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A comprehensive morphological and hydrological analysis of the Dharla River, northwestern Bangladesh

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Abstract

The Dharla River is one of the right bank tributaries of the Jamuna River. It is a trans-boundary river and flows through the countries of Bhutan, India and Bangladesh. In its upper course, the river originates in the Lower Himalaya and passes through the piedmont plain of northeastern India. The riparian area of this river is known for flash flood and recurrent bank erosion. However, study related with the Dharla River is very insignificant. In this study, different types of dataset ranging from chronological satellite image, river discharge, water level, cross-section, precipitation and Digital Elevation Model have been employed for a comprehensive understanding of the morphological and hydrological characteristics of the river so that a sustainable riparian landuse planning can be implemented. The study indicates that on a basin scale, the morphology of the Dharla River is influenced by complex interplay of relief, climate and tectonics. In Bangladesh part, the river shows two distinct types of planform, the upstream part is characterized by braided and the downstream part shows meandering planform. Satellite image indicates that the overall width of the Dharla River decreased about three times from 600 m to 200 m in the past 45 years. The river is now migrating its channel mostly in the north-eastward direction often with the rate of about 66 m/year. The confluence location of the Dharla River with the Upper Jamuna River is not stable and is influenced by the backwater effect from the Jamuna River. The backwater effect induces erosion adjacent to the confluence area. Considering the complex nature of the bank erosion a setback buffer at the most erosion prone area like in Holokhana union is recommended for the sustainable landuse management of the area.

Keywords: Dharla River, River morphology, Satellite image, Cross-section, DEM, Confluence, Backwater effect

Introduction

Rivers are one of the most sensitive geomorphic entities on the earth, which can respond and adjust to different environmental triggers very quickly. The adjustment is especially rapid in the alluvial rivers, originated from a tectonically active mountain with high slope, rainfall and sediment load. Every single aspects of the morphology and the changes of such river, whether it could be a movement of meander bend, changes

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in channel width, braiding intensity or sinuosity, indicate a change in flow regime, sediment load, topography or lithology either in close vicinity or far upstream/ downstream directions. The consequent channel instability causes damage to various socio-economic and environmental components in terms of flood, bank erosion, modification of the navigation route and alteration of aquatic and riparian ecosystems.

Being a monsoon dominated sub-Himalayan country, hardly there is any river in Bangladesh, which has a stable morphology. The whole country is a unique place in the world to understand the dynamic fluvial processes. Moreover, the river morphological and hydrological instability inflicts enormous social and economic stress every year, causes forced migration, damage to infrastructure consequently affects the overall economic growth of the country. Therefore, in addition to scientific understanding of the underlying processes, knowledge of river morphology and hydrology also has a profound societal impact in this country.

The Dharla River is one of the right bank tributaries of the Upper Jamuna River bounded by the Teesta River in the south and the Dudhkumar River in the north. It is a trans-boundary river, which originates in Bhutan, then flows southeasterly direction from the foothills through India and enters Bangladesh at Kurigram district. Most of the course of the Dharla River lies in the upstream where it is known as the Jaldhaka River. In this study, the decadal changes of morphology, yearly changes of bottom topography, flow analysis and confluence characteristics of the Dharla River have been analysed using digital elevation model, precipitation, discharge, water level, cross-section and chronological satellite imagery data.

The Dharla is a relatively less studied transboundary river. Among the studies associated with the Dharla River are related with flood inundation modeling (BOSE & NOVERA 2017), bank protection revetment design (KHAN *et al.* 2015), sediment provenance studies (RAHMAN *et al.* 2021). In the upstream part, studies related with the Jaldhaka River are associated with the upstream tributary confluence (CHAKRABORTY & DATTA 2013; CHAKRABORTY & MUKHOPADHYAY 2014), interfluve study (GOSWAMI *et al.* 2019), tectonic activity and geomorphology (STARKEL *et al.* 2008; STARKEL *et al.* 2015) and agricultural water management (de BRUIN *et al.* 2012; de CONDAPPA *et al.* 2012). A huge knowledge gap therefore exists regarding the understanding of the morphology and hydrology of the river. Besides, on a catchment scale, no previous study is known yet. Depending on the data availability, some of the analysis have covered the whole catchment while the other components are focused only on the Bangladesh part of the River.

The study area

The transboundary Dharla River flows over three countries with a total length of about 208 km. In Bhutan, it originates in the southwestern Samchi district, has three

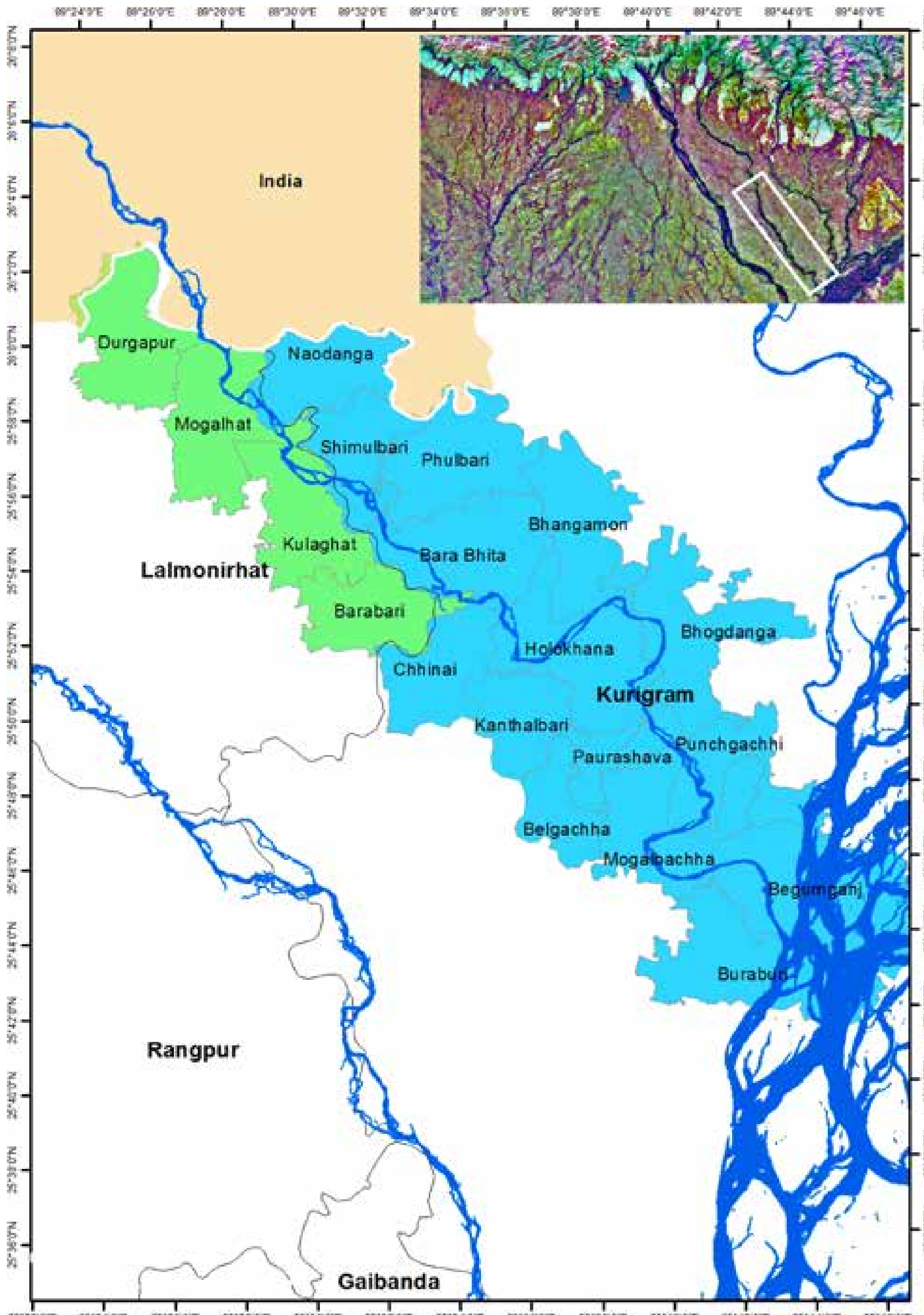

Fig. 1. The Dharla River of northwest Bangladesh from entry to the confluence point. The inset map shows the alignment of the upstream course known as the Jaldhaka River.

main tributaries namely Murti, Jaldhaka and Diana, with a length of about 15 km. The upper three tributaries converge close to the Bhutan-India international boundary and flows as Jaldhaka River. In India, the Jaldhaka River enters from Bhutan into the northern Jalpaiguri district of West Bengal State, flows about 141 km through Mekhliganj, Mathabhanga and Dinhata of Cooch Behar district.

