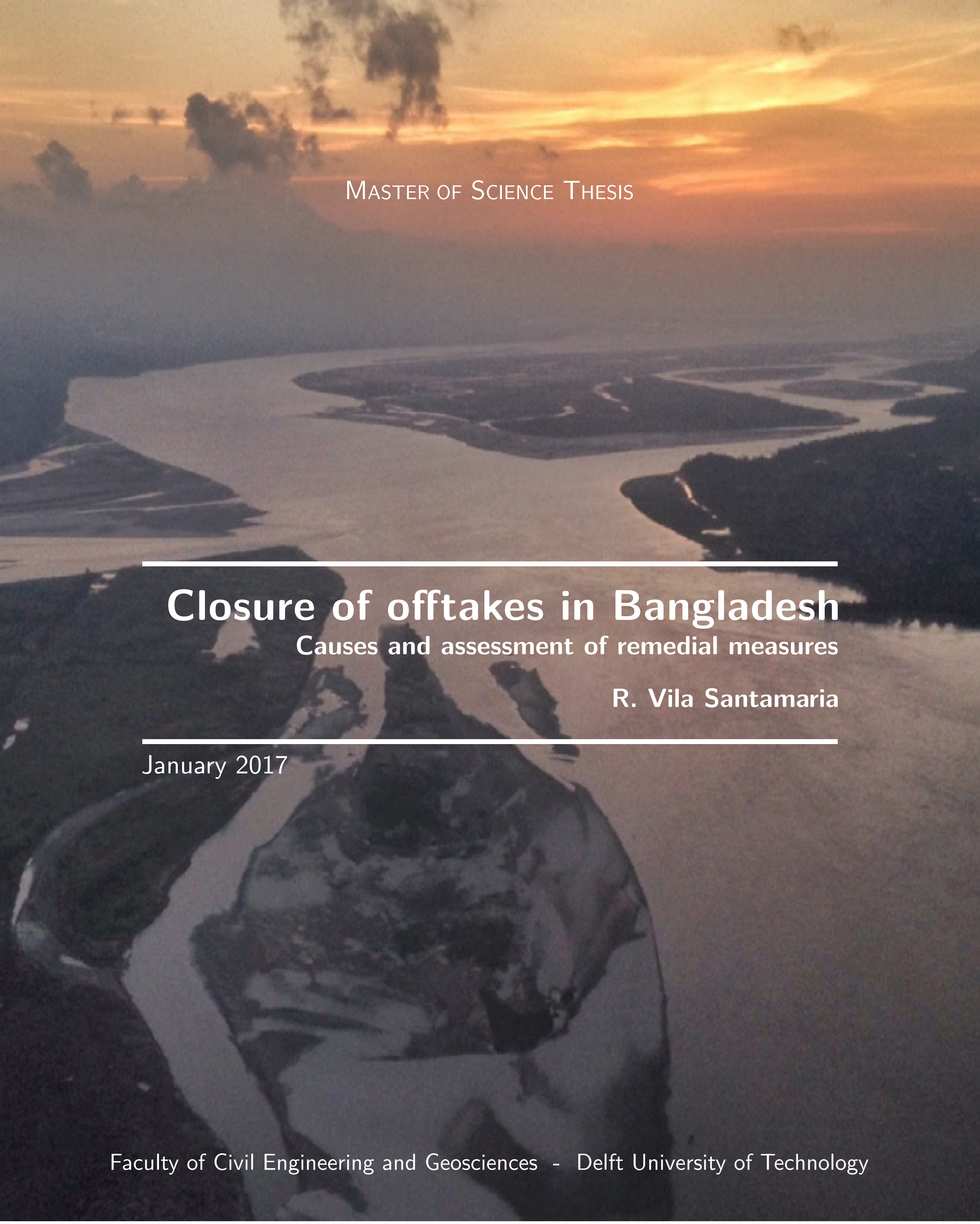

Master of Science Thesis

# Closure of offtakes in Bangladesh

## Causes and assessment of remedial measures

R. Vila Santamaria

January 2017

Faculty of Civil Engineering and Geosciences - Delft University of Technology

TU Delft

Witteveen + Bos

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For obtaining the degree of Master of Science in Civil Engineering at
Delft University of Technology

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Delft University Of Technology
Department Of
Hydraulic Engineering

The undersigned hereby certify that they have read and recommend to the Faculty of Civil Engineering and Geosciences for acceptance a thesis entitled **"Closure of offtakes in Bangladesh"** by **R. Vila Santamaria** in partial fulfillment of the requirements for the degree of **Master of Science**.

Dated: January 2017

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# Preface

This thesis report is the final step for completing the Master of Science degree in Hydraulic Engineering at Delft University of Technology. This research has been conducted in collaboration with Witteveen+Bos.

First of all, I would like to thank my daily supervisor, ir. Leon de Jongste, for his guidance and encouragement throughout the duration of this thesis, and for the many discussions about the challenges of river engineering in Bangladesh and numerical modelling of river dynamics. Furthermore, I would like to thank dr. ir. Erik Mosselman for his indispensable advice, sharing his knowledge about offtake dynamics and for sending me all the documentation he found on this issue during his visits to Bangladesh. I also want to express my gratitude for the other members of the assessment committee, prof. dr. ir. Wim Uijttewaal and dr. ir. Astrid Blom, for their critical comments and constructive advice, which helped improve the final outcome of this research.

I would like to thank Md. Ruknul Ferdous and Jakia Akter, PhD students at UNESCO-IHE in Delft with an extensive expertise in river engineering in Bangladesh. It was a unique opportunity to talk with them during the early stages of my research, and I am grateful for the relevant documents and flow data on the Ganges and Jamuna rivers that they provided me.

I would like to thank Witteveen+Bos for giving me the opportunity to conduct this research and providing me with a working space in their office in Rotterdam. Special thanks go for the colleagues of the "Hydrodynamics and Morphology" group for the nice conversations, "borrels", group meetings and "lessons-learned sessions" that made my stay very enjoyable. I also want to thank the graduate students and interns with whom I have shared all this time in the office, who helped me adapt to the Dutch environment and made my stay even more interesting and fun.

I also want to thank my family. I wouldn't have made it this far without their unconditional encouragement and support. And last, I want to thank Alba for all her love and support, always being there sharing with me all the enjoyable and stressful moments during my studies and research.

Delft, The Netherlands R. Vila Santamaria
January 2017

# Abstract

Bangladesh is characterised by its complex river system, which includes the downstream ends of two of the largest rivers in the world: the Ganges and Brahmaputra. Extremely variable flows and fast morphological changes are the principal characteristics of this system, which presents exceptional challenges for river engineering. Distributary rivers from the major rivers in Bangladesh are a key element in providing fresh water to the South-West and Central regions of the country. With the arrival of the dry season and the drop of water levels in the rivers, some of the distributaries become disconnected during several months from their parent rivers because of aggradation at the offtake during the monsoon season.

Acquisition of all the field data required for a detailed morphodynamic study of those offtakes is very often not possible, specially for preliminary designs or during the initial stages of a project. For the rivers of Bangladesh, bed topography data are even outdated in a matter of months because of the extremely dynamic nature of those rivers.

In order to overcome this lack of data, the approach of this MSc thesis is to use a physics-based morphodynamic numerical model based only on the most significant characteristics of the offtake system to be analysed. If this model correctly reproduces the most important characteristics and evolution of the river and offtake system, it is then possible to use it for an initial assessment of remedial measures to prevent offtake closure.

An analysis of the offtake systems is made before setting up the numerical model. The focus of this analysis is on the relevant physical processes for the evolution of offtakes, with the conclusion that processes such as helical flow, transverse bed-slope effects on sediment transport or retarded scour need to be taken into account in the numerical model to reproduce the morphodynamics of the system. Furthermore, the causes of offtake closure occurring at the main distributaries of Bangladesh are identified and possible remedial measures are proposed to prevent them.

The setup of the model is based on the findings from these previous analyses. The choice is for a 2-D depth average numerical model using the software package Delft3D. A schematised geometry roughly based on the Ganges and Gorai rivers and offtake is used, with a total length of 100 km for the parent river and 20 km for the distributary channel. The simulation is initialised with a flat bed and a constant slope, which then develops into a realistic bed topography shaped by the morphological module of the numerical model.

Because this model cannot be properly calibrated, as data available are not sufficient, the order of magnitude of model results is compared with observations of the river system for hydrodynamic and sediment transport processes; and with satellite images for the morphological evolution of bars and channels. With this comparison it is found that the model is able to reproduce the behaviour of the river system with enough accuracy to obtain the correct orders of magnitude for the evolution of the offtake system and the effects of interventions.

The offtake behaviour simulated by the model is then analysed and used as reference scenario for the assessment of different engineering measures. The results of this assessment show that dredging the upstream part of the distributary river during the recession period of the monsoon can prevent the discontinuation of flow in the distributary river for the entire dry season, and improves the flow conditions for the following year. However, this measure needs to be applied regularly and does not stabilise the offtake in the long term.

Other measures tested in the model are major dredging at the parent river to improve its alignment; construction of submerged erodible weirs; a flow divider and the use of longitudinal training walls to reduce the width of the parent river. However, these measures seem not to be effective in maintaining flow in the distributary river when implemented in the numerical model.

