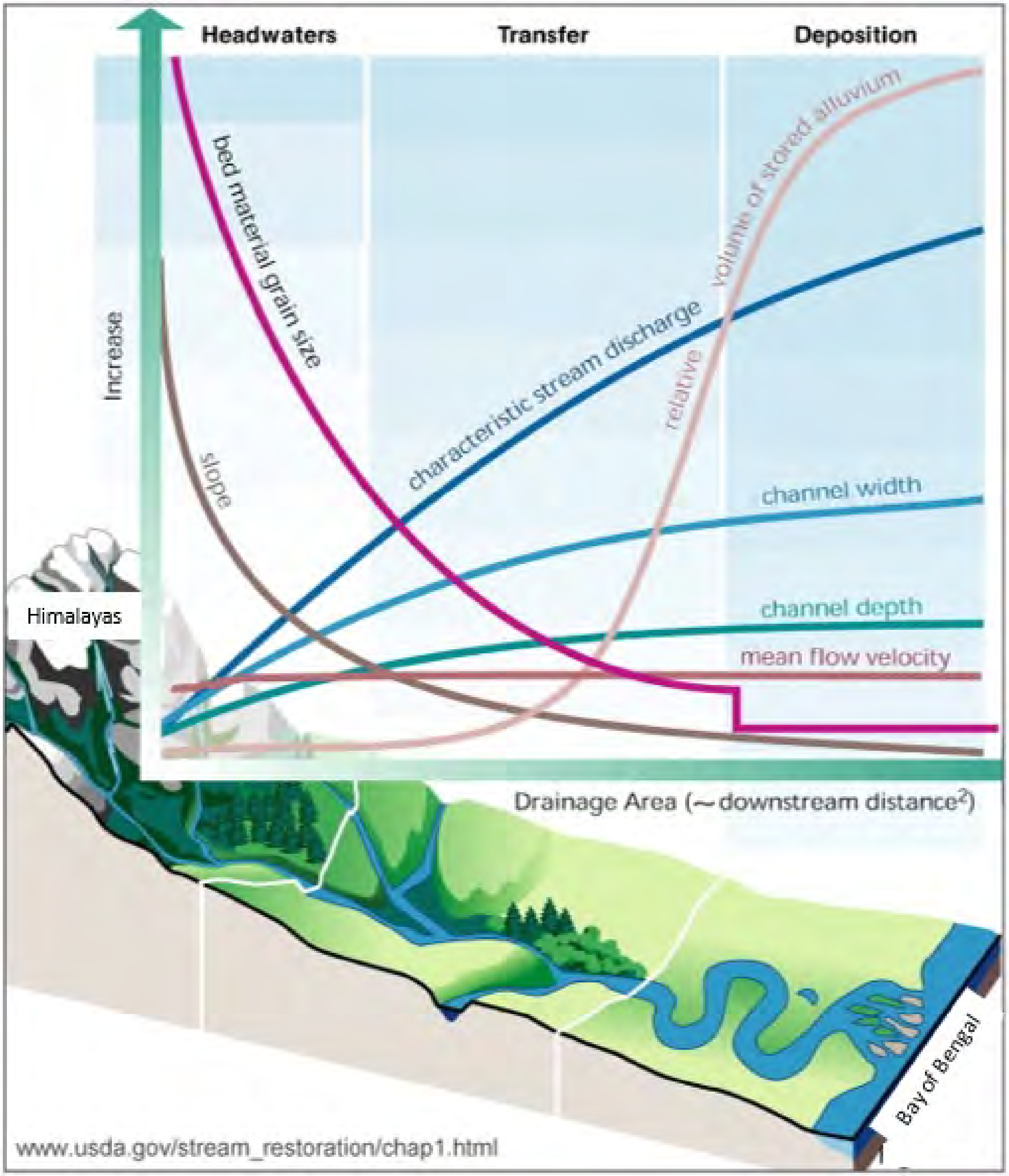


Figure 4: A schematic diagram (modified version) showing increasing channel width of a river flowing downstream as discharge increases. The increase in width from Headwaters through Deposition area is likely to correspond to an increase in depth and thereby increase cross-sectional area (width*depth) of river flowing downstream. Source: https://link.springer.com/chapter/10.1007/978-3-319-73250-3_3

Figure 5: Aerial image showing the changes in width of the Jadukata River between 2004 and 2017. Both of these Goggle images were taken in December. The changes in river morphology and landuse are visible in the images. The sandbars in the river (left panel) are converted to agricultural land (right panel), reducing the carrying capacity of the river.

pacity of rivers and streams. Recent changes in landuse practices can be visually assessed using Goggle images taken in different years.