In Bangladesh part, the river is about 54 km long and enters from India in a northwest-southeast direction at Mogolhat union of Lalmonirhat District. However before this point, part of a braided channel of the river intrudes in the boundary of Durgapur union, which is situated about 4 km upstream of Mogolhat union. The Dharla River makes confluence at the right bank (western side) of the Jamuna River at Ulipur union. Within Bangladesh, the rivers flow through Lamonirhat and mainly across the Kurigram district (Fig. 1).

In the northwest Bangladesh, two other transboundary rivers flow almost parallel to the Dharla River. Distance between the southern Teesta and the Dharla River is about 16 km and with the northern Dudhkumar River is about 13 km. In the Indian part, several tributaries join with the river especially at the upper course (BANDYOPADHYAY *et al.* 2014). Two tributaries join at the right bank of the river at Lalmonirhat district. Besides, several minor tributaries are noticed in the satellite imagery, which have very low flow at the moment and are only active in the monsoon season.

The Dharla River is infamous for its disastrous flood and bank erosion hazard. The average population density of the riparian area is 1,060 person per sq. km as per the census of 2011 (BBS 2014) which indicate the magnitude of population displacement vulnerability due to flood and bank erosion hazards. The national media frequently publish news about such hazard of the Dharla River during the monsoon season, especially in late June. The riverbank erosion has complex social impact in this remote part of the country. Not only it displaces people multiple times in their lifespan, and affects agriculture; many infrastructures are also impacted by this hazard. In the absence of any land use zoning or setback distance, often the educational institutions are constructed along the riverbank or in the direction of meander cutbank. Once affected by the erosion, it requires long time to construct it again. As a result, the educational system of the area suffers for long time. Therefore, the morphological impact is multi-dimensional in this area. Besides, Kurigram district is the poorest region of the country (BBS 2020) therefore, the people has very low coping capacity. Many of the poorest of the poor, live in the river bar (char) where the vulnerability is even more. One of the main reasons of this social and economic backwardness of the region is frequent flood and bank erosion hazard. However, there is no existing landuse guideline for constructing the riparian infrastructures neither any setback limit from the riverbank is considered. Prioritizing areas for bank protection therefore based on authority's perception not on morphological prediction consequently turns unsustainable.

One of the main reasons of the flood and bank erosion, is aggradation of the river bed, which increase the flood height and deflects the thalweg towards the riverbank. As a response, the government plans to minimize the erosion and restore the navigability of the Dharla River along with three other rivers (Old Brahmaputra, Tulai and Punorbhoba) of the country by June 2024. The Executive Committee of the National Economic Council (ECNEC) on October 2019 approved the project worth about Taka 43.71 billion (4,371 crore). Bangladesh Inland Water Transport Authority (BIWTA) under the Ministry of Shipping will implement the process. The whole length of the River would be dredged into 38 meter width and 2 meter depth to transform it to Class-3 (2.13 to 3.66 m) navigational route (Daily Sun 2018). It is expected that after completion of the project, the flood and erosion magnitude will be reduced. However, in a semi-braided river like Dharla, the riverbed sedimentation is an inherent continuous process. The expensive dredging process requires prioritizing dredging sites and for which the river morphological and bottom topographic analysis are quite necessary. But for the Dharla River, such analysis was not carried before.

Data and methodology

Regarding the objectives of the study, different types of data are necessary to understand the basin characteristics, drainage network, precipitation, river discharge, water level and channel geometry. Consequently, enormous time and effort has spent to organize, quality check, sort, finding data gap and correlating the dataset. For analyzing the topographic characteristics of the drainage basin, SRTM 30 meter DEM is collected from the USGS Earth Explorer site (http://earthexplorer.usgs.gov/). For river morphological analysis, satellite images of different years are also collected from the USGS site. Morphological change detection requires at least two satellite images, one is older and the other is from recent time. As Landsat archive span from 1972, level 1T Landsat imagery with 60 m resolution from 1972 was employed as the earlier image. The recently acquired Sentinel-2 image with 10 m resolution from 2019 was employed to understand the decadal planform changes. However, high cloud cover during the monsoon and often in non-monsoon months limits the image availability. As a result, considerable time has spent to select the cloud-free time series images. The selected images are from the winter season (March). At this time the river is at low flow stage, the bank lines are clearly delineated and the river-bars are exposed fully. Historic and contemporary imagery are also obtained from the Google Earth archive for high resolulation morphological understanding. The study area is covered by one Landsat scene with path row ID of 148-42 for the MSS images. The Sentinel 2A & B Level 1C images are extracted from the path row ID of 45RYJ.

There is no precipitation measurement station close to the Dharla River, therefore precipitation data from nearby Rangpur station is used which is about 35 km southwest from the main river channel. Precipitation, river discharge, water level and cross section data are collected from Bangladesh Water Development Board

(BWDB). The measurement datum for the water level and cross-section data is the Public Works Datum (PWD), which has established by the Department of Public Works, Bangladesh. The PWD datum is 0.46 m below the Mean Sea Level (MSL) datum. Cross-section lines are denoted by numbers like RMDLA 01 to RMDLA 10 (Fig. 2). For each section, the depth of the thalweg is calculated. Cross section for the year 2011 or 2014 is compared to understand the changes in river bottom profile. The orientations of cross-section lines are imported in GIS environment to visualize the positions along the river and also to understand the relationship between the river bottom profile with adjacent landform and land use. Sinuosity of the whole river as well as of individual reaches are calculated to understand the degree of channel meandering. Confluence locations are extracted from chronological satellite imageries. An intensive fieldwork was carried out from 15 to 18 February 2018 to collect bank sediments, to identify the erosion prone areas and to validate the result of image based morphological change detection.

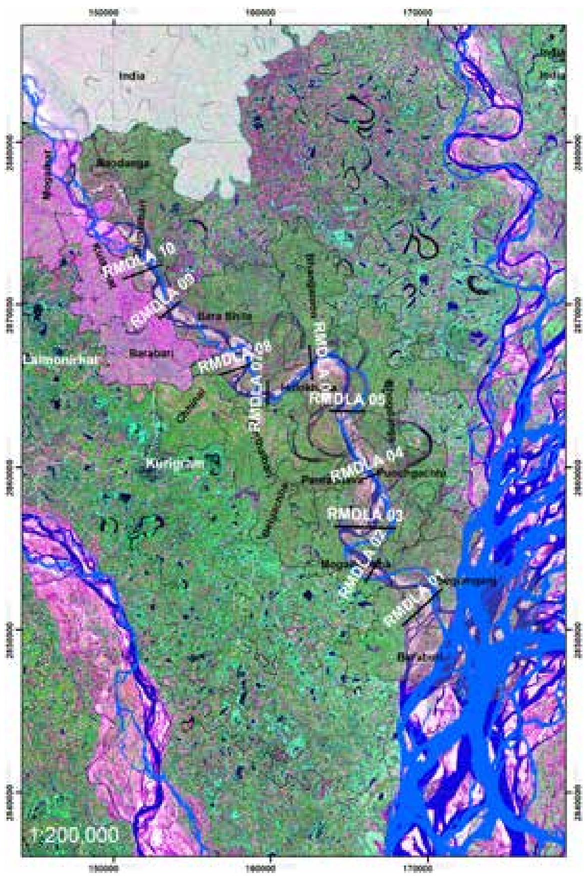

Fig. 2. The positions of the ten cross-section lines along the course of the Dharla River.

Results and discussions

Drainage basin characteristics

The drainage basin is a system, which converts the precipitation into runoff and weather the rock into sediment. The geomorphic and geologic characteristics of the drainage basin control this rate of runoff, groundwater recharge and sedimentation. The behavior of downstream flood, the water velocity, bank erosion and the overall channel morphology is directly related with the drainage basin characteristics. Therefore, the drainage basin characteristics are often analyzed first to understand the underlying process, which controls the fluvial morphology and the related hazards (SINGH 1994).

