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Results of hydrological studies and channel analysis of the Ganges (Padma) River at the construction site of the "Rooppur" NPP

Abstract: This work presents the results of research on channel processes in the Padma River (Republic of Bangladesh) at the construction site of the "Ruppur" Nuclear Power Plant (NPP). The fluvial characteristics of the Padma River were presented, including: the water outflow regime, characteristics of anthropogenic impact on the river outflow and assessment of the present state of the channel and floodplain. The research was conducted based on field expeditions, during which data on morphology, dynamics, hydrological and hydraulic conditions for the formation of the floodplain-channel complex were collected. Moreover, the water discharges and suspended sediments, as well as the longitudinal profiles of the water level and the channel morphology were measured. The presented research has shown that comprehensive and planned regulation of selected sections of rivers could lead to the channel stabilization and support the rational use of water resources for different purposes, e.g. power plants, municipal purposes, etc. Moreover, detailed research on channel deformation in selected areas indicated the major role of natural factors (geological structure, the type of sediments delivered to the river, vegetation cover, etc.) in the past and present fluvial processes.

Keywords: Nuclear Power Plant "Ruppur", Ganges (Padma) River, channel processes, bottom and suspended sediment, anthropogenic impact, channel deformations

1. Introduction

In April 2015, a team of specialists from the N. I. Makkaveev Research Laboratory for Soils Erosion and Riverbed Evolution completed complex hydrological and riverine studies on a 50-km stretch of the Ganges River in the People's Republic of Bangladesh. The research was related to the beginning of the "Rooppur" NPP project, implemented with the participation of the "Rosatom" Russian corporation. The main NPP facilities are located on the left bank of the main channel of the Ganges River (locally called the Padma River), 80 km upstream of its confluence with the Brahmaputra. At this point, the river is crossed by the Lalon-Shah Bridge, built in 2001 and connecting the districts of Pabna and Kushtia. The Hardinge Bridge railway runs 300 m upstream of the Lalon-Shah Bridge.

The natural conditions of the study area are determined by its location in the largest delta system in the world, which is formed by the Ganges, the Brahmaputra and the Meghna rivers flowing into the Bay of Bengal (Fig. 1). The drainage system of the Ganges River in the delta area has a complex structure and a hydrological behaviour, determined by the mutual influence of the river and the sea. The average annual water discharge of the Ganges at the head of the delta (Farakka town) is 12,300 $m^3 \cdot s^{-1}$ (388 km^3/year). This value corresponds to the specific runoff of 13.6 $l \cdot s^{-1} \cdot km^{-2}$; the runoff depth is 429 mm; the runoff coefficient is 0.36. The Ganges, the Brahmaputra and the Meghna rivers bring together on average 1,230 km^3 of water per year to the delta. These three rivers account for 31.5, 55.4 and 13.1% of the total runoff, respectively. Given the lateral inflow to the delta, their total runoff into the Bay of Bengal is 1,460 km^3/year (Reki i ozera mira, 2012).

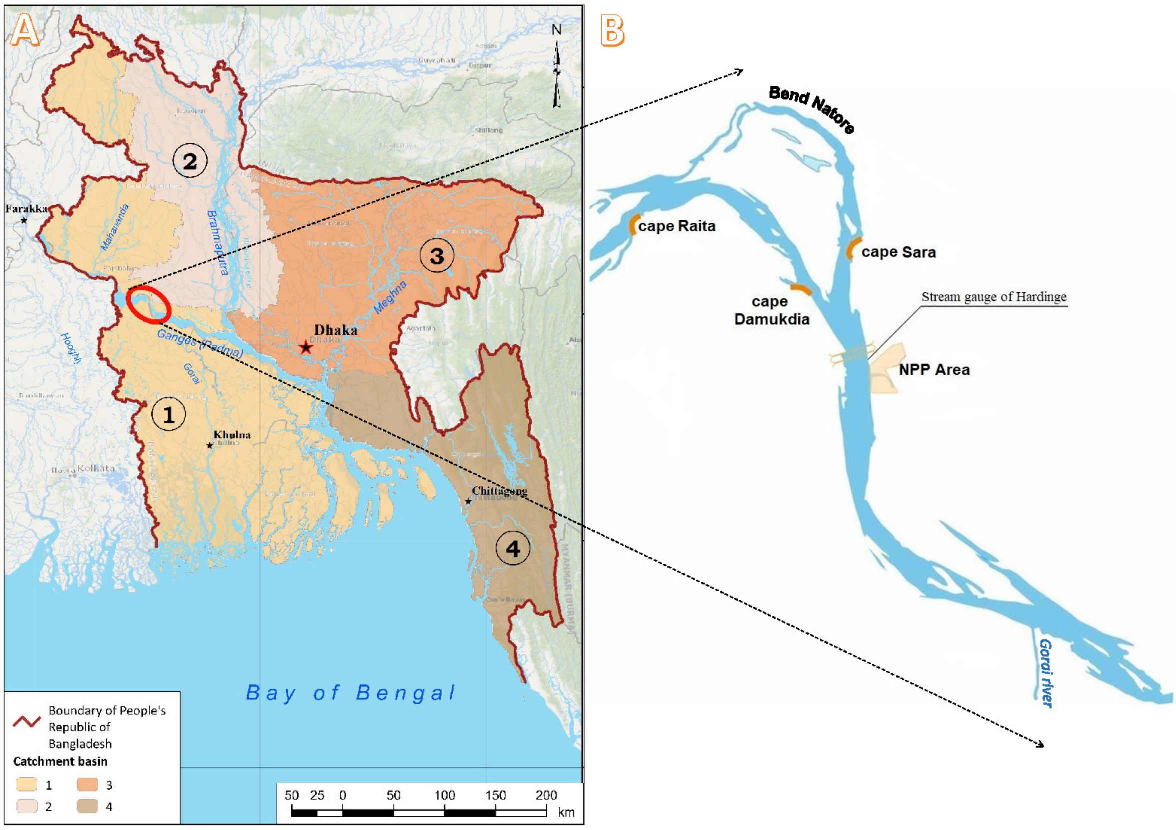

Figure 1. The scheme of river basins in the territory of the People's Republic of Bangladesh (A) and the study area (B): 1 – the Ganges (Padma); 2 – the Brahmaputra (Jamuna); 3 – the Meghna; 4 – the rivers of the east coast (Karnaphuli and etc.)