In conclusion, the methodology developed in this thesis is able to overcome the lack of data availability and simulate realistic scenarios of the complex process of offtake closures. With this tool, it is possible to perform fast and inexpensive modelling of the behaviour of offtake systems and assessment of engineering measures to prevent offtake closure that otherwise would require much more resources.

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# Nomenclature

## Latin Symbols

| | | |
|---|---|---|
| $C$ | Chézy roughness | [m$^{0.5}$/s] |
| $c_f$ | dimensionless resistance coefficient | [-] |
| $D_{50}$ | sediment median grain size | [mm] |
| $F_c$ | centrifugal force (in a river bend) | [N] |
| $g$ | acceleration of gravity | [m/s$^2$] |
| $h$ | water depth | [m] |
| $i_b$ | bed slope | [-] |
| $I_{hf}$ | intensity of helical flow | [m/s] |
| $L$ | length | [m] |
| $M$ | Grid index in m-direction | [-] |
| $MF$ | Morphological acceleration factor | [-] |
| $N$ | Grid index in n-direction | [-] |
| $p$ | porosity of sediment at the bed | [-] |
| $Q_a$ | average discharge | [m$^3$/s] |
| $Q_b$ | bankfull discharge | [m$^3$/s] |
| $q_s$ | sediment transport per unit width | [m$^2$/s] |
| $Q_{max}$ | maximum discharge | [m$^3$/s] |
| $Q_{susp}$ | suspended bed-material load | [m$^3$/s] |
| $Q_{wash}$ | wash load (sediment transport) | [m$^3$/s] |
| $R$ | radius of a river bend | [m] |
| $t$ | time | [s] |

| | | |
|---|---|---|
| $u$ | depth-averaged flow velocity in x-directio | [m/s] |
| $v$ | depth-averaged flow velocity in y-direction | [m/s] |
| $W$ | channel width | [m] |
| $x$ | longitudinal horizontal coordinate | [m] |
| $y$ | transversal horizontal coordinate | [m] |
| $z_w$ | water level of the free surface (above reference) | [m] |

# Greek Symbols

| | | |
|---|---|---|
| $\kappa$ | von Kármán constant | [-] |
| $\nu_H$ | horizontal eddy viscosity | [m$^2$/s] |
| $\phi_T$ | deflection of bed-load transport by helical flow | [deg] |
| $\rho_s$ | density of sediment | [kg/m$^3$] |
| $\rho_w$ | density of fluid (water) | [kg/m$^3$] |
| $\sigma_g$ | Grain size geometric standard deviation | [-] |
| $\tau_b$ | Shear stress near the bed | [N/m$^2$] |

# Abbreviations

| | |
|---|---|
| 2DH | 2-dimensional, depth averaged (numerical models) |
| BanDuDeltAS | Bangladesh Dutch Delta Advisory Services |
| BDP 2100 | Bangladesh Delta Plan 2100 |
| BWDB | Bangladesh Water Development Board |
| FAP | Flood Action Plan project |
| FAP24 | FAP project n. 24: River Survey Project |
| OLI | Operational Land Imager, sensor on board of the Landsat 8 satellite. |
| PWD | Public Works Datum |
| USGS | United States Geological Survey |

# Chapter 1

# Introduction

## 1.1 Background

The Ganges, Brahmaputra and Meghna Rivers flow through Bangladesh, where they confluence and discharge into the Bay of Bengal (see Figure 1.1). Sediment brought by these rivers has build up over thousands of years what is now one of the largest deltas in the world: the Bengal Delta (Sarker et al., 2013).

Socio-economic development of Bangladesh largely depends on these three major rivers and their numerous tributaries and distributaries. This complex and extensive fluvial system brings fresh water, fish and a means of transportation to the rural areas of the country. It plays an important role for urban areas as well, with an ever increasing water supply demand, an industrial sector heavily dependent on river resources and navigation being a key aspect for future economic growth (BanDuDeltAS, 2014, 2015; EKN, 2013).

However, rivers also produce immense suffering to the people in Bangladesh. The country has a large and growing population, with an extremely high population density[1]. Climate in the region is of tropical nature dominated by the south-west monsoon of the Indian Ocean and 75% to 80% of the annual rainfall occurs during the monsoon season, from June to October. The remaining 20% to 25% rainfall mostly occurs during the pre-monsoon period (March to May) and from November to February there is almost no precipitation. With this climate, the discharge of the rivers in Bangladesh is extremely variable and floods are frequent all around the country. While annual floods are essential and desirable for the overall growth of the delta and associated economic activities, extreme floods have caused millions of casualties in the last decades alone and suppose an important set-back to the developing economy (BanDuDeltAS, 2016; Khalequzzaman, 1994).

Apart from flood hazard, large scale river bank erosion has also a huge impact in Bangladesh. As stated by BanDuDeltAS (2015) and Northwest Hydraulic Consultants (2013), the land

[1] Bangladesh is the country with the highest population density in the world (excluding small countries of less than 1000 $km^2$), with a density of over 1200 hab/$km^2$ and 160 million inhabitants. (The World Bank, 2014)

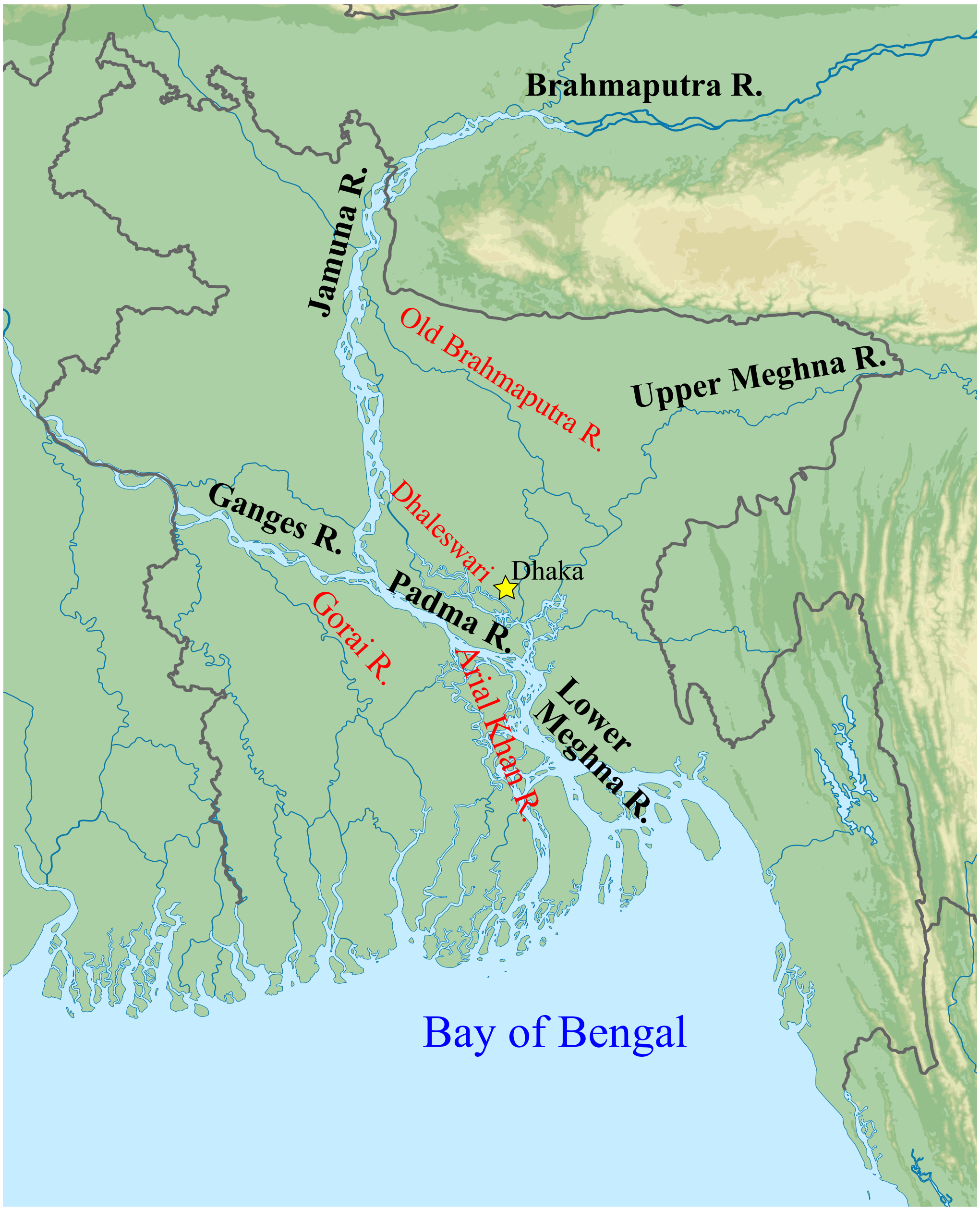


**Figure 1.1:** Major rivers of Bangladesh and their main distributaries (in red).

mass of the Bengal Delta is mostly composed of recent deltaic deposits that are easily eroded, which makes the rivers in Bangladesh extremely dynamic. This process leads to several thousand hectares of fertile farmland lost and about 100 000 people loosing their homes each year (Sarker et al., 2014).