Geomorphology and geology

The drainage basin of the Dharla River shows marked variation in altitude, precipitation and gradient. The southern slope of Himalaya consists of two zones: the Higher Himalaya and the Lesser Himalaya. Only two rivers, the Teesta and the Torsa (Dudhkumar), originated in the glaciated Higher Himalaya (MANDAL & CHAKRABARTY 2016; PROKOP & WALANUS 2017). The upstream part of the Dharla River originates in the Lesser Himalaya. Rivers with headwaters in the Lesser Himalaya, is fed by heavy rains in the monsoon season and by groundwater in the dry season. The upstream area is influenced by active tectonics and traversed by a number of faults (GUPTA 2008). The upper course intersects the Main Frontal Thrust (MFT) and Main Boundary Thrust (MBT) faults, which are almost parallel to the mountain front. From its origin, down to the mountain front, the river traverses mainly through the metamorphic rocks of gneiss, quartzite, slate, phyllites and then through the alluvium after the mountain front (PROKOP *et al.* 2020). The southern end of the Darjeeling-Bhutan Himalaya is composed of unconsolidated alternating sequences of mudstone, sandstone and conglomerate of the Siwalik Group. Along the southern Himalaya, the Siwalik belt is up to 5 km wide (PROKOP & WALANUS 2017; PROKOP *et al.* 2020). At the steep front of the eastern Himalaya, the Siwaliks are very narrow and even between the Teesta and the Torsa Rivers i.e. along the upper course of the Jaldhaka-Dharla River, it is totally missing (CHAKRABORTY & DATTA 2013; STARKEL *et al.* 2015).

The geomorphology of the foothill area is dominated by alluvial fan. Satellite image indicates that from the west to the east, the entire sub-Himalayan front is marked by series of alluvial fans of different dimensions and elevations. These alluvial fans form a piedmont zone. In India, the piedmont zone east of Teesta River is known Duars and the western part as Terai (BISWAS, 2014). The river courses are often deflected by these alluvial fans. In the study area, the Teesta and the Jaldhaka Fan markedly influence the Jaldhaka River course. From the origin, the river is deflected towards southwest by the Jaldhaka alluvial fan and following the fan boundary it turns towards southeast in a remarkably straight, probably through a fault-controlled course. If the river course had not deflected in the upstream, the flood magnitude would be more intense in the downstream part. The whole area is tectonically uplifting therefore with the interaction of high monsoon precipitation, supply abundant runoff and sedimentation.

Topography

The Digital Elevation Model (DEM) indicates that the elevation at the source of the river at southeastern Bhutan is about 310 m. At the India-Bhutan boundary, it is reduced to 290 m. The elevation rapidly decreases in the piedmont zone and at the boundary of the Jaldhaka Fan, it is about 88 m i.e. within 40 km, the elevation drop is about 200 m. This is the zone of intense braiding and the intensity reduced towards the downstream. From this point, another slope break is observed at 55 m elevation in the Indian part, where conspicuously several tributaries join the main river channel on the left side. From this point, the elevation gradually decrease and the Dharla River enters in Bangladesh at 34 m elevation and make confluence with the Jamuna River at 24 m within a distance of 55 km (Fig. 3). Elevation change is rapid at the entry and also at the confluence. In the Bangladesh part, the overall gradient is 0.18 meter per kilometer. The overall elevation profile is concave with different gradient across the length (Fig. 3). The reduction of gradient implies decrease in flow velocity, carrying capacity and subsequent widening of the channel.

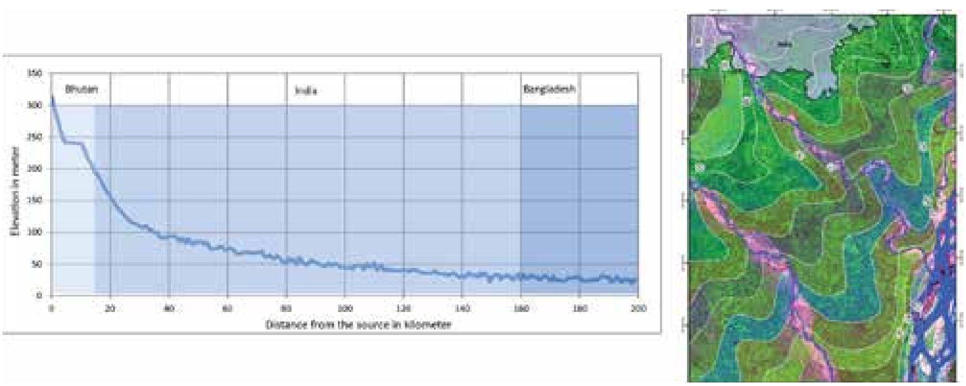

Fig. 3. The elevation profile of the Dharla River in three countries along with the elevation contour in Bangladesh part.

Precipitation

Across the Jaldhaka-Dharla drainage basin, the rainfall show high spatial variation and is directly linked with the elevation. The rainfall amount gradually decreases towards the downstream direction. In the Bangladesh part, the closest rainfall measurement station is at Rangpur, which is about 35 km southwest of the Dharla River. At the source in the southwestern Bhutan, the annual precipitation amount is about 4,365 mm at Samtse, in the Indian part it is about 3,557 mm in Cooch Behar and in Rangpur the amount is 2,340 mm. In all three stations, highest rainfall occurs in the month of July and no rainfall in both December and January.

Geomorphology has great impact on the precipitation to runoff conversion process. As the origin of the river is at higher elevation with steep slope, most of the rainfall is immediately converted into surface runoff. It is estimated that in the southwestern part of Bhutan, about 72% of the rainfall flows as surface runoff and 18% percolate as groundwater (SHARMA 1974). Geology also has profound impact on the runoff to groundwater recharge ratio. Hard impermeable metamorphics of the Lesser Himalayas along with high slope resulted rapid flowing of water therefore, less groundwater recharge in the upstream area. In the deltaic plain, where the slope is less, the runoff and floodwater retains longer time on the floodplain, underlain by permeable lithology consequently has much higher groundwater recharge potential. In contrast, the heavy precipitation and the steep hill supply a large amount of sediment whereas in the plain land, the sediment source is much smaller and mainly generated from the runoff and bank erosion. The precipitation induced mass movement along the steep hill also supplies huge amount of coarse sediment into the river, which is carried mainly as bed load and the higher is the bed load, the faster will be the planform change.

Discharge

River discharge has profound impact on the river morphology. Higher discharge may produce higher sediment loads and also result in rapid planform change and vice versa. LEOPOLD *et al.* (1964) and LEOPOLD (1994) confirm that the erosion rate and the sediment transport rate are most active when discharge is near bankfull. Generally, the monthly fluctuations of sediment load correlates well with the mean monthly discharges.

In this study, the discharge of the Dharla River is calculated from two stations. The upstream Taluk Shimulbari (SW 76) and the downstream Kurigram (SW 77) station (Fig. 4). The distance between the stations is about 30 km. The objective of discharge analysis is to understand the nature of the daily, monthly, seasonal and annual river flow characteristics. However, by looking at the data it is found that in some years there are questionable discharge values therefore discarded for the analysis.

For most rivers, the discharge increases in the downstream direction as the groundwater baseflow, runoff and other tributaries contribute to the main stream. For the Dharla River, the Taluk Shimulbari station (SW 76) is located 30 km upstream than the downstream Kurigram station (SW 77). Therefore, the discharge at Kurigram should be greater than upstream Taluk-Shimulbari. The monthly discharge data agrees with the norm and there is about 28% increase in discharge at the downstream station compared to the upstream station (Fig. 5). The average discharge of the upstream Shimulbari is 462 m^3/s and for Kurigram station, it is 628 m^3/s. The discharge variation between the stations is most apparent in the monsoon months

(June-October), however in the dry months (November-May), the differences are also significant (Fig. 5).

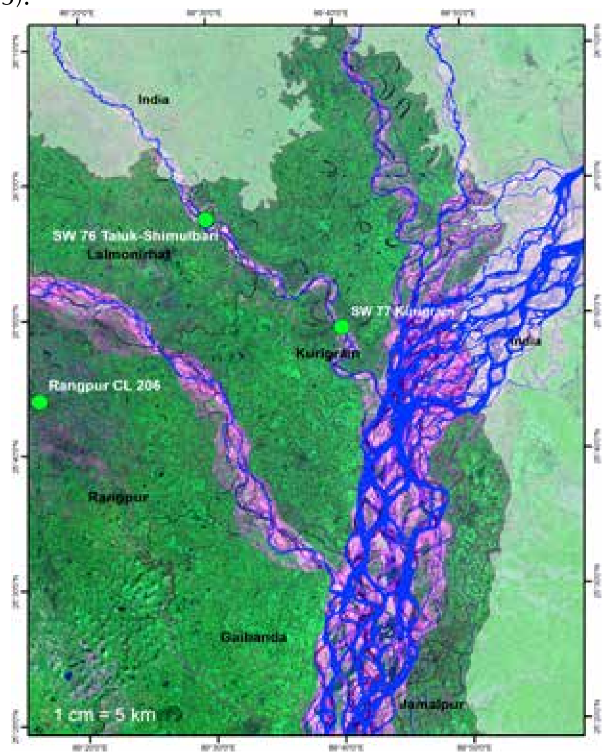

Fig. 4. The precipitation (CL 206) and discharge measurement stations (SW 76 & 77) in the study area.