The main channel in the delta of the Ganges – the Padma is represented by a braided and sinuous channel, 1.5-3.0 km wide with a lot of sandbars. A large number of distributaries branch off from the main channel. At present, most of them have silted sources and are inadequately recharged. The distributaries split and flow separately, then they connect, and then they split again. At the same time, they have different names in different sections. The largest distributaries of this system are the Bhagirathi-Hooghly, the Bhairab and the Gorai. The Gorai, with its sources located 17 km below the "Rooppur" NPP construction site, is the largest one, have the largest discharges and plays an important role in watering the western part of the Republic of Bangladesh.

The seasonal changes in the Ganges water runoff in the lower reaches are reflected in two seasons – wet and dry. The wet season is caused by the south-western monsoon and represents a summer flood period that lasts 4 months on the Ganges (from June to October). This season accounts for over 80% of the annual outflow. The most wet month is August. The dry season lasts from November to June. The minimum discharges in the Ganges delta are less than 1,000 $m^3 \cdot s^{-1}$ the maximum in the cross section of the NPP construction site ranges from 70,000 to 75,000 $m^3 \cdot s^{-1}$. The maximum discharges of the Ganges and the Brahmaputra do not usually coincide in time, but when they do, catastrophic floods occur in the delta. The maximum discharges occurred simultaneously in 1962 and were equal to 60,600 $m^3 \cdot s^{-1}$ on the Ganges and 68,200 $m^3 \cdot s^{-1}$ on the Brahmaputra; the total discharges were about 130,000 $m^3 \cdot s^{-1}$ (Reki i ozera mira, 2012). Three catastrophic floods were recorded over the past 30 years – in 1987, 1988 and 1998, when about 37%, 63% and 72% (respectively) of the territory of the People's Republic of Bangladesh was flooded (Mirza et al., 2001).

2. Sediment grain-size composition, methods and results of field studies

Field studies were carried out during the period from 13 April to 28 April 2015. The obtained results provided information on morphological, hydraulic and dynamic characteristics of the Ganges river channel (its main distributary – the Padma) under conditions of the low water phase of the water regime. During the floodplain survey, the river bank mapping was carried out according to the degree of manifestation of accumulative and erosion processes, the most common types of floodplain vegetation and the human-induced transformation of floodplain landscapes were analysed, the features affecting the water flow in the channel and floodplain were identified.

The scope of engineering and geodetic work included: horizontal and vertical measurements of the terrain surface, association with the state geodetic network, levelling (measurements) of longitudinal and transverse morphological cross sections, and measurements of the water surface slope. In the Republic of Bangladesh, a rectangular BUTM-2010 coordinate system, created by the Bangladesh Inspectorate (SOB) as a derivative of the UTM projection, is used in land surveying and mapping. As an altitude geodetic base, the MSL (Mean Sea Level) altitude measuring system is used, developed by the Tidal Observatory in Chittagong, where continuous data collection has been carried out since 1993.

A digital elevation model (DEM) was prepared based on geodesic measurements and used for correction of existing topographic maps. Moreover, altitude measurements along 68 morphological cross sections, with a total length of about 200 km were carried out, 740 elevation marks in the floodplain, dams, road embankments, and eroded banks were measured.

Measurements of the water surface were carried out on 22 April 2015 at a relatively stable water level. The average slope of the water surface within the whole area was 0.03‰, which is typical for the areas near the mouth of large rivers in the low-flow period. Along the river, slopes generally increased in the narrowing channels (up to 0.06‰) and decreased at their extensions (up to 0.015‰). The hydrographic survey consisted of continuous measurements of the channel depths. The result was a 1:10,000 map of channel relief. Hydrometric measurements of discharges were carried out on 8 cross sections. As a reference, the cross section near the existing river gauge (between the Hardinge Bridge and Lalon Shah Bridge passages) was made.

Sampling of bottom sediments was carried out to analyse their grain-size composition and their spatial distribution. A total of 254 samples of bottom sediments were collected. They were analysed in laboratory conditions; the type of sediment was determined according to the ratio of fractions and the mean diameter (Tab. 1).

Table 1. Particle-size distribution of bottom sediments (% of the riverbed area with low water level)

Sediment type	Sub-area			Total area
	the main channel from Cape Raita to Cape Damukdia	the old channel (Natore bend) and the bridge's intersection	the lower part of the area	
Silty sand and silts	19%	86%	31%	39%
Very fine-grained sand	6%	8%	12%	10%
Very fine-grained and fine-grained sand	10%	5%	11%	9%
Fine-grained sand	5%	---	22%	14%
Fine-medium grained sand	44%	1%	24%	24%
Medium-grained sand	16%	---	---	4%
Average diameter of deposits, mm	**0.21**	**0.08**	**0.15**	**0.16**

In order to assess the runoff of suspended sediments, 38 water samples were collected along with other hydrological works at 7 hydrometric stations on 22-23 April. This allowed a reliable assessment of the total runoff of suspended sediments and its variation in the area. The obtained turbidity values were small, which is explained by the low-flow period and small slopes of the water surface. Minimum values of the concentration of suspended particles in water within the area (5-7 g·m^{-3}) are characteristic of the old channel (the Natore bend), representing an old branch in the conditions of the low-flow period, connecting near Cape Sara with the main channel. There is almost no current in the old channel at a depth of 30-40 m and the suspended particles gradually settle to the bottom, which results in siltation. The concentration of suspended sediments in the main channel is 3-10 times higher and reaches 30–50 g·m^{-3}. The rates of suspended sediments *R* (Tab. 2) were calculated based on the comparisons of the measured values of turbidity and discharges. The results of the estimates of turbidity and runoff of suspended sediments show that, despite the low-flow conditions, the channel is still being transformed. It is obvious that the extent of deformations occurring in the low-flow period is not comparable to the channel changes in the flood period, when the water turbidity increases by 2 orders (up to 2,100 g·m^{-3} according to the observations of OES CJSC). The ripple marks move over the surface of macroforms of the riverbed relief, and the bank erosion rates reach hundreds of meters.