Reduced discharge of the major rivers during the dry season is also a matter of concern in Bangladesh. Distribution of fresh water throughout the country largely depends on smaller distributary rivers that branch off from the major rivers. Some of these distributary rivers are affected by siltation problems and do not convey enough water during the dry season to satisfy the demands of an ever growing population.

In this context, in 2012 the Government of Bangladesh requested the Government of The Netherlands to provide advice and recommendations for the formulation of a delta master plan to reduce the vulnerability of the country to the aforementioned natural disasters and to develop an adaptive strategy for a long-term sustainable socio-economic development for the next 100 years. This master plan was named Bangladesh Delta Plan 2100 (BDP 2100) and a preparatory team was created combining Dutch and Bangladeshi experts to assist and advise the Government of Bangladesh in the development of such Delta Plan (EKN, 2013).

A consortium of Bangladeshi, Dutch and international engineering companies and research institutes called Bangladesh Dutch Delta Advisory Services (BanDuDeltAS) was created in 2014 for the formulation of the BDP 2100, of which Witteveen+Bos is a part as engineering consultant.

Combining the findings of the BDP 2100 project, the interests of Witteveen+Bos and the author's personal background and interests, the decision was made to focus this MSc thesis on one of the knowledge gaps identified during the project, in particular on how to maintain the connectivity between the major rivers and their distributaries during the dry season. The next section describes this problem in more detail.

## 1.2 Problem description

As stated in the previous section, the focus of this MSc thesis is on maintenance of the connections between the major rivers and the secondary, distributary rivers. In particular, the offtakes of distributaries from the major rivers are a key element in the complex river system of the country and further studies of their dynamics were considered necessary and of great importance during the formulation of the BDP 2100 for both the short and mid-term (BanDuDeltAS, 2016).

There are 4 important distributaries in Bangladesh, shown in red in Figure 1.1: the Old Brahmaputra and Dhaleswari rivers, which take off from the left bank of the Jamuna River and discharge into the Upper Meghna River; the Gorai river, which offtakes from the right bank of the Ganges; and the Arial Khan river, which takes off from the right bank of the Padma River. Both Gorai and Arial Khan discharge directly into the Bay of Bengal.

Several aspects make these rivers extremely important for the socio-economic development and environmental balance of the South-West and Central regions of Bangladesh, which comprise the divisions of Dhaka, Khulna and Barisal. Distributary rivers, as the name indicates, distribute water from the major rivers across the aforementioned regions. Drinking water supply as well as irrigation in those regions largely depend on the flow carried by the distributaries, specially during the dry season. Navigation along these secondary rivers is also important for the stimulation of economical growth as well as necessary for the areas that depend almost entirely on waterway transport for accessibility.

The Gorai River is also the main source of fresh water for the coastal region of the Sundarbans, the world's largest mangrove forest. This zone depends on fresh water from the Gorai River for maintaining its rich ecosystems and to prevent salinity intrusion from the sea, expected to increase with sea level rise associated with climate change (Hore et al., 2013). Another example of the environmental importance of distributaries is the urban area of

Dhaka, the capital of Bangladesh. This city relies on water flowing in the Dhaleswari river system to reduce the alarming high concentration of pollutants along its entire waterway system (Alam and Marinova, 2006).

During the monsoon season, the major rivers are extremely dynamic and their planform can experience important changes. Channel migration, formation or abandonment; formation of mid-channel bars and changes in channel width are examples of such morphological changes that take place mostly during the rainy season. One important consequence of this dynamic behaviour is how it affects the distributary offtakes, changing their shape, position or eventually silting them up completely and disconnecting them from the main flow of their parent river.

Siltation and closure of offtakes has been documented throughout the last years and decades. The Gorai River flow was discontinued during the dry season between 1987 and 1998, and again from 2005 to the present (CEGIS, 2012b); while the Old Brahmaputra river has only been conveying a marginal discharge in the dry season for the last decades (Noor, 2013). The offtakes of the Arial Khan River and the of the Dhaleswari River do also experience siltation problems and changes in shape and location (Akter et al., 2013; CEGIS, 2012a; IWM, 2015).

Several authors and studies (e.g. Akter et al., 2013; Delft Hydraulics and DHI, 1996a; Hore et al., 2013; Northwest Hydraulic Consultants, 2013) conclude that offtake dynamics is one of the most important factors for the hydrodynamic and morphological development of distributary rivers. Variable characteristics of the offtake will certainly lead to an unstable flow regime and a more or less dynamic distributary river. Offtake stability is therefore a crucial step before any attempt of river stabilisation or training is made.

The current approach to this problem is the analysis of each individual case with the development of 2D morphodynamic numerical models using detailed bed topography data and boundary conditions. However, in an extremely dynamic environment as is the case of the rivers in Bangladesh, the applicability of these model results is very limited. With the huge sediment transport rates and gradients present in those rivers, river planform and bed topography changes cannot be predicted down to such a fine level of detail for a reasonable period of time (of the order of months for engineering purposes). The results and designs from such studies cannot be generalised: they are limited to the specific location of the study and are only reliable for a short period of time. Physical scale models have also been used to predict the evolution of offtakes in Bangladesh (den Dekker and van Voorthuizen, 1994; Roosjen and Zwanenburg, 1995) but they require large facilities, long times for implementation and suffer from scale effects when dealing with fine sediment. For this reason scale models cannot be used on a regular basis to predict the morphological evolution of the rivers.

With the present approach to offtake maintenance, there is a lack of global understanding of the processes that are governing the evolution of those bifurcations. The aim of this MSc thesis is to overcome some of the limitations mentioned above and get more insight in the offtake siltation problem, to then propose remedial measures and a new approach to assess their effectiveness and impacts.

## 1.3 Objective and research questions

Given the scarcity of available data presented in the previous section, the objective of this thesis is to propose a method to assess the effectiveness and impacts of possible remedial measures to prevent the closure of offtakes in Bangladesh.

In order to achieve this objective, the following research questions need to be answered; first to propose engineering measures to prevent offtake closure...

1. Relevant physical processes: What physical processes are relevant for the morphodynamic evolution of offtakes?
2. Causes of offtake closure: What are the main causes and drivers of offtake closure?
3. Possible remedial measures: What remedial measures can be defined which might prevent offtake closure?

... and then to assess the effectiveness and impact of those measures:

4. Suitable tool for assessment: What is a suitable tool and approach to assess the effects of remedial measures for offtake stabilisation, given the dynamics of the system and the scarcity of available data?
5. Reliability of tool: How well is this tool able to reproduce the morphological evolution and offtake closure processes observed in Bangladesh?
6. Effectiveness of remedial measures: How effective are the remedial measures proposed in preventing offtake closure, and what impacts do they have associated?

## 1.4 Data availability

The most important source of information about the rivers of Bangladesh comes from the Flood Action Plan 24 (FAP24) project, called the River Survey Project (Delft Hydraulics and DHI, 1996a). The reports from FAP24 contain the most in-depth description of the main river system of Bangladesh to date. This includes some bathymetric, hydrologic and sediment transport surveys as well as studies on specific processes occurring in those rivers. This information has been the basis for many later studies and projects on the rivers of Bangladesh, and is still very valuable as a general background of the river system in the present—20 years later by the time of writing this thesis. However, bathymetric surveys were limited to specific locations (e.g. the only offtake included was the Gorai) and large morphologic changes have occurred since then.

In practice, carrying out bathymetric surveys of such large and dynamic rivers is very costly, and such data are quickly outdated by the natural development of the rivers itself. For this reason, a consistent time-series record of bed topography around offtakes is inexistent in the present—and is not likely to be available in the near future.

Another source of quantitative data are the gauging stations of the Bangladesh Water Development Board (BWDB). A number of automatic and manual gauging stations are maintained by BWDB and provide water levels and—in some cases—discharge data at different locations. Data from two of these automatic gauging stations were available for this thesis—one for the Jamuna River at Bahadurabad, downstream of the Old Brahmaputra offtake, and the other for the Ganges River at the Hardinge Bridge, upstream of the Gorai offtake. These data consist of daily measurements of both water level and discharge between 1980 and 2009.

Finally, satellite images provide time-series of the rivers' planform with spatial resolutions of down to 30 m. The images used in this study are from the Landsat missions available via the United States Geological Survey (USGS). Landsat imagery is available since 1972, providing a time-series extending 44 years. However, acquisition of satellite imagery is limited by cloud cover and is thus very limited during the wet season in Bangladesh.

## 1.5 General approach

In order to overcome the problems of the current approach to offtake maintenance in Bangladesh described in Section 1.2, and taking into account the lack of sufficient morphology data around offtakes—and practical difficulties to obtain such data—, a new approach is proposed in this thesis for a preliminary assessment of engineering interventions for offtake maintenance.

This new approach consists of the use of physics-based numerical models to simulate simplified offtake geometries based on the available data. The hypothesis is that by reproducing as good as possible the individual physical processes relevant for offtake development in a computational model, it is possible to obtain a sufficiently realistic bed topography and morphodynamic behaviour of the system to allow the investigation of different engineering solutions. In order to confirm the validity of this hypothesis, simulation results are compared with qualitative and quantitative data of the real rivers to the extent possible.