The hydrograph of the two stations indicate marked seasonal fluctuations of river discharge, which is directly related with precipitation. About 87% of the total discharge occurs in 5 months (June-October) and the rest 13% is from November to May (Fig. 6). Highest discharge occurs in the month of July and lowest in March when the precipitation is low and due to increase in summer temperature, evaporation is high. The lean months of December to February therefore can be selected for the dredging operations in the Dharla River.

The mean daily discharge hydrographs indicate that there are several flood peaks of different amplitude starting from the month of July and extends up to the month of October (Fig. 6). This indicates that the Dharla is a flashy stream and responses very quickly to the changes of water input. When the hydrograph data of the year 2014 and 2016 are compared, it is found that not only the flow volumes are different in the monsoon months but also the flood timing are different. In 2014, the flood peak came late on 27 August whereas in 2016 the peak was one-month earlier on 27 July (Fig. 6). Due to this yearly shift of flood peak, flood management is difficult in this area and requires real time data.

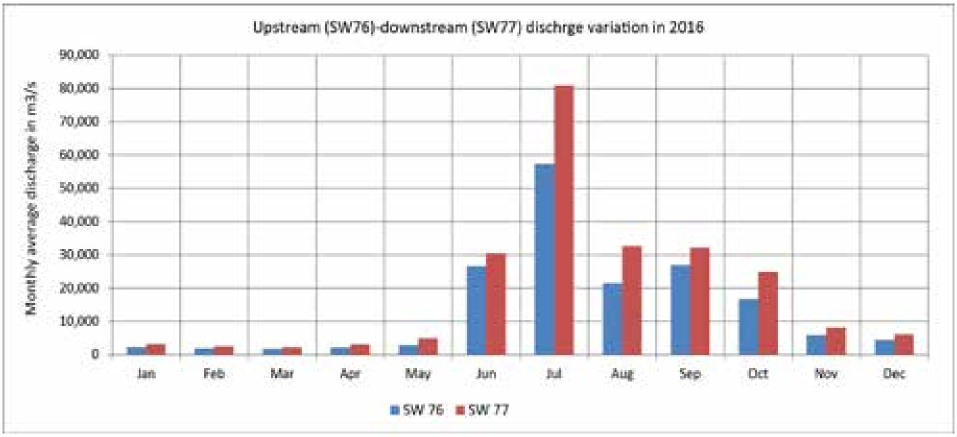

Fig. 5. Dicharge comparison of the upstream (SW 76) and downstram (SW 77) stations of the Dhrala River.

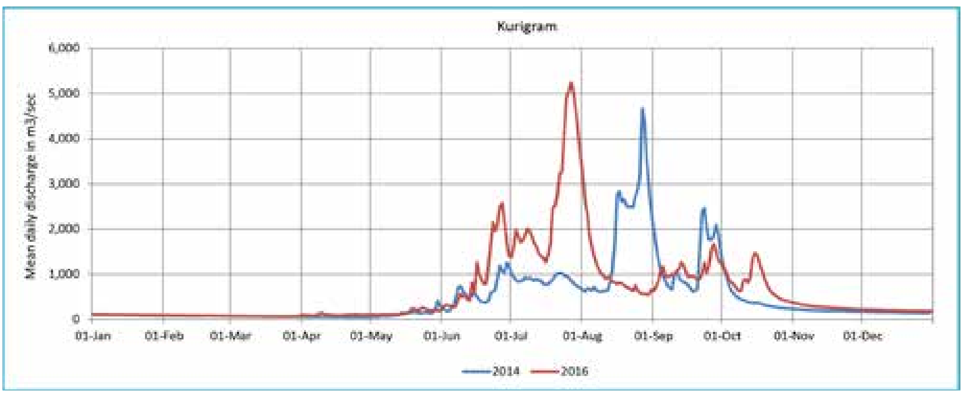

Fig. 6. Discharge characteristics of the downstream station (SW 77) at Kurigram for the year 2014 and 2016.

Water level

River water level is profoundly linked with flood management, riverbank erosion, navigation and dredging operations therefore is crucial for the riparian landuse management. The water level data of the Dharla River is measured in two stations like the discharge data but compared to discharge, it seems that the water level data is more accurate.

The water level height correlates well with the precipitation pattern i.e. highest in the monsoon season and lowest in the dry season. In 2016 at the downstream station Kurigram, highest water level of 27.56 m is observed on 27th of July and lowest height of 22.5 meter on 5th of March when the temperature is high also (Fig. 7). After March in spite of higher temperature, the input from upstream increases the water level. Therefore, it seems that the river water level is very sensitive to climatic parameter of precipitation and evaporation.

The overall hydrograph show stepwise increase of water level compared to the declining phase in the both stations (Fig. 8). When the water level data of these two stations are plotted together, it is observed that the average differences of water level elevation between 30 km distance is about 4.7 m (Fig. 8). Generally, multiple flood peaks are observed in each year in both stations and the number and magnitude of flood peaks also varies every year. When the water level data of the downstream Kurigram station is compared with the danger water level, it is found that in 2016 the flood peak was quite high compared to 2014 level (Fig. 9).

Although the floodwater danger level for the downstream Kurigram station is fixed at 26.5 m by the national Flood Forecasting & Warning Center (FFWC), there is no such level for the upstream Shimulbari station. Considering the land elevation and water level height of this area, it seems that 30.5 m could be the approximate danger water level for the upstream Shimulbari station.

Fig. 7. Water level height of the downstream Kurigram station in 2016 based on daily data.

Fig. 8. Comparison of the upstream and downstream water level height in 2016. The distance between the stations is about 30 km.

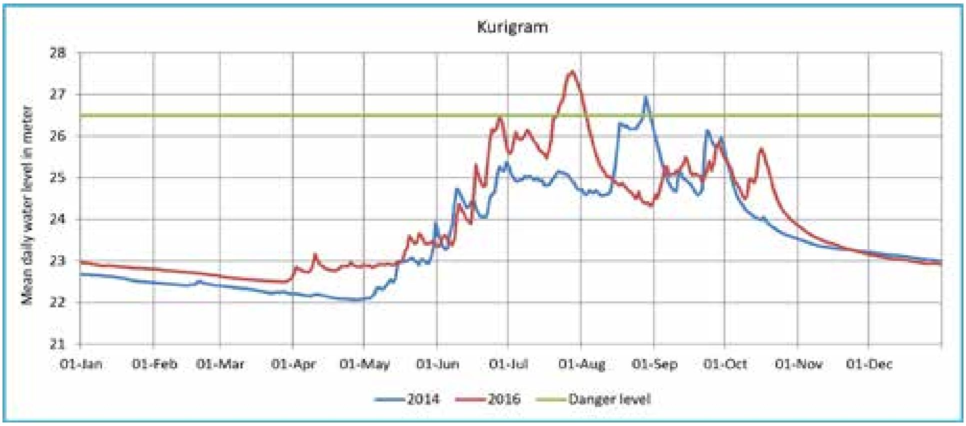

Fig. 9. Comparison of water levels in Kurigram area between 2014 and 2016 along with the danger water level.

River bottom topography

River surface morphology and bottom morphology are mutually related. Most of the surface morphological changes are triggered from the bottom. For example, most of the riverbank erosion of Bangladesh is triggered through toe scouring (Thorne *et al.* 1993). The braided river dynamics completely depends on riverbed deposition. Changes in river bottom profile has wide practical implications like for the selecting of the dredging sites, finding best navigational way with highest vessel draft, for adjusting the danger level of river flooding, detecting bed scour, for identifying location of ports and for finding the optimal gradient for storm water discharge or sewage from the riparian land.