To determine the morphometric and dynamic parameters of dune forms of the channel geometry, which influence the sediment load runoff, the motion of mesoforms was observed by combining the observations with longitudinal echograms of the bottom obtained for different dates. Observations were carried out on a key section in the main channel with clearly expressed dune relief, 8-9 km upstream of the Hardinge Bridge. To this end, a series of echo-sounding surveys was carried out on a longitudinal section. The measurements were carried out on 26 April at 11.00 and on 28 April also at 1 1.00. Thus, the interval between the observations was 48 h. The satellite positioning system in the RTK-mode was used to correct the measurements, hence the planned deviations along the whole section did not exceed 1 m. The bottom sediments in the key section are formed by fine- and medium-grained sands with an average grain diameter of 0.2-0.3 mm. The average flow rate in the measured cross section was 0.6 m·s^{-1}. According to the measurement results, the combined longitudinal profiles of the bottom were constructed (Fig. 2), based on which morphometric parameters of dunes and their dynamic characteristics were determined.

The measurements show that the height of moving dunes h_r for the low-flow period changes from 0.2 to 2.0 m, length l – from 8 m to 48 m; mean values: h_r – 0.7 m; l – 21 m. The dune movement rates vary within the range of 0.4–4.2 m/day, on average 2.5 m/day.

To calculate the runoff of sediment load, a method developed at the Department of

Table 2. Measured rates R and daily run-off of suspended sediments W_R at the hydrometric section at the construction site of the "Rooppur" NPP

Date of water sampling	Cross section	Water level at the reference station, MSL [cm]	Discharge *Q* [m^3·s^{-1}]	Mean turbidity *s* [g·m^{-3}]	Sediment rate *R* kg·s^{-1}]	Sediment load W_R, [t·day^{-1}]
22.04.2015	Upper limit of the section	477	1,400	28.9	40.5	3,499
22.04.2015	Straight branch of the Natore bend	477	1,264	23.5	29.7	2,566
22.04.2015	NPP site cross section	477	1,381	26.2	36.2	3,128
23.04.2015	1 km downstream the Hardinge Bridge	480	1,303	21.8	28.4	2,454
23.04.2015	Lower limit of the section	480	1,299	34.0	44.1	3,810

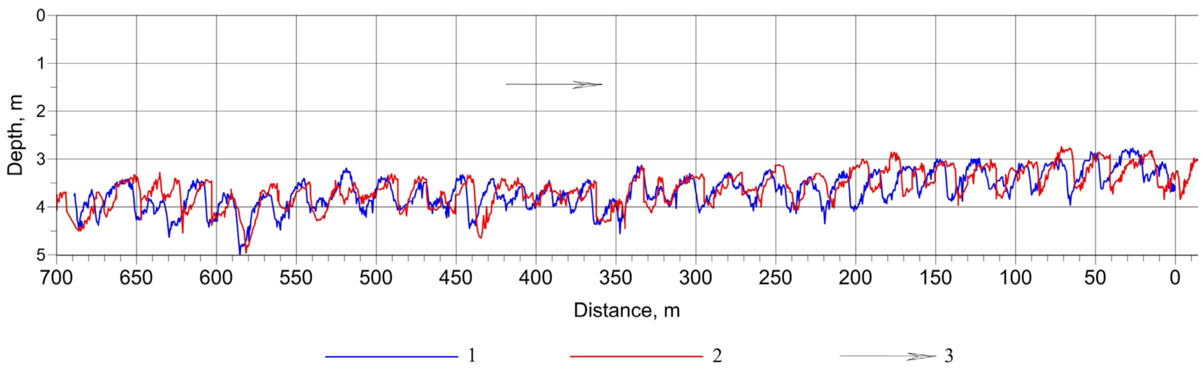

Figure 2. Combined longitudinal profiles of the channel bottom in the key section: 1 – 26.04.2015 (11 a.m.); 2 – 28.04.2015 (11 a.m.); 3 – the flow direction

Geography of M.V. Lomonosov Moscow State University was used, taking into account bedload and suspended load, as well as the method of the State Hydrological Institute (Russia, St. Petersburg) for the bedload. Under such assumptions, the bedload is considered morphogenic. Moreover, part of the suspended sediment whose size is similar to that of alluvial deposits has also channel-forming capacity. In the investigated section of the Padma River, the diameter of channel-forming sediment (CFS) particles exceeds 0.05 mm.

Calculation of the sediment load using two different methods gave relatively similar results (Tab. 3). Their average value should be used as a final value, i.e. 20.9 million t/year. With the ratio of W_G/W_{BFS} = 0.62, the total CFS runoff is 33.6 million t/year.

Table 3. Results of calculations of bed-forming sediment runoff

Method	Bottom sediment load, m t/year	Suspended sediment load CFS, m t/year	Total sediment load CFS, m t/year
MSU	18.7	11.5	30.2
SHI	23.0	-	-

3. Morphology and dynamics of the Ganges (Padma) river channel in the study area

There are almost no data available in the scientific literature on the issues related to the morphology and dynamics of the Ganges channel in the People's Republic of Bangladesh. The interest in the channel and hydrological processes in the lower reaches of the Ganges was only expressed in the last 10-15 years in connection with the commencement of the "Rooppur" NPP construction. In 2000-2001, the Bangladesh Atomic Energy Commission (BAES), with the assistance of the Institute of Water Modelling (SWMC, later – IWM), prepared a technical report on the safety validation of the NPP site location (Pavodki, morfologicheskie..., 2001). In July 2001, the Institute of Water Modelling (IWM) produced a "Roopppur" NPP report: "Hydrological, hydraulic and morphological studies" (Otchet po matematicheskomu..., 2001). In 2011, a report was published on the results of mathematical modelling (the contract between BAEC and IWM) of hydraulic processes at the NPP construction site cross section (Mathematical Modelling ..., 2011).