Before the development of the numeric model, it is of capital importance to have a good understanding of the behaviour of the system—in this case of the four main offtakes in Bangladesh—and of the relevant physical processes for the evolution of offtakes and river bifurcations. This corresponds to answering the 1st research question (relevant physical processes). The basis for this first part is a review of available literature on the river system of Bangladesh and on the current knowledge on river and bifurcation morphodynamics.

Following this first analysis of the system, the focus is on the specific causes that have been identified for the closure of offtakes in Bangladesh. This is also done by reviewing the extensive literature available on the subject, mostly from a series of projects performed in the last two decades. This review is complemented with a link to the physical processes analysed before, and backed up by specific examples identified from satellite imagery. The results of this part constitute the answer to the 2nd research question (causes of offtake closure).

After that, a series of remedial measures is proposed, which could mitigate the specific causes identified before, giving an answer to the 3rd research question (possible remedial measures).

Based on all the findings up to this point and the data available, the specific requirements for the numerical model are defined and the detailed setup is decided. This gives the answer to the 4th research question (suitable tool for assessment) and is the start of an optimisation process to minimise the computational errors present in any numerical model. This is done by selecting appropriate formulations of physical processes and coefficients based on literature and expert opinions and advice. It is important to clearly distinguish this optimisation process from a normal calibration of a numerical model. For the latter, model parameters are adjusted so that the results fit as good as possible to data obtained from field measurements. Such a calibration makes no sense for the model of this thesis, because the model itself represents just a simplified river geometry for which no “real data” can be collected. For this reason, special care is given to not steer the numeric model artificially to show some preferred results with this optimisation.

At the end of this optimisation process, the output of the model is compared with quantitative and qualitative data from reports on the real river systems as well as with observations from satellite imagery. Special attention is paid to identifying which of the causes of offtake closure are represented by the numeric simulations. With this comparison it is then possible to answer the 5th research question (reliability of tool).

Based on which causes of closure are identified in the numerical simulation without any intervention, a number of possible remedial measures is then implemented in the numerical model. The effectiveness of such interventions is assessed with the duration of no flow into the distributary channel during the dry season. Impacts on the flow regime and morphological development are also analysed for each intervention. The results from this analysis constitute the answer to the 6th and last research question (effectiveness of remedial measures).

# Chapter 2

# Analysis of the system

## 2.1 The rivers and offtakes of Bangladesh

The evolution of an offtake depends to a large extent on the characteristics and behaviour of its parent river and distributary channel. This section presents a general overview of the characteristics and recent evolution of the major rivers, distributaries and corresponding offtakes in Bangladesh based on the large quantity of literature available on the subject.

### 2.1.1 Major rivers

The river system in Bangladesh has experienced important changes over the last centuries. Of special relevance is the last avulsion of the Brahmaputra River to the present Jamuna River because of the large consequences of this change. As described by Sarker et al. (2013), about 250 years ago the Brahmaputra River was flowing along the east side of the Madhupur Tract, discharging into the Meghna River and then reaching the Bay of Bengal as seen in Figure 2.1a. Around 200 years ago the Brahmaputra river started an avulsion process with a significant amount of its flow being diverted to the Jamuna River, which discharged into the Ganges (Figure 2.1b). The combined flow of the Ganges and Jamuna was then named Padma. By the early 20th century the Jamuna River had taken most of the Brahmaputra flow, with the old branch—renamed Old Brahmaputra—being just a distributary of the Brahmaputra-Jamuna system. Later, the Padma River moved eastwards to join the Meghna River, leaving its former course as a distributary of the main flow—just like what happened with the Old Brahmaputra. This distributary received the name of Arial Khan.

Tables 2.1 to 2.3 summarise some of the general characteristics of the major rivers as observed and measured in the recent past. The Meghna River has been excluded from this study as it does not have any important distributary and its geographic setting, hydrological regime and morphologic evolution present major differences from the rest of the river system in Bangladesh. Although the Padma River originates from the confluence

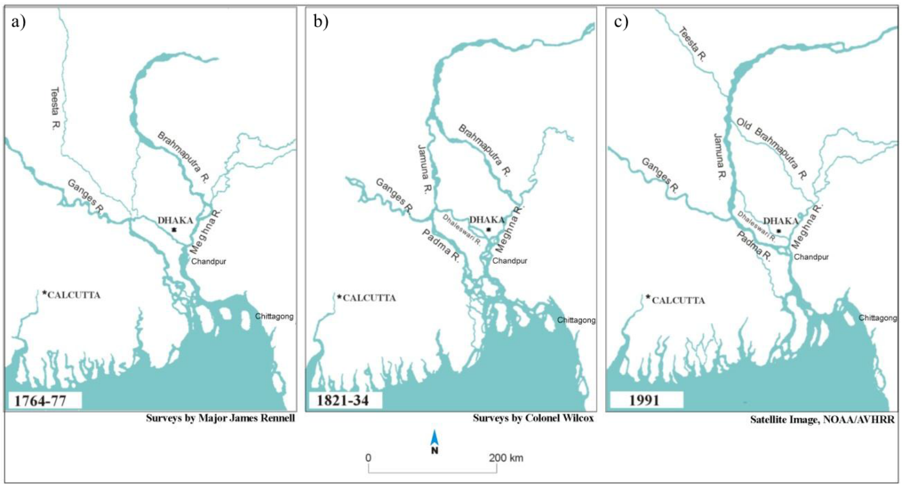


**Figure 2.1:** Development of the main rivers in Bangladesh over the last 300 years. From BanDuDeltAS (2015).

of both Jamuna and Ganges, the discharge of the Padma in Table 2.1 is lower than the sum of the other two rivers. This is because the distributary rivers from the Ganges and Jamuna are not taken into account and convey a significant flow, specially during high water events.

**Table 2.1:** Hydrological characteristics of the major rivers of Bangladesh.

| River Name | Total length[1,2] $L$ [km] | Basin area[1] [million km$^2$] | Average rainfall[1] [mm/year] | Average discharge[3] $Q_a$ [m$^3$/s] | Bankfull discharge[2,3] $Q_b$ [m$^3$/s] | Maximum discharge[1] $Q_{max}$ [m$^3$/s] |
|---|---|---|---|---|---|---|
| Jamuna | 2,900 | 0.55 | 1,900 | 19,600 | 48,000 | 100,000 |
| Ganges | 2,510 | 1.09 | 1,200 | 11,000 | 43,000 | 78,000 |
| Padma | 121 | 1.64 | | 28,000 | 75,000 | 128,000 |

Sources: (1) Hossain (2016); (2) BanDuDeltAS (2015); (3) Delft Hydraulics and DHI (1996a)

**Table 2.2:** Hydraulic and morphological characteristics of the major rivers of Bangladesh.

| River Name | Width[1,2] $W$ [km] | River gradient[2] $i_b$ [-] | Average water depth[2] $h$ [m] | Seasonal water level variation[2] $\Delta z_w$ [m] | Planform[1] |
|---|---|---|---|---|---|
| Jamuna | 12 | $7 \cdot 10^{-5}$ | 5 | 6 | Braided / Anabranching |
| Ganges | 5 | $5 \cdot 10^{-5}$ | 4.5 | 8 | Meandering |
| Padma | 7 | $4 \cdot 10^{-5}$ | - | 6 | Meandering |

Sources: (1) BanDuDeltAS (2015); (2) Delft Hydraulics and DHI (1996a)

**Table 2.3:** Sediment transport characteristics of the major rivers of Bangladesh.

| River Name | Suspended bed-material load[(1)] $Q_{susp.}$ [Mton/year] | Wash load[(1)] $Q_{wash}$ [Mton/year] | Representative bed-material grain size[(2,3)] $D_{50}$ [mm] | Geometric standard deviation[(2)] $\sigma_g$ [-] |
|---|---|---|---|---|
| Jamuna | 125 | 277 | 0.20 | 1.6 |
| Ganges | 76 | 558 | 0.17 | 1.4 |
| Padma | 227 | 721 | 0.09-0.15 | - |

Sources: (1) BanDuDeltAS (2015); (2) Delft Hydraulics and DHI (1996a); (3) CEGIS (2012b)

### Brahmaputra-Jamuna River

The Brahmaputra-Jamuna enters Bangladesh from its north border and has a length of around 240 km within the country until its confluence with the Ganges River (see Figure 1.1). Two distinct reaches can be identified: the upstream reach from the border with India until the Old Brahmaputra offtake is called Brahmaputra; the downstream reach from there until its confluence with the Ganges is called Jamuna. As described by Delft Hydraulics and DHI (1996a) for the FAP24 project, the river presents a number of major channels separated by large vegetated islands—described as second-order channels by Sarker et al. (2014)—that in general varies from three at the upper reach to two at the lower reach giving the impression of an anabranched river. However, during low river stages the river presents an obvious braided planform, with the emergence of numerous mid-channel sand bars.