In this study, the bottom profile changes of the Dharla River from 2011 to 2014 are analyzed to identify how the thalweg depth has changed in the past three years. In the next step, the possible causes of the changes are also analyzed. Thawleg is the deepest part of a channel where the main current of the channel flows. The changes of thalweg depth therefore provide clue about the deepening or shallowing of the river.

Ten cross-sections are analyzed for the detection of bottom profile changes. The distance between the sections are not even, some are closely spaced than others. Besides, the whole river length is not covered by the survey (Fig. 2). Generally, sections are placed along the meander bend, adjacent to bridge and tributary confluence locations. The upstream section is numbered as section 10, the section number decreased towards the downstream direction. The covered distance is about 40 km. Although cross-section data for several years were collected, some values are quite anomalous therefore discarded and only data for the year 2011 and 2014 are used for the analysis.

The studied cross-sections are asymmetrical in nature i.e. the channel thalweg is not at the center of the section, rather than often flow adjacent to the riverbank (Fig. 10). The cross-section profile changes every year. The river is deep near the confluence and the navigability decreases towards upstream. Most bottom topographical changes are observed in the middle part of the river. In general, the channel becomes shallower in 2014 compared to 2011 (Fig. 11). The magnitudes of the changes are given in Fig. 12. A zone of riverbed aggradation is identified covering the cross-section 7, 6 and 5 of the Holokhana union. This is the most erosion prone area. The section 5 shows the highest amount of aggradation. The reason behind the channel aggradation is riverbed sedimentation either due to eroded material from the bank or reduced carrying capacity. Whatever the cause, this site should be prioritized for dredging

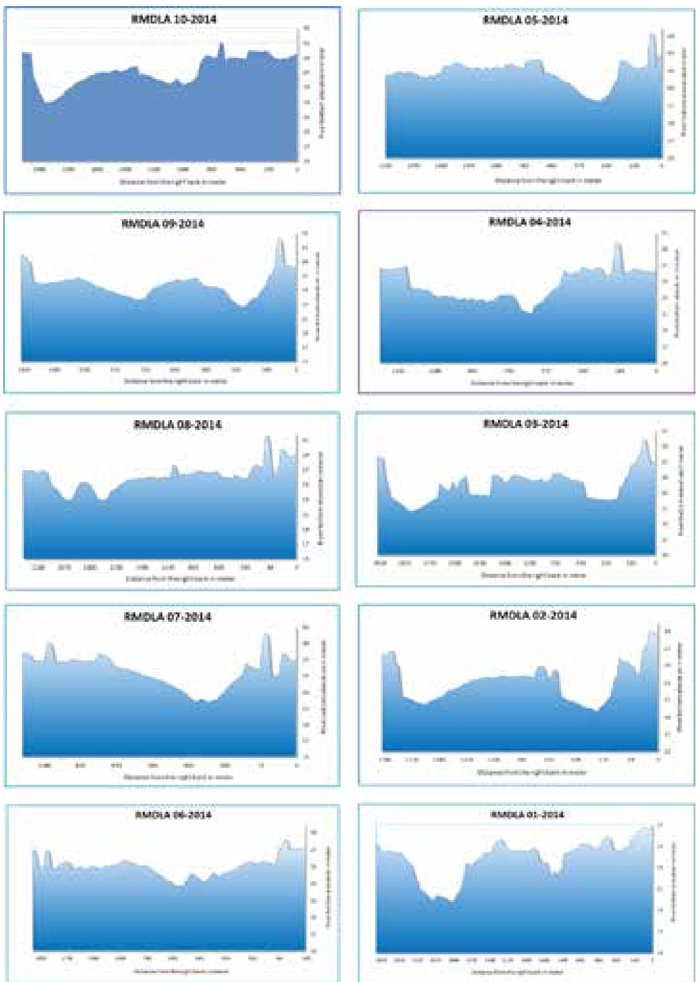

Fig. 10. The ten studied cross section profiles of the Dharla River, locations marked on Fig. 2.

operations, because removal of the riverbed material will also reduce the intensity of bank erosion of this area (Fig. 12). In contrast to aggradation, slight degradation of bed profile is observed at the upstream location and few stable locations are observed at cross-section 8, 4 and 2.

From the cross-sections, the river widths are also calculated. In general, the width increases towards downstream direction. The average width of the Dharla River is about 2.1 km. Lowest width of 1.3 km is observed at cross-section 7 and highest width of 3.6 km is found near the confluence.

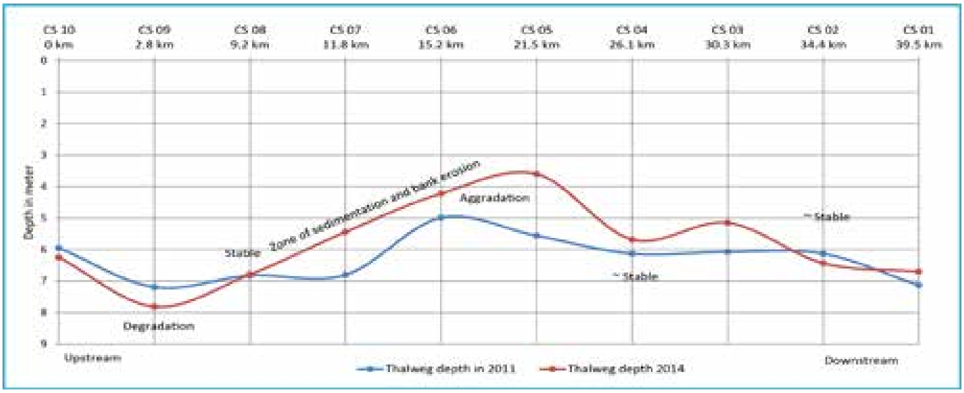

Fig. 11. Changes of thalweg depth in 10 sections in 2011 and 2014.

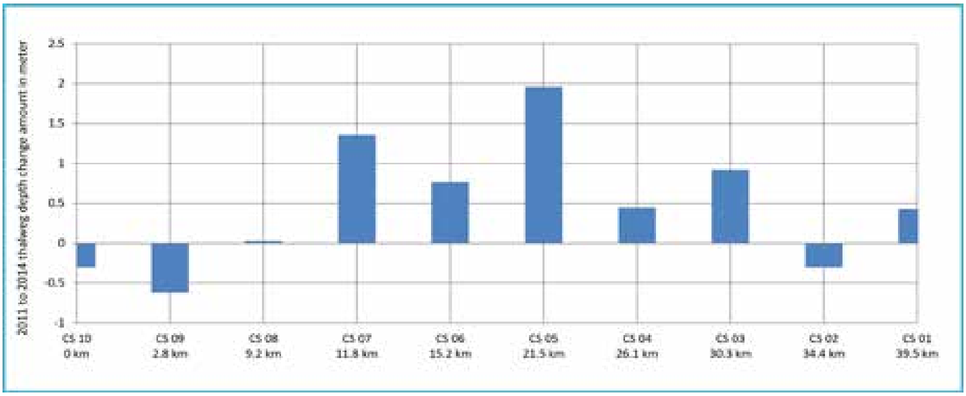

Fig. 12. Amount of thalweg depth change from 2011 and 2014 at different sections.

Channel morphology

Channel pattern is the planimetric geometry, or the form of a channel when viewed from above especially through the satellite imagery. Channel planform of an alluvial river response quickly on the changes of slope, discharge, sediment load and tectonics. Planform analysis provides opportunity to quantify the nature and magnitude of the changes so we can better understand the sensitivity, predict the response and select appropriate action. The morphological changes can be best studied by satellite images in a less expensive and quick way, which also has long chronological archive. In this study, the longitudinal planform and the nature of channel dynamics of the Dharla River is studied using multi-temporal satellite images from 1972 to 2019.

Channel planform from satellite imagery

LEOPOLD *et al.* (1964) introduced the conventional classification of straight, meandering, and braided pattern to distinguish between the channel types. Although additional patterns are now recognized (ROSGEN 1994), this original classification are still practiced widely to understand the underlying processes. There are two distinctly different morphological pattern observed in the Bangladesh part of the Dharla River. The upper braided segment has a length of about 20 km and the lower meandering segment has length of about 33 km (Fig. 13, Table 1).