The modern flood plain of the Ganges River (Padma) represents a complex hierarchy of depositional forms and floodplain levels of varying height. Their genesis and location are related to geological cycles of uplift and subsidence of the land, changes in the water level in the Bay of Bengal, long-term climate change and recently also intensive use of floodplains by man and anthropogenic transformations of the hydrological regime of the Ganges river basin. The significant thickness of alluvial and deltaic deposits, as well as predominantly sandy and sandy loamy structure of the channel banks determine the active transformation of the channel. According to some estimates (Rahman, 2010), the average rate of the Padma riverbank retrogression in the 1980s and the 1990s upstream and downstream from the confluence of the Brahmaputra amounted to 20-40 m/year and 50-120 m/year, respectively. At the same time, the maximum values in some reaches of the river exceeded 600 m/year.

No less intense channel deformations associated with the erosion of banks during the development of channel forms occurred in the historical past. In particular, rectification of a large bend (near the "Rooppur" NPP site), traces of which are currently clearly identified in satellite images (Fig. 3), took place at the turn of the 18th and 19th centuries. The branching formed during the process of rectification of the bend was functioning during the 19th century, after which the main channel shifted to the right side of the bottom of the valley. The location of the Padma channel together with the main floodplain channels for the period of 1973-2011 confirms the predominantly right-sided displacement of the Padma channel downstream the Hardinge Bridge.

A retrospective analysis of available cartographic materials suggests that before the 20th century, the width of the zone of active channel changes on the Padma River floodplain exceeded the current amplitude of the channel shifts from one side of the valley to the other. At the same time the meandering channel predominated, and the width of the meandering zone reached 20 km. In the present morphology of the Padma channel, branching predominates despite the generally meandering type of channel. The main reason for this transformation of the morphodynamic type of the channel is apparently related to the human factor.

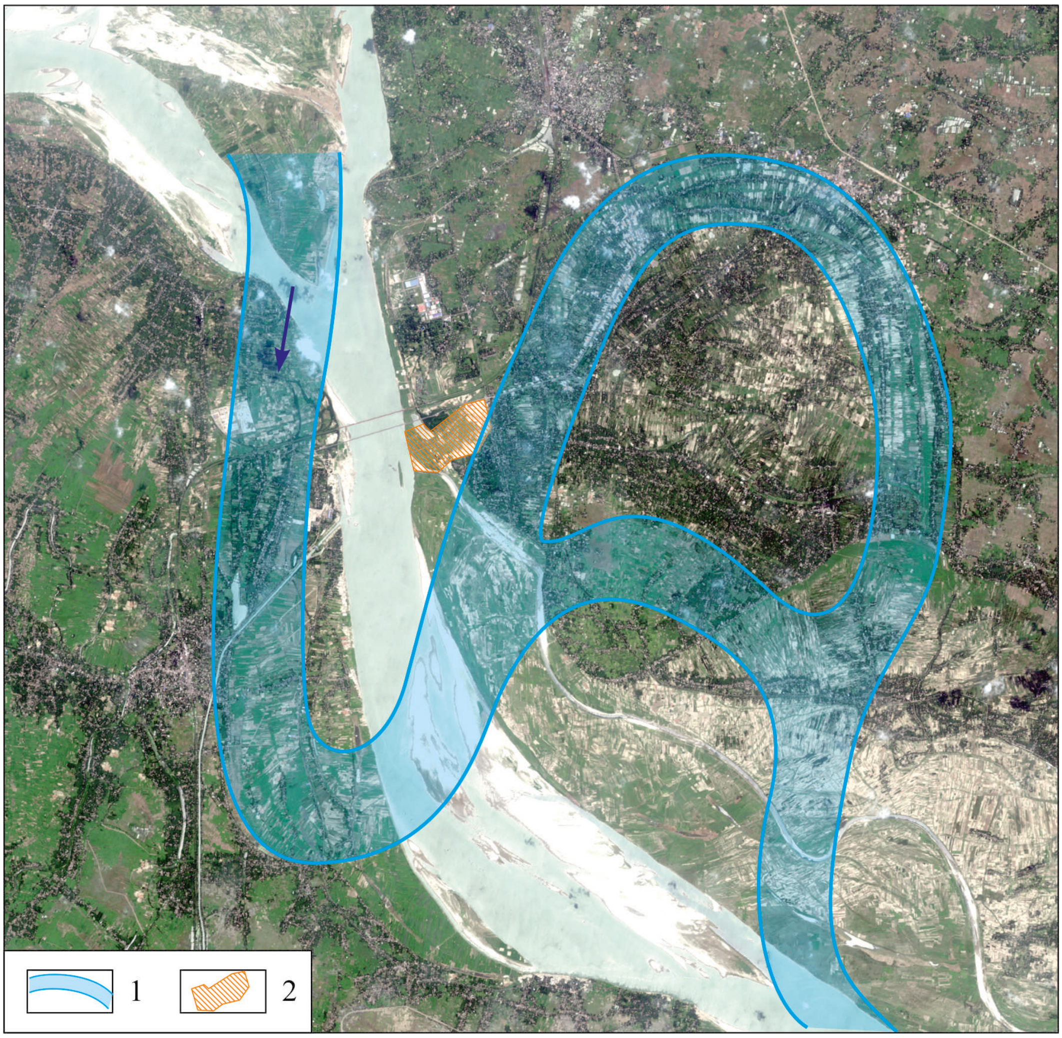

Figure 3. Reconstruction of the Ganges (Padma) channel location at the "Rooppur" NPP construction site: 1 – the channel of the Padma at the end of the 18th century; 2 – NPP construction site.