The rivers in small watersheds in the haor region eventually drain into the Ghorautra-Meghna River system. The width and depth of the Ghorautra-Meghna River was calculated using Google images at various locations along its flow. The results of the calculations are shown in Figure 6. The Google image from 2017 shows that the width of the Meghna River at Kalipur, which is located one kilometer upstream of Bhairab Bridge, is 1,656 meters, but it decreases to 671 meters at the outlet point under the Bhairab Bridge. This is a reduction of width by 785 meters within a short distance.

However, the actual width of the Meghna River at Bhairab Bridge outlet point is less than the measured 671 meters when the widths of multiple pillars from three bridges are taken into account (Figure 7). This drastic reduction in width and carrying capacity of the river at its final discharge point is likely to be responsible for slowing down the discharge of the flow from upper reaches in the haor region, which in turn is likely to prolong the flooding due to congestion in the flow. This study recommends that a detailed survey of elevations along the river and surrounding land area at Bhairab Bridge, hydrography of the river along its course, sediment accumulation patterns upstream of the bridge, water flow simulation model along the main stem of Ghorautra-Meghna River be carried out to determine the water flow characteristics in the river and to assess the impact of three bridges on the flow of the river.

4 Reduction in Land Elevations with Respect to Riverbeds and the Mean Sea Level

The ultimate base level of all rivers is the ocean. If the mean sea level rises with respect to land elevations in a watershed then the river discharge slows down due to decrease in gradient in elevations (Mahtab and Convenor 1991). Damming on a river or drainage congestion in a river can also create a local base level, which can result in slowing down of a river flow due to backwater effect. The Bhairab Bridge is likely to have created a local base level for rivers in the haor region. Control of river flow by constructing dam can drastically change geomorphic characteristics of a river (Skalak, Benthem, Schenk, Hupp, Galloway, Nustad and Wiche 2013). Although the bridges on Meghna River at Bhairab are not dams, they are likely to impact the river flow upstream and geomorphic characteristics (Figure 7). This study recommends to analyze the impact of the three bridges at Bhairab Bazar on river flow in the haor region.

On the other hand, the gradient in elevations between land areas and the mean sea level can decrease if the land elevations in a watershed decreases due to sediment loss from land surface or subsidence of the watershed area (Sincavage 2017). The relative sea level in the Bay of Bengal has been increasing over the last several thousand years and it has been rising at accelerated rates during the last few decades. Some estimates predict relative sea level rise of up to 4 meters in Bangladesh by the year 2050 (Pethick and Oxford 2013). A 4 meter rise in relative sea level will inundate about 40% of the land area, including a large part of the haor region (Gardiner 2014). Additionally, land elevations in the haor region are also decreas-