The braided part is mainly characterized by two channels that split and rejoin. Mid-channel sand bars separate these channels. Generally, one wide braid channel conveys the greater portion of the flow than the others. The braided pattern develops when the flood flows begin to lose their sediment-carrying capacity during the recession stage and deposit the sediment within the channel. Channel aggradation results from increased sediment supply due to upstream landuse changes, higher weathering intensity or reduced carrying capacity due to flow reduction. Aggradation of the braided channel will trigger channel widening through bank erosion. Considering the rapid landuse changes of the upstream areas (CHAKRABORTY & DATTA 2013; PROKOP *et al.* 2020), it is expected that the braided part of the Dharla River will expand further in the future.

The lower reach of the Dharla River displays a meandering channel pattern. Channel meandering and in turn the likelihood of oxbow formation, is controlled by valley gradient. Generally higher channel sinuosities are associated with lower landform gradients (SCHUMM 1979). In this lower reach, there is a substantial decrease in velocity due to decrease in channel gradient and subsequent widening of the channel. Two distinct large meander bends are observed at Holokhana union around the cross-section line 6 and another at Mogalbaccha union around cross-section line 2 (Fig. 2). Sinuosity value indicates that the upstream part is remarkably straight with close to unity sinuosity value, whereas the downstream part is quite sinuous (Table 1).

Table 1. Different river reaches and corresponding sinuosities.

Reach	Location	Channel length (CL)	Valley length (VL)	Sinuosity
Segment 1	From entry to Holokhana Upazila	20	19.4	1.03
Segment 2	From Holokhana Upazila to confluence with the Jamuna River	33.4	20.3	1.64
Total reach	Entire length in Bangladesh	54	40.2	1.34

Meandering channel pattern of the Dharla River is restricted to the lower part of the river close to the confluence with the Jamuna River. Two broad, nearly symmetric meanders are identified. The upstream meander has cutbank towards northeast and the downstream meander is directed towards southwest. The two meanders are separated by a 7.2 km long relatively stable almost straight reach. The amplitude of both meanders are around 3.5 km and actively expanding their cutbanks (Fig. 13). As the necks are separated widely there is no chance of cutoff in the recent future, consequently further erosion are expected around these areas.

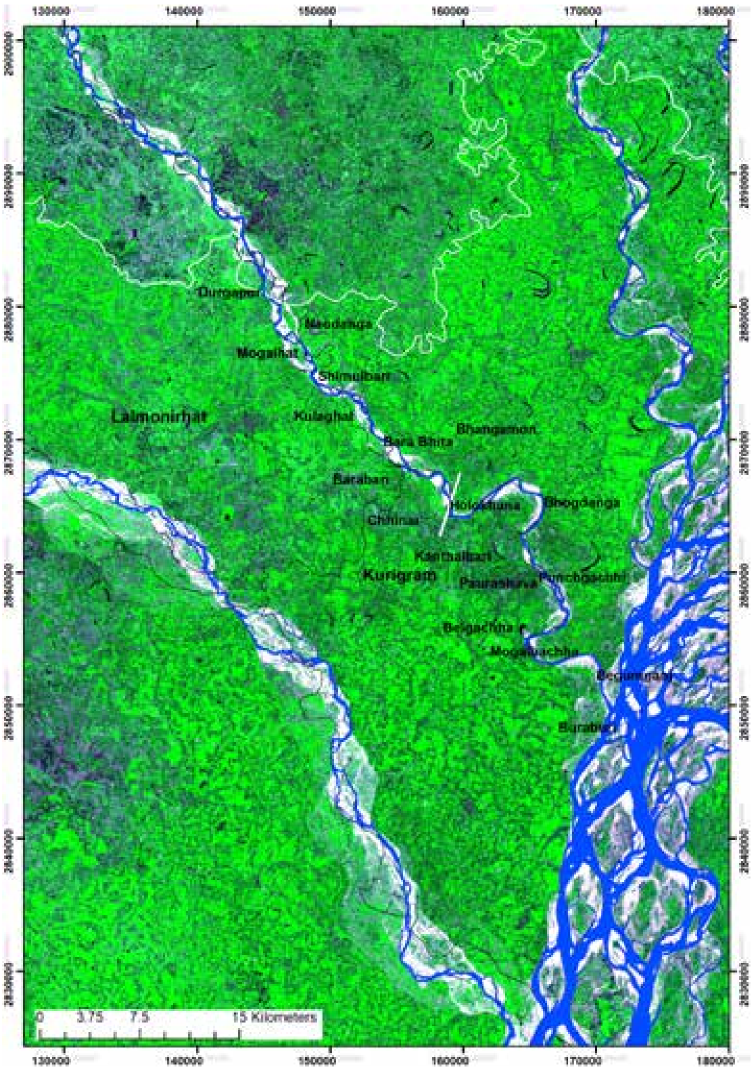

Fig. 13. The two distinct planform reaches of the Dharla River.

Past channel dynamics

Satellite images show number of oxbow lakes, dried channel and filled up paleo-channel on the left and right floodplain of the Dharla River (Fig. 14). The remnants of plaeochannel can be traced far upstream however the intensity greatly increases towards the downstream. Specially, the meandering reach near the confluence show many signatures of past channel migration. These signatures of dynamic channel migration indicate that the tributaries of the river as well as the main channel response quickly to the climatic and terrain parameter and still has not reached in the equilibrium stage.

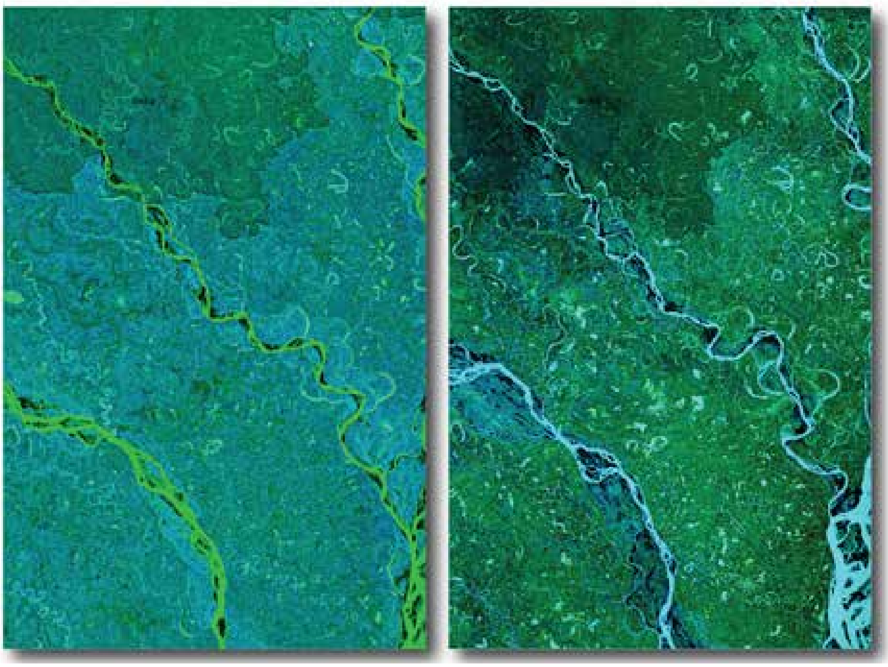

Fig. 14. Paleochannel and meander scars serve as a proxy of channel dynamics on the floodplain. The left Landsat image was acquired on 23 November 1972 with spatial resolution of 60 m. The scars highlight the signature of pre-1972 channel dynamics. On a higher resolution of 30 m, the right Landsat image was acquired on 15 November 1991. The enhanced resolution provides a better view of channel dynamics. However, present cultivation practices have obliterated many of these scars therefore may not be identified in the recent image.

Decadal scale channel migration and direction of shifting

A clear shift of the entire Dharla River in the Bangladesh part has been identified by comparing the 2019 Sentinel-2 satellite image with the 1972 Landsat MSS image (Fig. 15). The analysis indicates that the overall channel width decreased with time. The overall width reduced about 3 times from about 600 m to 200 m within the past 47 years. In general, the whole Dharla River is migrating on the floodplain except for few stable areas like the entry point of Bangladesh, near Holokhana of Kurigram district and around the Mogalbaccha union.