### Ganges River

The Ganges enters Bangladesh from the west and from the country border it flows for about 220 km until it meets the Jamuna River (see Figure 1.1). The river morphology is controlled by the presence of less erodible bank materials (clay outcrops) and human interventions, with a predominant meandering planform (CEGIS, 2012b). There are two major man-made structures along the lower reach of the Ganges: the Hardinge railroad bridge—which was finished in 1912—and the Farakka Barrage—constructed in 1975. The Hardinge bridge is located 16 km upstream of the Gorai offtake and constitutes a fixed point for the Ganges River because of its associated river training works (consisting of two guide bunds and the reinforcement of two natural hard points, see e.g. Ghoshal, 2015). The Farakka Barrage is located 20 km upstream of the border between India and Bangladesh and was build with the objective of diverting water into the Hoogly river to maintain navigability in the port of Kolkata. Since then the dry-season water levels downstream of the barrage have been reduced and various agreements and treaties between India and Bangladesh regulate the minimum flows through the barrage (Mirza, 2004).

### Padma River

The Padma River results from the combined flow of the Jamuna and the Ganges. It flows for 110 km until the confluence with the Upper Meghna and then for another 120 km under the name of Lower Meghna until it reaches the Bay of Bengal (see Figure 1.1). Its planform has changed during the last decades showing a braiding, meandering and straight channel behaviour (BanDuDeltAS, 2015). At present, the river is transforming again from straight to meandering (The World Bank, 2011). The only structure crossing this river will be the Padma Multipurpose Bridge—currently under construction—which will be located 15 km downstream of the Arial Khan offtake and include river training works extending for 1.6 km on the left bank and 12.4 km on the right bank (Bangladesh Bridge Authority, 2016; The World Bank, 2011).

### 2.1.2 Main distributaries and offtakes

#### Old Brahmaputra

The Old Brahmaputra is the former course of the Brahmaputra River as it flowed east of the Madhupur tract. Since the avulsion of the Brahmaputra into the Jamuna, the Old Brahmaputra River has been loosing its conveyance capacity, becoming a mere spill channel of the Brahmaputra at present. The offtake is the most dynamic part of the river and its location has shifted large distances over the last decades as can be seen in Figure 2.2. Some attempts and proposals have been made to stabilize this offtake and reopen the river for navigation (e.g. Boskalis-GRC, 2000) but non of them have completely succeded and the Old Brahmaputra offtake is still silted up each year.

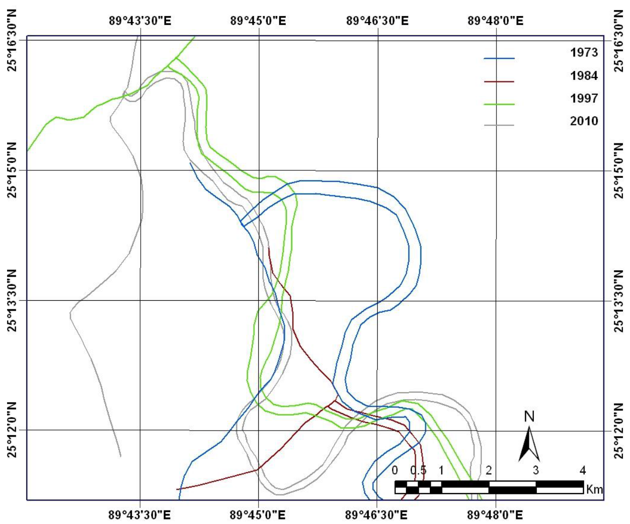


**Figure 2.2:** Location of the offtake of the Old Brahmaputra over the last decades. Source: BanDuDeltAS (2015).

#### Dhaleswari system

This river system feeds the metropolitan region of Dhaka, the capital of Bangladesh. The network of rivers comprises the Dhaleswari, Pungli, Bangshi, Turag and Buriganga—amongst other rivers—and has three active offtakes along the left bank of the Jamuna River. The most important offtake is called New Dhaleswari Spill Channel and is located just downstream of the Jamuna Bridge guide bunds. Even though the banks of the Jamuna have been stabilised at that location, the offtake receives a large amount of sediment and there is no flow at the distributary for 4 to 5 months each year (IWM, 2015).

Another offtake—the South Dhaleswari offtake—is located 4 km downstream of the first one.

Finally, a smaller offtake developed further downstream and reopened an old channel of the Dhaleswari. It has been named Old Dhaleswari offtake and has been a focus of interest recently because it silts up in the dry season, but presents high erosion rates during the rainy season, threatening villages along the river banks next to the offtake.

#### Gorai

Out of the four main distributaries, the Gorai has received the most attention due to its importance for the region and the Sundarbans mangrove forest. The Gorai takes off from the Ganges approximately 15 km downstream of the Hardinge Bridge and discharges into the Bengal Bay.

The bifurcation between the Ganges and the Gorai was largely studied in the context of the Flood Action Plan (FAP) with a morphology study including numerical modelling (Delft Hydraulics and DHI, 1996a), a feasibility study for measures to stabilize the offtake (DHV-Haskoning & Associates, 2001) and a pilot project (named Pilot Priority Works) for dredging of the upper part of the Gorai (GRC, 2002). More recently, an update of those studies was made by CEGIS (2012b) showing how siltation of the Gorai offtake is still an important issue for Bangladesh.

Since 1987, flow in the Gorai has been discontinued during the dry season—except for the duration of the Pilot Priority Works, from 1998 to 2002 and until 2004, when the offtake closed again. The possible reasons for these closures identified by CEGIS (2012b) and Hore et al. (2013) include the operation of the Farakka Barrage in India, supply of sediment from bank erosion upstream of the offtake, changes in the approach angle of the main Ganges channel, or the clay layer at the bed of the offtake which limits the morphological response of the river.

#### Arial Khan

As mentioned in the introduction to Section 2.1.1, the Arial Khan River was the main channel of the Padma River some 150 years ago until the Padma shifted towards the Meghna. After that, the discharge into the Arial Khan was significantly reduced and this river became very dynamic, adapting to the new flow conditions.

According to CEGIS (2012a), until around 1980 there were two distinct offtakes to this distributary, in occasions being up to four depending mostly on the planform of the Padma River. At that time, unfavourable morphological conditions at one offtake lead to the development of another one at a more favourable location. Human intervention (construction of roads and embankments) is probably one of the major causes for the stop of this behaviour and from the early 1980s only the northern offtake of the Arial Khan is active. This offtake is currently located around 50 km downstream of the confluence between the Ganges and the Jamuna rivers, but in the last 50 years it has moved within a range of 10 km (reduced to 3 km in the last 15 years), also according to CEGIS (2012a).

Despite the northern offtake being active throughout the last decades, the flow to the Arial Khan in the dry season has been oscillating and the conveyance capacity of the offtake has reduced over the last years (Mamun, 2012). The causes for this behaviour can be the shifting of the main channel of the Padma away from the offtake location, and the formation of bars in front of the offtake. The changes in location and characteristics of the offtake have significantly affected the overall planform of the distributary river, as analysed by Akter et al. (2013), requiring the development of training works along its course to prevent bank erosion near bridges and villages.

## 2.2 Physical Processes

This section contains a description of the most important physical processes that need to be considered when studying an offtake in the very dynamic fluvial environment described in the previous section. In order to understand how an offtake develops it is necessary to look at the system as a whole, because local changes at the offtake also depend on regional changes at both the parent river and the distributary channel (Kleinhans et al., 2008). For this reason, river morphodynamic processes occurring both at reach scale and locally at the bifurcation point are of importance for the present study. The first part of this section is focused on physical processes relevant in large sand-bed rivers in general, starting from the fundamental morphodynamic processes, going into more detail in phenomena occurring at river bends and then presenting some other specific processes. A second part is then focused on specific processes occurring at bifurcations and offtakes.

### 2.2.1 Fundamental processes of river morphodynamics

River morphodynamics describes the mutual interaction and adjustment between hydrodynamics, sediment transport and morphology. As stated in many river engineering books (e.g. Jansen et al., 1979; Martín Vide, 2007), the combination of these three fundamental processes govern the general evolution and characteristics of rivers.

#### a) Hydrodynamics

Flow in rivers is driven by gravity—because of a downwards longitudinal bed slope—and resisted by friction with the river bed and banks. It can be generally described with the shallow-water equations, also known as Saint-Venant equations. The numerical model used in this study (described in Chapter 4) solves the two-dimensional form of these equations, which are presented below[1]. Equation 2.1 is the conservation of mass:

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x} hu + \frac{\partial}{\partial y} hv = 0 \tag{2.1}$$

[1]For the full set of three-dimensional shallow water equations, the reader is referred to Jansen et al. (1979).

and Equations 2.2 and 2.3 are the conservation of momentum in $x$- and $y$-direction, respectively:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial z_w}{\partial x} - \nu_H\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + c_f\,\frac{u\sqrt{u^2+v^2}}{h} = 0 \tag{2.2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial z_w}{\partial y} - \nu_H\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + c_f\,\frac{v\sqrt{u^2+v^2}}{h} = 0 \tag{2.3}$$

where $x$ and $y$ are the longitudinal and lateral coordinates (m), $u$ and $v$ are the depth-averaged flow velocities in x- and y-direction (m/s), $t$ is time (s), $z_w$ is water level of the free surface (m), $h$ is water depth (m), $g$ is the acceleration of gravity (m/s$^2$), $\nu_H$ is horizontal eddy viscosity (m$^2$/s) and $c_f$ is a dimensionless resistance coefficient (-).