4. The impact of economic activity and existing hydraulic engineering structures on the channel regime

The key human-induced factor determining the dynamics of the Padma channel upstream and downstream the "Rooppur" NPP site at the present stage is the construction of a system of hydraulic structures stabilizing the channel, ensuring the safety of the Hardinge Bridge built in 1915. Noteworthy is the correct choice of both the location of the cross section of the railroad river crossing and the activities stabilizing the riverbed. According to the report of the Surface Water Modelling Centre (SWMC) (Mathematical Modelling ..., 2011), during the construction of the Hardinge Bridge, the guide banks were built at the same time, which allowed to secure the position of the channel within the bridge's intersection, as well as two reinforced capes: on the right bank – the cape Raita 13 km upstream; on the left – the cape Sara, 4.5 km upstream. In 1931, part of the protective structures near the cape Sara was destroyed due to the development of the left-bank channel, which later transformed into the Natore bend. This led to a violation of the straightness of the flow up to the bridge section and to the displacement of the dynamic axis of the flow to the right bank with the risk of its erosion. To prevent this negative process, the right bank was additionally reinforced with a bank-protecting dam and a new (third) "stabilising" cape, Damukdia. Thus, from the early 1930s, a system of 3 bank capes resistant to erosion is in operation, which provides a straight-line position of the channel when approaching the Hardinge Bridge, despite intensive channel rearrangements upstream and downstream. Therefore, when the question arose about the construction of a new bridge for motor vehicles, it was decided that it would be located 300 m downstream from the existing railway bridge. The choice of the "Rooppur" NPP construction site is also quite justified.

Along with the riverbed stabilising capes Raita, Sara and Damukdia, along the channel of the Padma River, the systems of bank protection structures are widely used. Currently, the largest bank protection works are carried out along the left bank within the Natore bend. After the catastrophic erosion of the bank in this area in the late 20th and the early 21st centuries, when the whole streets of residential houses located along the high terrace were destroyed, local authorities decided to carry out capital protection works. At present, over a three kilometre long embankment is being constructed to cover the entire 15-20 m long bank slope with concrete slabs and sandbags. A number of sections of the bank along the riverbed in the study area are reinforced with a massive rock embankment, which quite successfully performs its functions. The total length of bank protection structures is 12 km. In all cases, the stabilisation of the channel location in selected sections has a significant role in the long-term dynamics of the Padma channel.

The development and maintenance of a system of flood control dams is essential to the existence of the population in the People's Republic of Bangladesh. Under the conditions of an annual high water-level rise during the flood period on main rivers, only flood control dams and the related system of floodgates and canals can prevent flooding of residential areas located near rivers. In the study area, such a hydrotechnical flood control network is developed quite well. A significant part of houses is located below the level of annual floods, i.e. below the marks of flood control dams. The total length of the main dams that limit the water flood of the Padma river during the summer and autumn period (near the NPP construction site) is 116 km. In most cases, car roads (asphalt and dirt roads) were built along bridges connected with dams.

Another type of human interference in the natural riverbed behaviour in the area is the development of channel sediment quarries. First of all, this leads to the transformation of the channel geometry, contributing to the change in the flow rate and the formation of local zones of deep erosion and accumulation. Extraction of sand from the channel of the Padma is carried out during the shallow water phase of the water regime at two sites: downstream the bridge passages and near the headstream of the Gorai. Information on the extraction volume is contradictory and is unlikely to be reliable. The results of the measurements conducted in 2015 allowed an approximate calculation of the extracted sand material at the site downstream the bridge intersections. During the low-flow period of 2014-2015 (December-March), about 1.2 million m3 of sand were removed from the channel (almost the entire volume of extracted sand is used at the "Rooppur" NPP construction site). This has led to a riverbed deepening up to 13.5-17 m in some sections with an average depth along the stream line of 4-5 m. Such a transformation of the channel during the low-flow period results in the development of regressive deep erosion, which can reach the lower bridge girders (the Lalon-Shah motorway bridge). However, during the flood period, the total volume of transported sediment is substantially higher than the volume of sand extraction. All quarries created during the low-flow period are quickly filled with deposits during the flood, restoring the natural relief of the channel and compensating for all possible negative consequences.

Changes in the water regime in the downstream reaches of the Ganges became apparent after the construction of the Farakka barrage in India in 1975, 170 km upstream from the site of the nuclear power plant under construction. The main goal of the dam is the water flow redistribution into the Hugli distributary in the dry season of the year (from November to May) to provide water supply to the city of Calcutta and reduce the siltation of this river channel. The expected use of water in the Hugli during the dry season is 1,133 $m^3 \cdot s^{-1}$ (Abbas and Subramanian, 1984). The construction of the Farakka barrage has led to a decrease in the average annual minimum water flow in the Padma river by 60% (from 1932 to 770 $m^3 \cdot s^{-1}$). As a result, the low water-level flow in the channel, floodplain channels and canals downstream from the barrage decreased by about 50%, the groundwater level dropped, surface water quality deteriorated, delta landscapes salinized (Adel, 2002). According to the data (Mirza, 1997; 1998), the annual minimum water level decreased by 18% or by 1.12 m. In March, the decrease was 17%, in February – 15%, in other months of the dry season – about 12%. The decrease in the average monthly water discharge in the dry season varied from 14 to 54% compared to the period before 1975.

However, the redistribution of the flow into the Hugli channel is not the only reason for the reduction in the outflow of the Ganges (Padma) river. The use of water in the regions of India located upstream of this section, led to a gradual decrease in the water flow (in the downstream reaches of Ganges) in 1850, 1900, 1963, 1980 and 1993 at the ratio of 4.45:3.70:3.51:2.18:1 respectively (Adel, 2002). In the mid-20th century, the average annual discharge at the station near the Hardinge bridge was 12,066 $m^3 \cdot s^{-1}$ more than at the station of Farakka, due to the influx of tributaries, for example, the Mahananda River (left tributary of the Ganges (Padma) downstream the Farakka barrage), where two dams were also built in India (Satter, 1996).