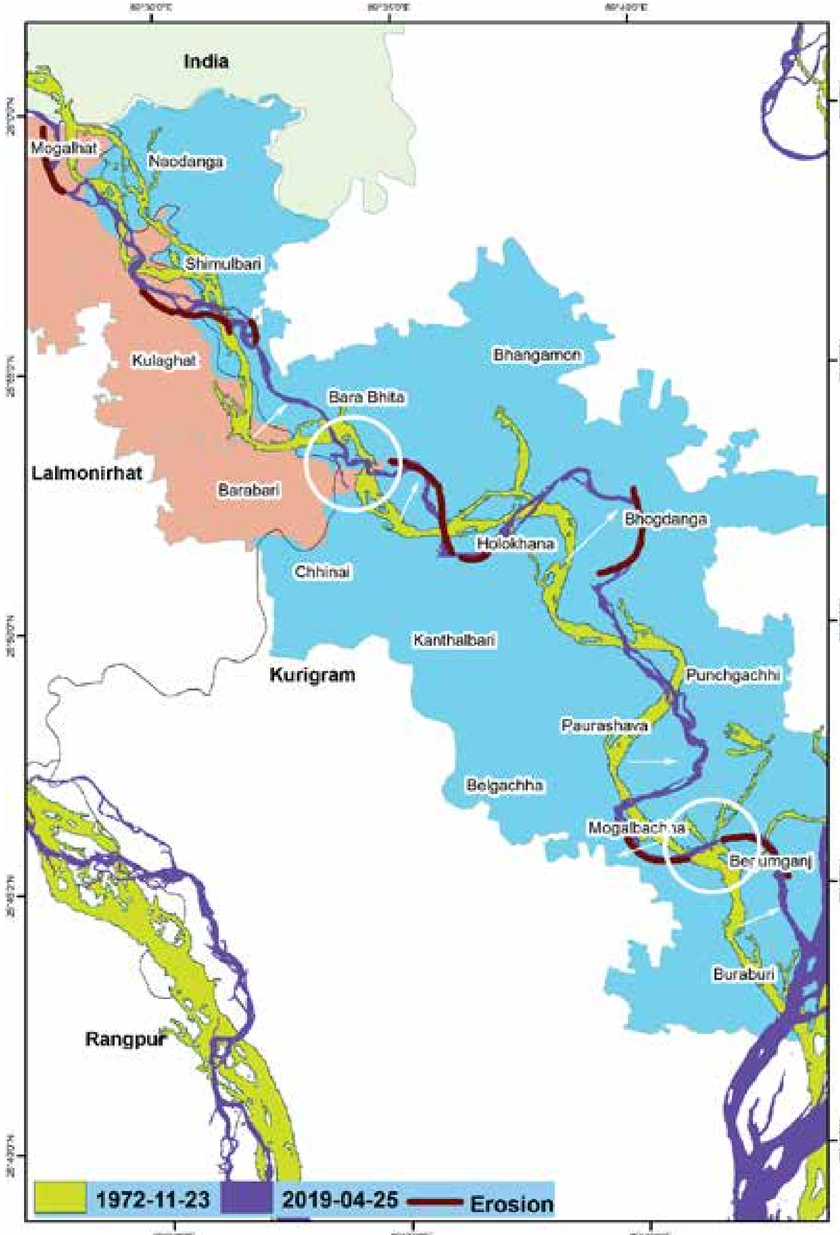

Fig. 15. Channel migration of the Dharla River from 1972 to 2019. The stable locations are shown in circles. The lateral movement directions are shown by arrows. Erosion prone areas are shown by darker lines.

At the upper reach around Mogalhat, the river has migrated westward about 2 km. The river was relatively stable at Shimulbari, from that point the channel migrates eastward. Another stable location was identified at Bara Bhitta union. From this point, it again show eastward migration trend. One of the factors that control the degree of lateral shift of stream is the bank resistance (HICKIN & NANSON 1984) which can be expressed by its silt-clay content (FERGUSON 1987). Riverbanks contain significant amounts of clay possess some degree of resistance and being the most stable (ROBERT 2003). Therefore, the lithology of the stable locations required further investigations to understand the controlling factor.

At the lower reaches in the Bhogdanga union of Kurigram district, the meander migrated eastward about 3 km in the past 45 years with erosion rate of about 66 m/year. Considering the meander dynamics the unions of Holokhana, Bhogdanga, Mogalbaccha, Begumganj and Buraburi seems most vulnerable areas to riverbank erosion.

Confluence characteristics

River confluences are sites of complex hydraulic interactions of different types of flow. The flow convergence results turbulence and vortex formation where scour can develop. Scour has significant impact on designing and construction of bridge and transmission line. In Bangladesh, many important river ports and terminal are located on the river confluence namely at Aricha, Daulatdia, Chandpur and often suffers profound instability. However, the planform morphodynamics of river confluences have received little attention in the country. Recently, a century scale project called Delta Plan 2100 has initiated for the sustainable development of this deltaic country. Although there are about hundreds of river confluence in the country, confluence study is completely unexplored in this plan. However, academic interest about river confluence is gradually increasing as evidenced by SIMON *et al.* (2018), SMITH *et al.* (2018) and GAZI *et al.* (2020). Being the right bank tributary of the Jamuna river, the confluence characteristics of the Dharla River deserve investigation mainly to observe the nature of movement of confluence points over space and time and to examine the factors behind these movements.

Confluence migration

The confluence of the Dharla River with the upper Jamuna River occurs at Begumganj union, Ulipur upazila, of Kurigram district. Series of satellite images from 1972 and 2017 have been employed to identify confluence point dynamics. The satellite image indicates that the confluence location is very dynamic and moved northward for about 4 km in the past 45 years. The zone of movement covers about 15 sq. km. From this pattern, it is predicted that the gradual shifting of the confluence point will induce further erosion at the northern part of the confluence (Fig. 16). SIMON *et al.* (2018) emphasized that the gradual westward migration of the main thalweg of the Jamuna River is the key factor for the longitudinal and transverse migration of confluence location. However, by analyzing the river morphology from the time series satellite image, it seems that backwater effect could be the key factor for the confluence dynamics of the Dharla River.

Fig. 16. Movement of the Dharla-Jamuna River confluence locations from 1984-2017. The confluence point of the respective year is shown by the circles.

Backwater effect

Backwater situation occurs when the flow of a low discharge tributary is blocked, pushed inside by a higher flow mainstream. Due to the backwater effect, the water level rises backward and induce pressure on the riverbank. Backwater effect induces bank erosion. At the confluence of the Dharla and the Jamuna River, backwater effect is very pronounced in the monsoon months. The intensity of backwater effect as well as confluence location is highly influenced by the presence of sandbar around the confluence zone (Fig. 17). Satellite image indicates that when there are no sandbar around the confluence, the adjacent area do not show any significant erosion. Presence of sandbars at the confluence disrupts the mixing and create vortex, which induce adjacent bank erosion. Presence of sandbar also reduced the confluence width and pushback the confluence point towards the tributary.

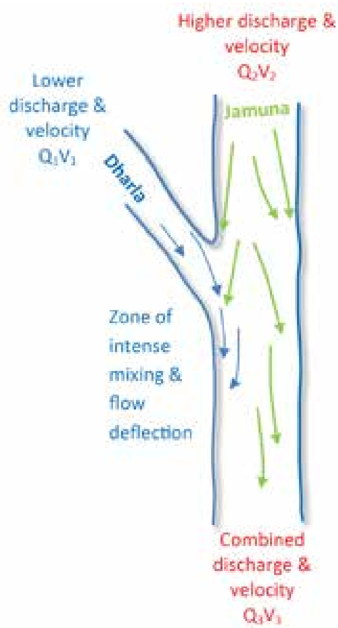

Fig. 17. Presence of sand bar near the confluence increases the backwater effect and induce adjacent and upstream bank erosion.

Implication on the landuse

The morphological behavior of the Dharla River has profound impact on the adjacent riparian terrain. The earlier analysis indicates that the upper part of the river is braided and the lower part shows meandering pattern (Fig. 13). The magnitude of bank erosion and channel migration is also different in these two reaches, therefore requires different landuse management practices. As the meandering river erode on the cutback and deposit on the opposite bank, the area adjacent to meander cutbank must adopt a buffer or setback distance for the constructions of any permanent structure especially educational institutions and hospitals. Three very active meanders are identified at Holokhana, Mogalbacha and Begumganj union. Presently, the meander neck is quite wide therefore, it is predicted that in future the erosion will continue due to the advancement of the cutbank. Instead of bank protection in these sections, dredging at the opposite bank point-bar to create a chute channel could decrease the erosion magnitude in these areas.

In the braided section, where the erosion pattern is hard to predict due to the thalweg movement, landuse planning should be focused in such a way which will prohibits the supply of sediment from the floodplain area. Therefore, agricultural landuse should be restricted in this bank adjacent region. Moreover, agricultural activities close to riverbank quickly increase the pore water pressure during the monsoon season which triggers further bank erosion. Cross-section studies found a long aggrading area covering the section of 7, 6 & 5 of Holokhana union. Due to riverbed aggradation, the bank erosion will increase in the areas therefore priority dredging is recommended in these areas to reduce the hazard.