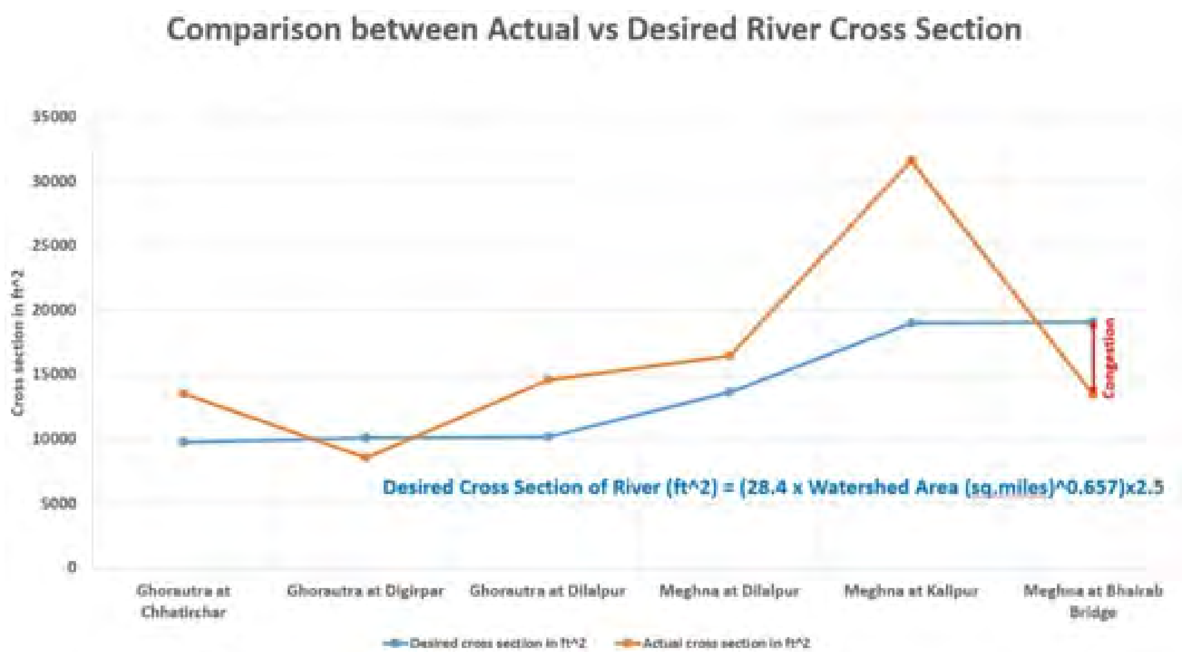


Figure 6: Graph showing changes in the cross-sectional areas of the Ghorautra-Meghna River from upstream (Chatirchar) to downstream (Bhairab Bridge). Note that the reduction in cross-sectional area of the river at the outlet point, which results in congestion in river flow at upstream locations. Such congestion due to narrowing of the river is likely to result in water-logging of flood water in the haor region. The narrowing of the river at Bhairab Bridge is attributed to construction of the railway bridge and two road bridges over the river.

ing due to sediment erosion in watershed areas, as well as subsidence of the greater Sylhet region. Reduction in land elevations and an increase in the mean sea level with respect to land are likely to contribute to an increase in flooding propensity in the haor region.

5 Conclusions and Recommendations

The meteorological data revealed that the timing and intensity of rainfall are changing for the month of April, which is a very crucial month for *boro* rice crop. Moreover, the frequency of early flood will likely increase in the future. It is essential to increase water carrying capacity of rivers in the haor region. A detailed land survey coupled with collection of high resolution digital elevation data can help in planning and managing elevations of land and water bodies in the haor region.

The water carrying capacity of the Meghna River at Bhairab Bridge has substantially reduced due to human interference and infrastructure building on the river. This reduction in cross-sectional area of the river needs to be compensated by increasing the water carrying capacity through capital dredging. A feasibility study to consider the possibility of constructing a bypass or diversion canal at an upstream location on the Meghna River near Kalipur to carry a portion of the discharge to a downstream location in the Meghna River needs to be considered on an urgent basis. It is suggested that a detailed survey of land elevations around Bhairab Bridge, hydrographic survey of water depths along the Meghna River, and a computer simulation of flow patterns along the river be carried out to identify any potential areas along the river that are experiencing flow congestion due to bridge construction and sediment accumulation on the riverbed.

The increase in rainfall in April is in congruence with the IPCC prediction about changes in meteorological processes in the haor region due to climate change (Mirza 2009). It is essential to carry out research to find flood-tolerant rice crop for the haor region. Adjustment in the design, planning, and building of embankments in haor region will be required in the future.

Since 67% of watershed and 56% of flow of the rivers draining the haor region originate outside of the country's territory, it is important that an integrated water, sediment, and landuse management compact be reached with upper riparian countries (MoWR 2012). Bangladesh should ratify the Convention on the Law of the Non-navigational Uses of International Water Courses 1997 (The UN 1997)

Figure 7: Google image showing the Bhairab Bridge on Meghna River and surrounding areas. Note the reduction in width of the river at Bhairab Bridge and widening of the river at upstream location near Kalipur (northeast corner of the image)

and negotiate with other co-riparian nations to adopt the convention.

Scarcity of meteorological data in the haor region is a hindrance to scientific research in water resources planning and management. This study is based on limited monthly rainfall data in the haor watersheds. Therefore, the analyses and conclusions made in this research have limitations. It is recommended that meteorological stations are established in every upazilas in the haor region. The cross-sectional areas of rivers are calculated based on Google Earth images and elevation data. To improve on the quality of the analyses, it is recommended that a land-based survey be carried out to validate the results of this study.

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