The reduction of low-level discharges with a significant suspended sediment load leads to siltation of the channel, which becomes evident in the form of an increasing area of depositional forms in the channel (sand banks, braid bars) in the shallow water phase of the water regime. During the period from 1973 to 1983, the area of the river water surface in the low-flow period was reduced by 19% (Elahee and Saleheen, 1992). The Gorai distributary almost completely dries in the low-flow period.

After the construction of the Farakka barrage, the regulation of the water flow in the river is carried out based on the agreements between India and Bangladesh. Currently, there is a 30-year agreement, concluded in 1996, but it does not provide any guarantees on the Indian part regarding the lowest water discharge below the Farakka barrage (Gain and Giupponi, 2014).

5. Riverbed evolution upstream and downstream from the "Rooppur" NPP under construction

During the hydrological and morphological analysis, forecasts of the horizontal channel deformations and at the evaluation of possible changes in the channel in a particular section of the riverbed, it is always necessary to take into account the probability of channel deformations, the interconnections of processes upstream and downstream. In this regard, it should be noted that the processes occurring upstream within a wide section (up to 20 km) of the valley bottom, between the village of Jalanga and Cape Raita (the upper edge of the research site), play a particularly important role in channel transformations along the studied section of the Padma. Therefore, the analysis of the dynamics of the Padma channel has been consistently carried out for three areas whose development is interconnected:

– a wide section of the bottom of the valley upstream from the cape Raita;
– from cape Raita to the Hardinge bridge;
– downstream of the Hardinge bridge to the source of the Gorai distributary in the delta.

All three sites underwent significant changes in the period for which high quality cartographic material and satellite images are available (1972-2015). At the first site – upstream the cape Raita – the channel is constantly transformed, having in different periods of time either branched-meandering or straight shape. In the early 1970s, it formed a bend, with several secondary, gradually dying channels. The bend intensively developed and by 1977 it was the only form of the riverbed. The upper and lower arms of the bend were moving down the river at a rate of up to 400 m/year. Gradually, the bend completely moved to the other section (between Raita and Hardinge bridge) and its upper part is located near the high left bank, and is called the Natore bend. Moreover, the cape Raita has a significant impact on the stream.

The development of the channel in the second section in the late 20th and the early 21st centuries is connected with the formation and transformation of the Natore bend. Its transformations are minor on the left bank of the lower part of the bend, up to the cape Sara. By 1993, the development rate of the bend increased almost 1.5 times (from 1.39 to 1.83). At the same time, the upper part (in the planar terms) of the bend reached the left “high” bank of the channel, which became extensively eroded and retreated by 300-350 m in 1988–2014; the highest rate of retreat was recorded in the period from 2005 to 2011, with an average rate of 25 m/year. The configuration of the shape of the Natore bend over the past 20 years has undergone significant changes not only as a result of its natural development, but also due to transformations in the upper river section.

In the early 2000s, the Natore bend reached critical values of its development and gradually lost its function as the main channel. Conditions were created for the formation of a straight arm in the rear part of the right-bank floodplain section with an outlet to cape Damukdia. In 2014, the water flow was distributed relatively evenly between the bend and the straightening arm, and by 2015 (in the low-flow phase of the regime), it completely concentrated in the rectifying arm, and the riverbed in the upper part of the Natore bend was completely covered by sediments. As a result, the main channel of the Padma river, upstream from the Hardinge bridge, was a relatively straight arm, causing the Natore bend to straighten. At present, it begins to form a new bend, the upper part of which is moving intensely to the left, eroding the high (up to 7-8 m above the low water line) bank of the floodplain island. In the period from 2011 to 2017, the development of the rectifying arm led to its expansion and displacement to the left-bank side, with the area of maximum erosion successively moving downstream, which is now located in the downstream section of the arm. The bank erosion in this part amounted to 850 m in 2011-2015, and over 1 km in 2015-2017 (Fig. 4). At the same time, the most intensive riverbed changes were recorded during the peak flood from mid-August to mid-September of 2014. The bank erosion in only one month reached here 280 m, i.e. about 10 m/day. The process of bank erosion continues even in the shallow water phase of the water regime. The rate of the river bank changes was assessed based on the comparison of the satellite image dated 14.05.2015 with the results of the river bank survey from 24.04.2015, which at selected sites amounted to 8–10 m in 20 days (up to 0.5 m/day).

In the current conditions, the lower part of the newly developing bend (straightening arm) rests on the single cape Damukdia stabilising the channel and directing the stream to the left-bank piers of the bridge intersections and the NPP construction site. Only 4–5 years ago, the main water flow passed along the Natore bend, the dynamic axis of the stream at the bend outlet shifted to the right bank, and a stable accumulation zone developed along the left