Conclusions

In a riverine country like Bangladesh, rivers are intricately related with the society, environment and people's livelihood. However a comprehensive study regarding the topography, morphology, bathymetry and flow characteristics of the transboundary Dharla River has not carried before. This study intends to fill the knowledge gap using decadal satellite imagery, bottom profile data, river discharge data to understand the hydrological and morphological characteristics of the transboundary Dharla River. Such understanding could be the baseline for overall effective management of the river, prioritizing dredging site and for the sustainable riparian landuse planning. The main conclusions of the study are as followings:

- The morphology of the Dharla River is influenced by complex interplay of relief, climate and tectonics of the catehment.
- Satellite image based morphological study indicates that in the Bangladesh part, the Dharla River shows two distinct planform patterns. The upper reach is braided and the lower reach has meandering planform.
- The overall width of the Dharla River decreased about three times from 600 m to 200 m in the past 45 years.
- The river is now migrating its channel mostly in the north-eastward direction. However few reaches, especially at the upper reach is migrating towards westward direction, there are at least two stable locations are identified which probably has more clay content in the adjacent riverbanks.
- The bottom profile generally shows aggradation of the riverbed. Highest aggradation is found at cross-section location 5, immediate dredging is

required in this location.

- The discharge of the Dharla River show marked seasonal as well as yearly variations. The average discharge of the upstream Shimulbari is 462 m^3/s and for Kurigram station, it is 628 m^3/s.
- By analyzing the water level data, new floodwater danger level for the upstream Shimulbari area can be fixed at 30.5 m.
- The confluence location of the Dharla River with the Jamuna River is not stable; currently it is migrating in a northward direction.
- The confluence location is influenced by backwater effect especially during the monsoon months.
- The presence braid bars at the confluence increase the backwater effect.
- For the erosion prone area like the Holokhana union, riparian infrastructure construction should be discouraged and a setback distance should be introduced for the sustainable landuse management of the area.

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মোঃ মাহফুজুল হক ও সালেহ শাকিল

সারসংক্ষেপ

ধরলা একটি আন্তঃ-দেশীয় নদী। উৎসপ্রান্তে এটি জলঢাকা নদী নামে পরিচিত। বাংলাদেশে ধরলা নদী আকস্মিক বন্যা এবং নদীভাঙ্গন বিপর্যয়ের জন্য বিশেষ পরিচিত। প্রতিবছর এসব বিপর্যয় নদীতীরস্থ ভূমি এবং অবকাঠামোকে ভীষণভাবে ক্ষতিগ্রস্থ করে। এ গবেষণাটি নদীতীরস্থ অঞ্চলের স্থানিক বিপর্যয়ের মাত্রা বুঝতে এবং তা প্রতিরোধে করণীয় ঠিক করতে সহয়তা করবে। নদীটি ভূটানের উৎসমূখে প্রায় ৩১০ মিটার উচ্চতায় উৎপত্তি হয়ে ভারতে ২৯০ মিটার উচ্চতায় প্রবেশ করে প্রবাহিত হবার পর বাংলাদেশে ৩৪ মিটার উচ্চতায় প্রবেশ করে। এ নদীটি বাংলাদেশের অভ্যন্তরে প্রায় ৫৫ কিলোমিটার প্রবাহিত হয়ে ২৪ মিটার উচ্চতায় যমুনা নদীর ডান তীরে (পশ্চিম প্রান্তে) মিলিত হয়। নদীউৎসমূখে বার্ষিক বৃষ্টিপাতের পরিমান প্রায় ৪৩৬৫ মিলিমিটার এবং বাংলাদেশে নদীপার্শ্ববতী এলাকায় প্রায় ৩৫৫৭ মিলিমিটার। উৎসমূখে প্রধানত অপ্রবেশ্য, উচ্চ ঢালের, রূপান্তরিত শিলার উপস্থিতির কারনে বৃষ্টিপাতের কমই ভূগর্ভে প্রবেশ করে, অধিকাংশই ভূপরিভাগের প্রবাহে পরিনত হয়ে দ্রুত ভাটিতে প্রবাহিত হয়। বাংলাদেশে ধরলা নদীর প্রবাহ উজানে তালুক-শিমুলবারি এবং ভাটিতে কুড়িগ্রাম এ পরিমাপ করা হয়। তালুক-শিমুলবারিতে গড় প্রবাহ প্রায় ৪৬২ কিউমেক এবং ৩০ কিলোমিটার ভাটিতে কুড়িগ্রামে এটি প্রায় ২৮ শতাংশ বৃদ্ধি পেয়ে প্রায় ৬২৮ কিউমেক পরিণত হয়। জুন হতে অক্টেবর এই সাত মাসে নদীপ্রবাহের প্রায় ৮৭ ভাগ প্রবাহিত হয়। বার্ষিক নদীপ্রবাহের গ্রাফ হতে বোঝা যায় যে ধরলা একটি আকস্মিক বন্যাপ্রবণ নদী। নদীজলপৃষ্ঠের উচ্চতা বিশ্লেষণে দেখা যায় ২০১৬ সালের জুলাই মাসে নদীজলপৃষ্ঠ ২৭.৫৬ মিটার উচ্চতায় উপনীত হয় যা এই এলাকার বিপদতল ২৬.৫ মিটারকে অতিক্রম করে যায়। সর্বনিম্ন নদীজলপৃষ্ঠ মার্চ মাসে ২২.৫ মিটার উচ্চতায় পাওয়া যায়। তালুক-শিমুলবারি হতে ৩০ কিলোমিটার দূরত্ব অতিক্রম করে কুড়িগ্রামে নদীজলপৃষ্ঠের উচ্চতা প্রায় ৪.৭ মিটার হ্রাস পায়। ১০টি ক্রস-সেকশনের সাহায্যে সময়ের সাথে নদীর তলদেশের পরিবর্তনকে বিশ্লেষণ করা হয়েছে। এই বিশ্লেষণে দেখা যায় ২০১১ হতে ২০১৪ সালে ধরলা নদীর গভীরতা অধিকাংশ স্থানই হ্রাস পাচ্ছে। সবচেয়ে বেশি হ্রাস দেখা যায় সেকশন ৭, ৬ ও ৫ অংশে এবং এই অংশগুলো অন্যতম ভাঙ্গনপ্রবণ এলাকা। উপ্রগহচিত্রের মাধ্যমে নদী গঠনের পরিবর্তন বিশ্লেষণে দেখা যায় ধরলা নদীর বাংলাদেশ অংশে, নদীটি প্রথমে বেনীপ্রবাহ (ব্রেইডেড) ও পরবতীতে বাঁকবহুল (মিআন্ডারিং) গঠন প্রদর্শন করে। এই গঠনের পরিবর্তন মূলত ভূখন্ডের ঢালের সাথে সম্পকযুক্ত। ধরলার নিম্ন অংশটি অত্যন্ত পরিবর্তনশীল, ফলশ্রুতিতে এর প্লাবনভূমিতে অনেক পুরোনো প্রবাহচিহ্ন, অশ্বখুরাকৃতি জলাধার দেখা যায়। ১৯৭২ এবং ২০১৯ সনের উপ্রগহচিত্র তুলনা করে দেখা যায় ধরলার গড় প্রশস্ততা ৬০০ মিটার হতে ২০০ মিটারে হ্রাস পেয়েছে। অধিকাংশ স্থানেই নদীটি পূর্বদিকে সরে যাচ্ছে। কিন্তু কিছু সুস্থির স্থানও চিহ্নিত করা যায় যেখানে প্রবাহটি ৪৭ বছরে স্থান পরিবর্তন করে নাই। যমুনা নদীর সঙ্গে ধরলা নদীর মিলন স্থানটি খুবই পরিবর্তনশীল এবং বর্তমান মিলনস্থানটি ৪ কিলোমিটার উত্তরে সরে এসেছে। এর একটি মূল কারন অধিক প্রবাহের যমুনা নদীর পার্শ্বচাপ (ব্যাকওয়াটার প্রভাব)। মিলনস্থানে চরের উপস্থিতি এই পার্শ্বচাপকে প্রভাবিত করে এবং পার্শ্ববতী স্থানে নদীভাঙ্গনকে বৃদ্ধি করে।