The shallow water equations are derived from the Reynolds-averaged Navier-Stokes equations by and introducing a number of approximations: considering the fluid (water) incompressible, a hydrostatic pressure distribution and deviations in density being much smaller than the actual density. The shallow water equations are integrated over depth to obtain the 2D shallow water equations. Furthermore, for the equations presented above, external forces such as wind friction, atmospheric pressure gradients or the Coriolis force are neglected, as well as using the Boussinesq eddy viscosity assumption (with the use of a horizontal eddy viscosity coefficient $\nu_H$) to model the effects of turbulence.

### b) Sediment transport

The river bed is composed of loose sediment particles. When flow velocity near the bed exceeds a certain threshold (called the *threshold of motion*) individual sediment particles start to move along the bed. With increasing flow velocities, more particles are set in motion and move at higher speeds. The motion of these particles, known as sediment transport, can be classified by origin and by transport mechanism. Wash load consists of sediment of those sizes that are hardy found at the river bed surface, originating at the catchment area and always transported in suspension—kept in the water column by turbulence. Bed material load does interact with the bed surface sediment and can be transported as suspended load or as bed load—rolling, sliding or jumping along the bed.

### c) Morphology

Sediment entrained from the river bed and deposited at another location produces changes in the bed topography, also known as morphology changes. The fundamental principle behind morphological changes is that a spatial difference (gradient) in sediment transport produces a change in bed level. The Exner equation is widely used to represent this principle. In its one-dimensional form:

$$(1-p)\,\frac{\partial z_b}{\partial t} + \frac{\partial q_s}{\partial x} = 0 \tag{2.4}$$

where $p$ is the porosity of sediment at the bed (-), $z_b$ is the bed level (m) and $q_s$ is the sediment transport per unit width ($m^2/s$). From Equation 2.4 it can be seen that a negative gradient in sediment transport $\left(\frac{\partial Q_s}{\partial x} < 0\right)$leads to aggradation and an increase in bed level $\left(\frac{\partial z_b}{\partial t} > 0\right)$, and a positive gradient $\left(\frac{\partial Q_s}{\partial x} > 0\right)$ leads to degradation of the bed $\left(\frac{\partial z_b}{\partial t} < 0\right)$.

### 2.2.2 River bends

Flow in river bends has a three-dimensional nature with important effects for morphodynamics. This three-dimensional flow structure is known as helical flow. It influences sediment transport and is responsible for the characteristic cross-sectional profile of river bends: shallow inner bends and deeper outer bends. It is also the driver behind the processes of bank erosion and accretion, which combined produce the phenomenon of channel migration.

#### a) Helical flow

Helical flow in river bends is produced by the interaction between the centrifugal force due to the curvature of the channel, the vertical distribution of flow velocities and the transverse pressure gradients caused by the inclination of the free water surface (Rozovskii, 1957). A simplified way of describing helical flow is by assuming an infinitely long bend with constant curvature, slope and cross-section—known as the axisymmetric case—in which the flow is said to be fully-developed. The centrifugal force ($F_c$) is proportional to the flow velocity ($u$) and curvature of the bend (expressed as the inverse of the bend radius $R$):

$$F_c \propto \frac{u^2}{R} \tag{2.5}$$

and pushes the water towards the outer bend, creating a transverse water level slope (with higher water levels at the outer bend and lower water levels at the inner bend). This produces a transverse hydrostatic pressure gradient with a resulting force towards the inner bend, which is constant over depth. The centrifugal force is stronger at the water surface—with faster flow velocities—than near the bed—with slower velocities. The combination of centrifugal force and pressure head produces a circulation current directed towards the outer bend at the water surface and towards the inner bend near the bottom. This current, combined with the longitudinal flow produces the helical flow characteristic of river bends (Figure 2.3a).

Natural rivers are characterised by irregular channel geometries and a succession of bends. In these cases helical flow cannot fully develop and instead one can speak of an intensity of helical flow, which adapts to the changing channel geometry. Typically, helical flow in natural rivers is several orders of magnitude lower than the main flow (Jansen et al., 1979), and is therefore not taken into account for hydrodynamic calculations. However, helical flow does have important consequences for sediment transport and morphology: the shear stress near the bed ($\tau_b$) responsible for bed load transport will have a direction slightly different than that of the depth averaged velocity (Figure 2.3b), also changing the direction of bed-load sediment transport. Concentration of suspended sediment is higher near the bed and therefore helical flow will also change the direction of suspended sediment transport with respect to the depth averaged velocity direction.

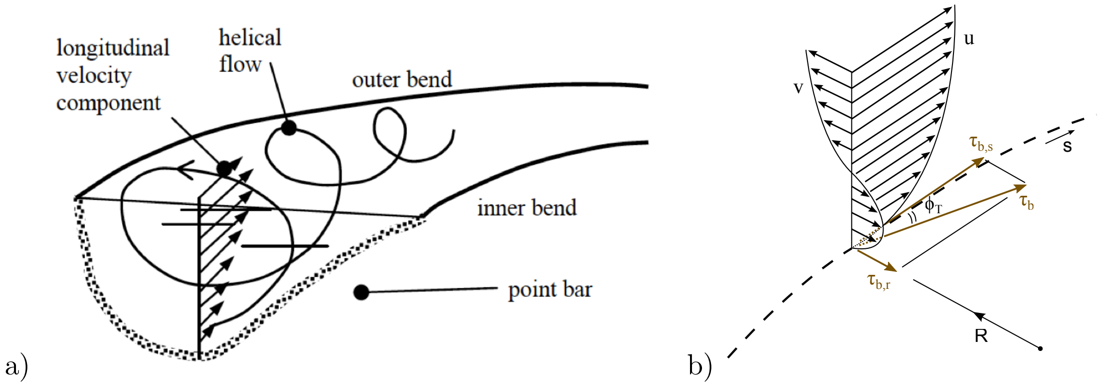


**Figure 2.3:** a)Representation of helical flow along a river bend. From Crosato (2008). b) Vertical distribution of the longitudinal flow velocity ($u$) and transversal, secondary flow ($v$) over depth. Shear stress at the bed ($\tau_b$) is deviated an angle $\phi_T$ from the depth averaged velocity. Adapted from van der Mark and Mosselman (2013).

### b) Transverse bed slopes

The deflection of sediment transport due to helical flow described above produces a transverse bed slope with relatively deeper outer bends and relatively shallow inner bends, creating the characteristic cross-sectional profile of river meanders (see Figure 2.3a). The opposing force to the formation of this transverse slope is gravity. Apart from helical flow, sediment transport along transverse slopes is also deflected by gravity, as illustrated in Figure 2.4. The effect of transverse slopes on sediment transport was first incorporated into morphological models by van Bendegom (1947). Both helical flow and the effect of transverse bed slopes need to be considered in order to adjust the direction of sediment transport, which is of major importance for the morphological modelling of river bends (Olesen, 1987).

### c) Bank erosion

Another important aspect of non-straight flow in rivers is bank erosion. Helical flow itself does not produce bank erosion, but the lowering of the bed near the outer bank induced by helical flow increases the loads on the banks (Simon et al., 2000) that can then fail according to soil mechanics' mechanisms. Another important mechanism for bank erosion as mentioned by Simon et al. (2000) is the formation of positive pore-water pressures when water levels drop down after storms that reduce bank stability.

Bank erosion is a major concern for the rivers in Bangladesh, as the bank materials are generally recent alluvial deposits that are easily eroded during high water flows (BanDuDeltAS, 2015).

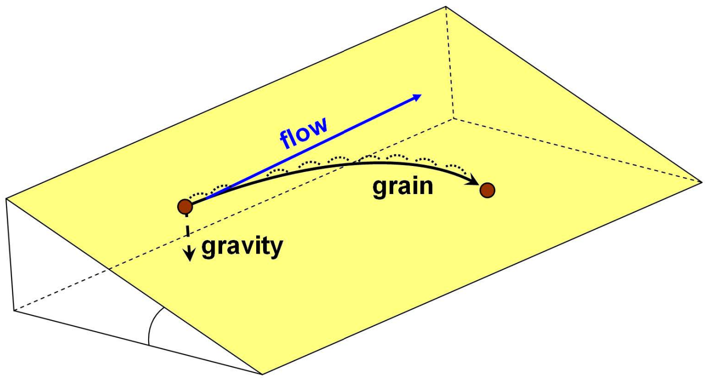


**Figure 2.4:** Transverse bed slope effect: steering of sediment to downslope by gravity. From Schuurman (2015).

### 2.2.3 Other morphodynamic processes

#### a) Bedforms

Sediment transport can lead to the formation of bedforms, which are of major importance in river engineering as they affect the bed roughness, thus the water level for a given discharge. Different types of bedforms have been identified depending on the flow and sediment transport conditions: ripples, dunes and antidunes form at increasing flow velocities and propagate along the river at different speeds. More details on bedform characteristics and behaviour can be found e.g. in Jansen et al. (1979).