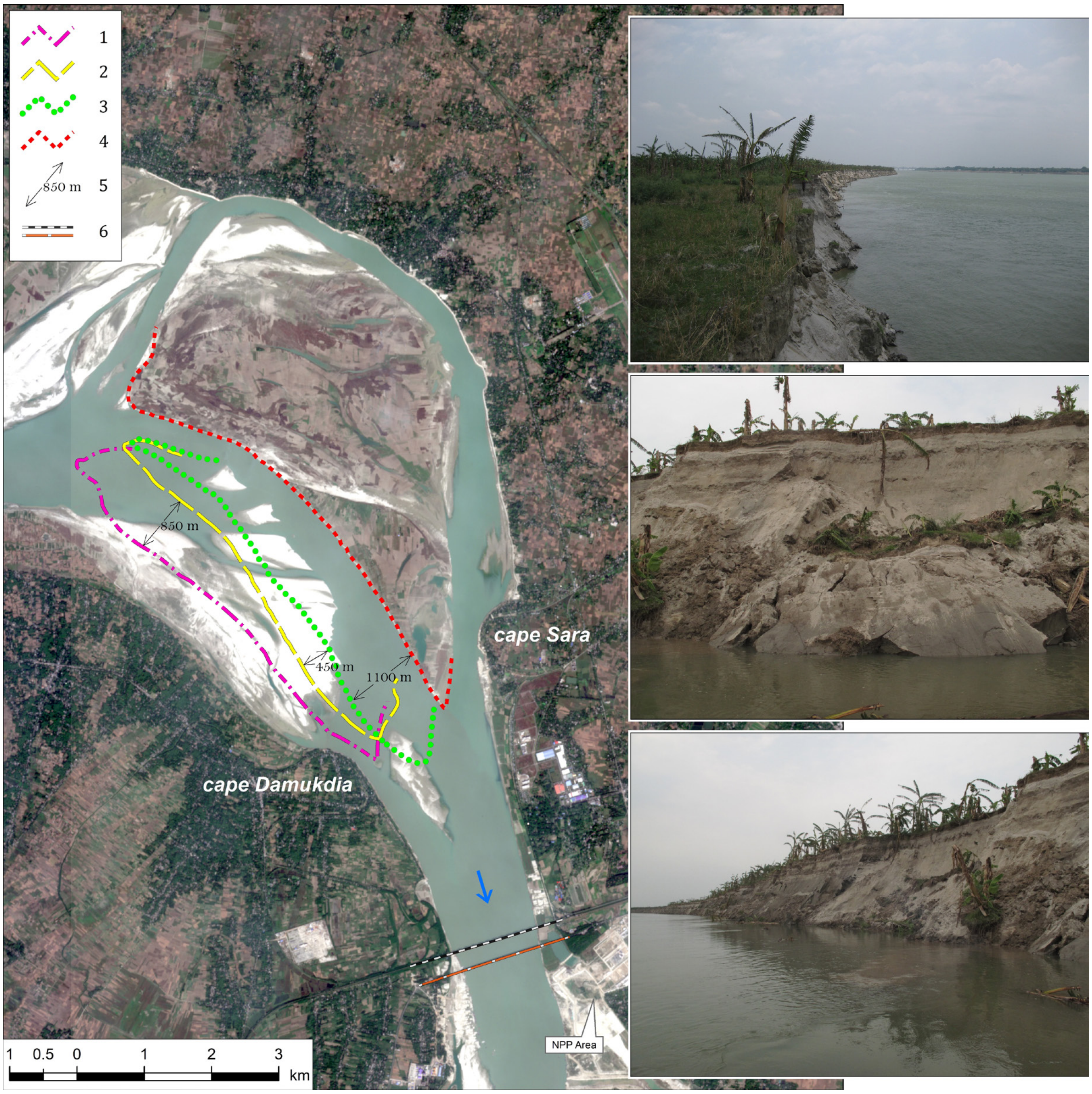

Figure 4. The position of the edge of the left bank of the rectifying arm: 1 – February 2011; 2 – March 2014; 3 – March 2015; 4 – December 2017; 5 – the section and the maximum value of the displacement of the left bank edge for different time intervals; 6 – bridge intersections (base – space image of 01.12.2017).

bank. Currently, the situation is different. Along the right bank, upstream and downstream the bridge piers, a wide (up to 300 m) sandbank was formed from the products of erosion of the newly developing arm. On the opposite bank, the erosion processes have become more active, leading to a washout of a large meander bar at the left bank within 3 years (Fig. 5), with only a narrow elongated island remaining in 2015 and completely eroded in 2016.

When summarizing the collected information on the dynamics of the Padma riverbed at the 1st and the 2nd site, one can speak of two different cycles (nested in one another) of channel transformation upstream of the NPP construction site. A short cycle is associated with the development of the bend between the capes Raita and Sara. The cycle started in the early 1990s and lasted for 25 years, when the rectification of the Natore bend took place. These changes overlap with the longer cycles of the channel development, covering the entire site. The last of those started in the mid-1970s, when bends formed between two contractions (upstream the capes Raita and Sara). It lasted for over 50 years. At the same time, it appears that the channel transformation during this large cycle depends on changes in the upstream branched section, located 45 km upstream of the Hardinge bridge near the city of Rajshahi. The latter determines the development of the left (current) or the right (1960-1970) chan-