Delft Hydraulics and DHI (1996b) analysed the bedforms present in the rivers of Bangladesh, concluding that dunes (with an average amplitude of 15 cm and a length of 4 m) are the dominant bedform in most active channels, being also the dominant mode of bed-load sediment transport.

#### b) Sediment sorting

Sediment transported by rivers is never of a uniform grain size, and because larger grains are less mobile than fines, spatial variation in grain size distribution can occur at the river bed. This adds more complexity to the sediment transport processes as different particle sizes need to be treated separately, but they also interact with each other (Blom, 2014). Sediment sorting processes include bed armouring (when the top layer of the bed contains coarser material than the layers below), downstream fining over an entire reach, changes in bedform formation or lateral sorting at river bends.

An indicator used to assess the relevance of sediment sorting processes is the geometric standard deviation ($\sigma_g$) of the grain size distribution. For the rivers in Bangladesh, $\sigma_g$ is between 1.4 and 1.6 (see Table 2.3) and the bed material can be considered well sorted (narrow range in grain sizes) (Delft Hydraulics and DHI, 1996b), with sediment sorting mechanisms being of marginal importance. For this study it has been decided to not take sediment sorting into account based on the recommendations from the Delft Hydraulics and DHI (1996a) studies.

### c) Retarded scour

Erosion processes observed during a flood event generally obey the following principle, as described by Z. Y. Wang (1999) and Mosselman and Verheij (2000): during the water rising period, the flow lines converge under the flood front (see Figure 2.5) increasing flow velocities and sediment transport capacity in downstream direction. According to the Exner principle (Equation 2.4) this causes bed degradation as $\frac{\partial Q_s}{\partial x} > 0$. The opposite behaviour occurs after the flood peak, with decreasing flow velocities in downstream direction causing bed aggradation.

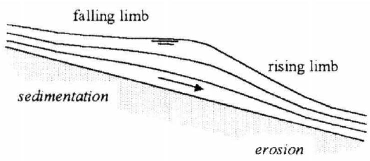


**Figure 2.5:** Erosion and sedimentation processes produced by a flood wave. From Mosselman and Verheij (2000)

However, in wide rivers or with the presence of meanders, where 2D effects become relevant, there are cases where this erosion behaviour is reversed and erosion occurs during the recession period (Mosselman and Verheij, 2000). This reversed behaviour is called retarded scour and can be observed at locations where flow is concentrated during the recession period. This behaviour can be observed at the transition between two consecutive bends, the so-called bend crossings. During high discharges, point bars and deep pools are generated in river bends. With lower discharges, the dry-season channel flows along the deeper parts of each cross-section (see top half of Figure 2.6). As can be seen from the longitudinal profile along the dry-season channel in Figure 2.6, at the location of the bend crossing (around section B-B) bed levels are higher than at the pools (around sections A-A and C-C). The reduction in conveyance area ($A_c$) at the bend crossing can cause an increase in flow velocities sufficient to erode the bed.

## 2.2.4 Bifurcations and offtakes

At a bifurcation both discharge and sediment are divided over the two branches. The discharge distribution is governed by the conveyance capacity and hydraulic gradient at the bifurcates with the condition that water levels at the bifurcation point must be the same (Jansen et al., 1979; Kleinhans et al., 2008). However, the division of sediment depends on the details of local conditions at the bifurcation point. In 1D computations, an empirical nodal point relation needs to be used to determine how sediment splits between the two branches Z. Wang et al. (1995). In principle, 2D (and 3D) models are capable of calculating this division of sediment transport (van der Mark and Mosselman, 2013) without the need of a nodal point relation. But even in 2D and 3D models, a number of singular physical processes need to be taken into account at bifurcations for its effects on the distribution of water and sediment between the two branches. These processes are described in the following paragraphs.

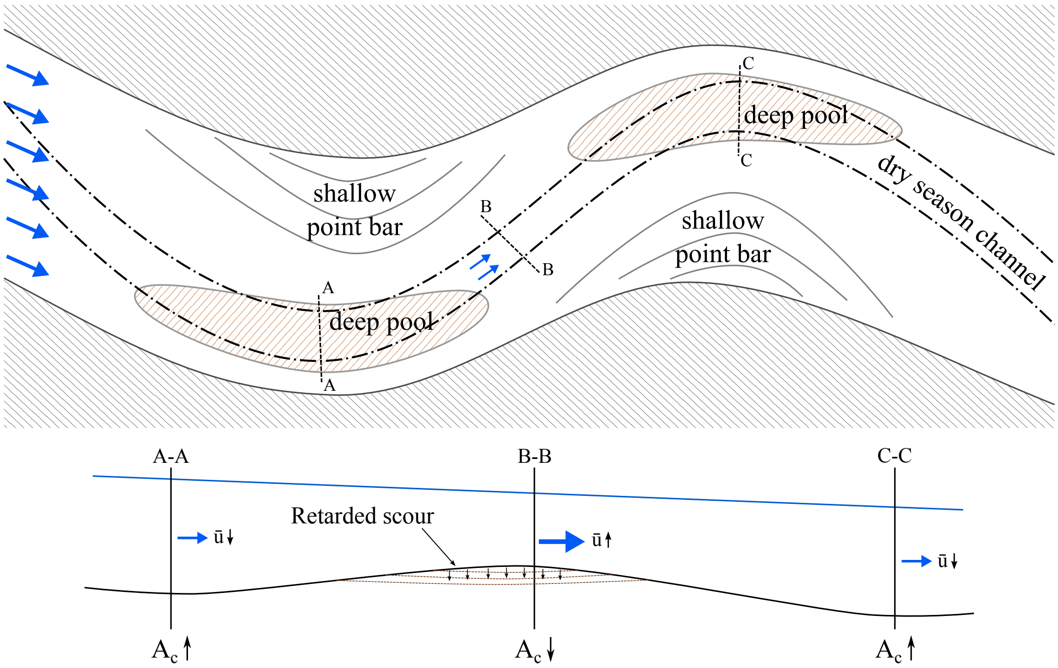


**Figure 2.6:** Retarded scour at bend crossings. Above: top view of the meandering river showing the characteristic point bars and pools. Below: longitudinal profile along dry-season channel.

### a) Bulle effect

In a laboratory experiment, Bulle (1926) investigated the sediment transport division at a bifurcation between a straight channel and a lateral offtaking channel at different angles, with the same discharge flowing into both branches. Under these conditions it was found that more sediment was diverted into the lateral channel than continued in the straight channel. This phenomenon is often referred to as the *Bulle effect* and has been corroborated later on by multiple studies (e.g. Riad, 1961 or Dutta et al., 2016).

This phenomenon is due to the curvature of the streamlines at the bifurcation, which induce a helical flow analogous to river bends (see Section 2.2.2). This helical motion directs near-bed flow—responsible for sediment transport—towards the offtaking channel, as illustrated in Figure 2.7. The consequence of this is that sediment transport into the offtake is larger than would be expected on the basis of simple depth-averaged considerations.

The intensity of the Bulle effect increases for large bifurcation angles, as the curvature of the streamlines increases; and for low width-to-depth ratios. It also depends on the local geometry of the dividing point and the discharge distribution between the two branches.

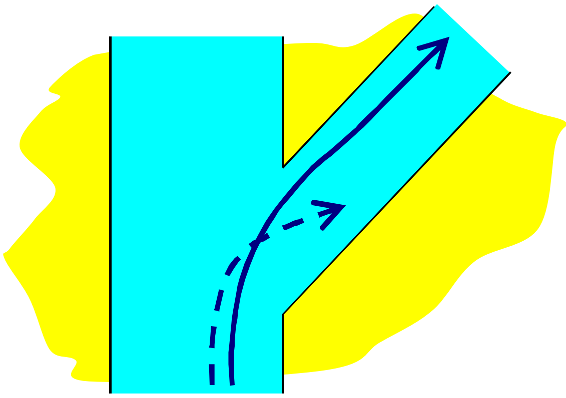

**Figure 2.7:** Illustration of the Bulle effect at a river bifurcation. The solid arrow represents the direction of surface flow while the dashed arrow represents near-bed flow. From Mosselman (2014).

### b) Flow separation

From his experiments, Bulle (1926) also describes the phenomenon of flow separation at the entrance of an offtake. Flow separation occurs at sharp edges, where flow can no longer follow the banks. In that situation, there is a region behind the sharp edge where flow velocities are smaller than the main flow. This difference in velocity creates a turbulent mixing layer that extends downstream of the sharp edge. In the case of an offtake, this sharp edge is located at the start of the bifurcation if the offtake angle is too large (see Figure 2.8). Further downstream in the offtaking channel there is a reattachment point, where the flow is again connected with the bank. An eddy is formed between the sharp edge and the reattachment point. Because of the circulation inside this eddy, sediment near the bed moves towards the centre of the eddy (a visual analogy can be found when steering a cup of tea: the tea leaves concentrate in the centre of the cup). At the boundary of the eddy there is some exchange with the main flow due to turbulence. As this happens, sediment particles near the bed that enter the eddy are trapped in its centre, while flow escaping the eddy at the water surface is relatively clear. With the mechanism described here, the formation of this eddy at the entrance of the offtake steers sediment transport into the bifurcated channel.