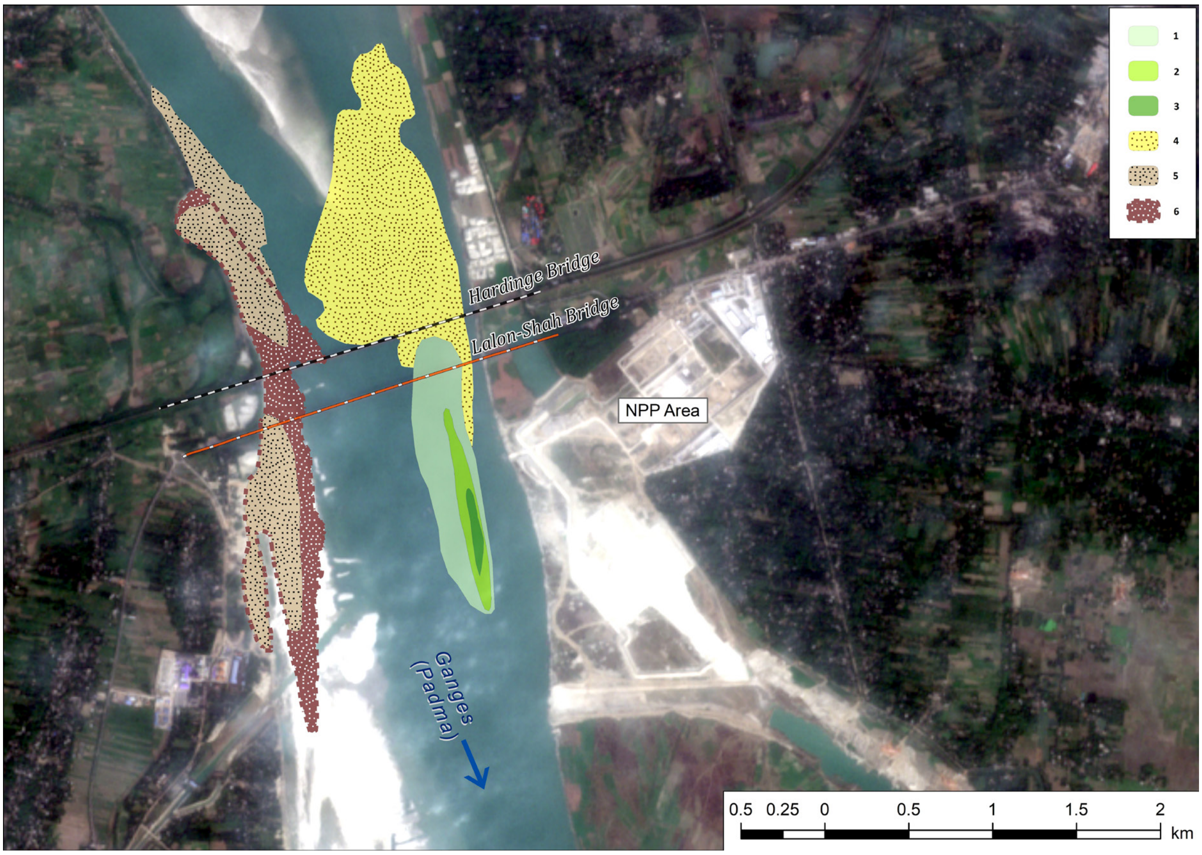

Figure 5. Changes in the channel in the bridge pass area due to the displacement of the stream dynamic axis from the right to the left bank. The configuration of the island at the left bank: 1 – in 2011; 2 – 2014; 3 – 2015. The status of the site: 4 – 2011; 5 – 2014; 6 – 2015 (based on a satellite image from 10 January, 2018).

nel location upstream of the cape Raita. Thus, the channel condition at the "Rooppur" NPP construction site is predicated based on the river transformation upstream. The choice of the location for the NPP in terms of channel deformations should be considered as optimal, which is evidenced by the stable state of the bridge's intersection for many years.

Changes in the channel at the third site also depends on the upstream deformations, although they are determined by the stable horizontal position of the banks between the second and the third sites. In this section, only the dynamic axis of the flow migrates along the width of the channel without migration of the bend.

In the early 1970s, when the development of the Natore bend had not yet begun, the Padma flow downstream of the Hardinge Bridge migrated to the left-bank floodplain, parallel to its current position, and gradually migrating to the Gorai distributary. An island was located 2.6 km upstream, in front of the right-bank cape, where the main channel of the river meets the left arm. Downstream of the entrance to the Gorai channel, the river bents gently, remaining further a relatively straight channel.

As the Natore bend was developing in the second section, the riverbed was gradually migrating to the right, and the displacement value for the period of 1972-2015 was 1.5 km. A large floodplain was formed in the place of the old riverbed, in the rear part of which the traces of the former channel were preserved in the form of a narrow floodplain channel. As a result, in 2010–2012, directly downstream of the bridges near the NPP site and the entrance into a secondary floodplain channel (where, according to the preliminary design solutions, the NPP water outlet is provided for), the left bank, located in the sediment accumulation zone was stabilised by vegetation overgrowing the riffles.

The situation has changed in the last 2-3 years with the development of the arm, straightening the Natore bend. Already in 2014, when the old channel (the Natore bend) and the new one (straightening arm) were operating simultaneously, and in 2015, when the old channel became completely shallow in the upper section, turning into an isolated water reservoir during the low water period, the dynamic axis of the flow shifted to the left bank in the bridge cross section. The riffles and part of the high (up to 4-5 m) floodplain were eroded, and by 2015 only a small island remained. Downstream of the cape Damukdia, a sandy meander bar was formed along the right bank, with a shallow spit in the lower end, stretching for 3 km downstream of the motorway bridge. The development of the rectifying arm of the Natore bend obviously stabilises the riverbed near the NPP site, preventing the current from moving towards the left bank.

Formation of large sandbars, mainly along the left-bank, is accompanied by erosion of the right bank within the downstream (third) described site. These processes show the general trend in the channel migration to the right. The erosion of the banks at this site occurs at an average rate of 5-15 m/year. However, the left high floodplain bank is partially eroded, mostly near the entrance to the Gorai arm. This is facilitated by the chequered arrangement of meander bars, due to which the midstream migrates to the left bank. During the last 10 years, it has been eroded at the rate of 20-30 m/year. The return of the dynamic axis of the stream to the right bank is already evident downstream of the entrance to the Gorai arm, where the bank retreats at an average rate of 60 m/year (for the period of 2014-2015 – up to 150 m/year).

A stable zone of sediment accumulation is located near the entrance to the Gorai arm. This is an economically important water body supplying water to the south-eastern regions of the Republic of Bangladesh. The use of water in the low-flow period has become increasingly difficult in recent years, due to changes in the main channel, associated with the migration of the dynamic axis of the stream towards the left bank. Below the Gorai, the axis migrates in the opposite direction, where a large sandbar is formed.

6. Conclusions

The results of the field research and measurements regarding the morphology, dynamics, hydrological and hydraulic conditions for the formation of the floodplain and riverbed complex of the Padma River have been presented, including: the distribution of water discharges, the bottom sediment load and suspended sediments, the changes in the water surface slopes, the distribution of bed-forming deposits, the rates of displacement of the dune relief forms, and characteristics of the flow rates. The analysis of the conditions for the formation of the Ganges (Padma) channel, a retrospective assessment of its development near the planned "Rooppur" NPP site allowed to obtain an overview of current trends in channel deformations, to develop a forecast of possible channel changes and to prepare recommendations regarding the location of a water intake and sluiceway structures of the "Rooppur" NPP. The conducted research showed that comprehensive and planned regulation of selected sections of rivers could lead to the channel stabilization and support the rational use of water resources for different purposes. Moreover, detailed research on channel deformation in selected areas indicated the major role of natural factors (geological structure, the type of sediments delivered to the river, vegetation cover, etc.) in the past and present fluvial processes.

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