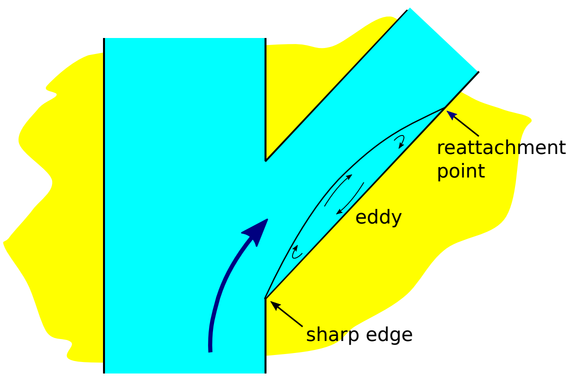


**Figure 2.8:** Illustration of flow separation at a river bifurcation.

### c) Transverse bed slope advantage

Local geometry of a bifurcation or offtake does have a large impact on the sediment distribution. The previous sections focussed on planform characteristics, but bed topography can also play an important role. Transverse bed slopes, as described in Section 2.2.2, influence sediment transport direction. The presence of a transverse bed slope upstream of a bifurcation can therefore influence the distribution of sediment between the two downstream branches, favouring the branch located in downslope direction (see Figure 2.9).

This effect was studied by Bolla Pittaluga et al. (2003), who concluded that transverse bed slopes upstream of the bifurcation point up to a distance of 2 to 3 times the channel width will affect the sediment distribution and can be a determining factor for the evolution of bifurcations, specially when sediment transport occurs mainly as bed-load.

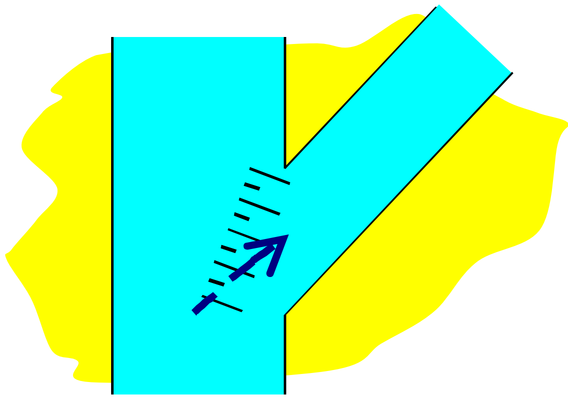

**Figure 2.9:** Illustration of the effect of a transverse bed slope upstream of a bifurcation. The arrow represents the direction of sediment transport (downslope). From Mosselman (2014).

### d) Asymmetrical approach

While the transverse bed slope advantage describes a local effect near the bifurcation point, asymmetrical approach conditions refer to a larger scale upstream of the bifurcation.

Sediment transport at the bifurcation can be altered if bed topography upstream of the bifurcation presents large differences in transverse direction—for example because of the presence of a river bend upstream of the bifurcation. Deeper parts of the channel will concentrate higher flow velocities and sediment transport, which can lead to a larger sediment input into one of the bifurcates on top of the local geometry effects of the bifurcation mentioned in the previous paragraphs (Sloff and Mosselman, 2012).

The presence of a bend upstream of the bifurcation can also produce lateral sediment sorting (bend sorting), where coarser sediment is found at the outer bend due to helical flow. The branch bifurcating from the outer bend will then receive relatively coarser sediment than the branch at the inner bend. An example of these asymmetric conditions including sediment sorting can be found at the *Pannerdense Kop* bifurcation of the Rhine River in The Netherlands, as described by Sloff and Mosselman (2012).

# Chapter 3

# Closure of offtakes

## 3.1 Introduction

The objective of this chapter is to give answers to the 2nd research question (in Section 3.2):

> *What are the main causes and drivers of offtake closure?*

And to the 3rd research question (in Section 3.3):

> *What remedial measures can be defined to stabilise an offtake?*

The approach used to get more insight on the causes of offtake closure is based on a review of the existing literature—with a focus on specific cases observed in Bangladesh—along with an analysis of existing satellite imagery to verify and illustrate the different mechanisms.

Based on the findings of this first part, and on the physical processes involved, a number of possible remedial measures is proposed as solutions linked to specific causes and drivers.

## 3.2 Causes of offtake closure

During the monsoon season, when sediment transport is larger and the rivers are more dynamic, the river bed morphology experiences the most significant changes—especially the large rivers. In some cases these changes produce a more favourable configuration for an offtaking distributary, but they can also lead to an unfavourable layout that reduces the conveyance capacity of the distributary, increasing the probability of closure. The objective of this section is to identify which factors contribute to the development of favourable and unfavourable conditions for offtakes.

Closure of an offtake occurs when the water levels of the parent river drop below the lowest bed level at the offtake. Basic causes and drivers of this disconnection process are summarised in Table 3.1 and further explained in the following subsections.

**Table 3.1:** Causes of offtake closure and their drivers.

| Cause | Drivers |
|---|---|
| • Water level of the parent river becomes too low during the dry season | • Natural hydrological variability<br>• Operation of hydraulic structures |
| Bed level at the offtake is too high, because... | |
| • Sediment input becomes too large | • Offtake is located at an inner bend<br>• Angle of approach becomes less favourable<br>• Main channel of the parent river moves away from the offtake<br>• Presence of chars (mid-channel bars) in front of the offtake reduces flow velocities |
| • Erosion becomes insufficient | • Recession period after the Monsoon is reduced<br>• Shallow bend crossings at the distributary reduce the hydraulic gradient<br>• Stronger sediment layer limits adaptability of the offtake |

### 3.2.1 Water level of the parent river becomes too low

Seasonal variation of water levels at the major rivers of Bangladesh is significant—of the order of 6 to 8 m on average, see Table 2.2—compared to the flat terrain that characterizes the delta. A consequence of this seasonal variation is that water levels—and thus water depths—are, in general, rather low during the dry season. These low levels are a critical factor against maintenance of flow to the distributary rivers throughout the year.

On top of the seasonal variation there is also a yearly variation in minimum water levels. Yearly variations depend on the available discharge flowing in the rivers, which in turn depends on the changing hydrological conditions at regional and even catchment scales. Historical records (e.g. CEGIS, 2012b; Delft Hydraulics and DHI, 1996a) show these yearly variations of minimum discharges and water levels. However, the analysis performed for the FAP24 project (Delft Hydraulics and DHI, 1996a) showed that in most cases it is not possible to identify a trend directly linking naturally occurring low discharges with offtake closure.

This is not the case for rivers affected by man-made hydraulic structures. A specific example can be found in the Ganges river with the operation of the Farakka barrage (Mirza, 2004). After the construction of the barrage in 1975, water was diverted upstream of Farakka into the Hoogly river during the dry season, with a 40 % reduction of the minimum mean monthly discharge (from 2000 $m^3/s$ to just 1200 $m^3/s$) and minimum mean monthly water levels decreased around 1 m (from 7 to 6 m PWD). The situation got even worse between 1988 and 1996, when the agreement between India and Bangladesh was broken and more water was diverted to the Hoogly, reducing minimum mean monthly flows to only 550 $m^3/s$ and minimum water levels to 5.2 m PWD (CEGIS, 2012b). During this period, flow in the Gorai River was discontinued each dry season for more than 100 days. From 1997 to the present, with a new treaty, minimum discharges increased to 935 $m^3/s$, still 50 % lower than before the construction of the barrage. Between 1998 and 2004, dry-season flow was maintained in the Gorai River through intense dredging for the Gorai River Restoration Project (GRC, 2002; CEGIS, 2012a) but since then this offtake has been closing again each year. Even though the effects of the Farakka barrage on water levels only affect the Gorai offtake, this is an issue of major concern in Bangladesh as there are ongoing studies to apply similar measures to the Brahmaputra river in the future (Misra et al., 2007; NWDA, 2014).

From the literature consulted, it seems that large difference in water levels between peak flow and base flow do not directly lead to the closure of an offtake, while accretion at the offtake and distributary river play a more important role (as will be described in the following sections). However, keeping the water levels—artificially—high enough during the dry season could help prevent offtake closure, as will be investigated in Section 3.3.

### 3.2.2 Sediment input into the offtake becomes too large

As seen in Section 2.2.4, specific geometric configurations and flow characteristics can cause an increase of sediment transport into the offtake and distributary river. If this additional sediment input exceeds the sediment transport capacity of the flow it will be deposited at the river bed producing accretion, reducing the conveyance capacity of the offtake and eventually leading to a flow discontinuation. The most important configurations and flow characteristics that can be responsible for an increase in sediment load are presented below:

#### a) Offtake located at an inner bend

For a distributary river offtaking from a larger parent river the difference between the location of the offtake at the inner or outer bend becomes of major relevance. Because of the difference in magnitude between parent and distributary rivers, morphology near the offtake will be largely dominated by the direction and magnitude of sediment transport at the parent river. Development of point bars at inner bends of the parent river will increase the input of sediment into inner-bend distributaries.

Generally, offtakes located at an inner bend are not stable and will tend to silt up. For this reason, inner bend offtake configurations are difficult to find in nature. However, because of the braided and meandering nature of the large Bangladeshi rivers, the planform around a

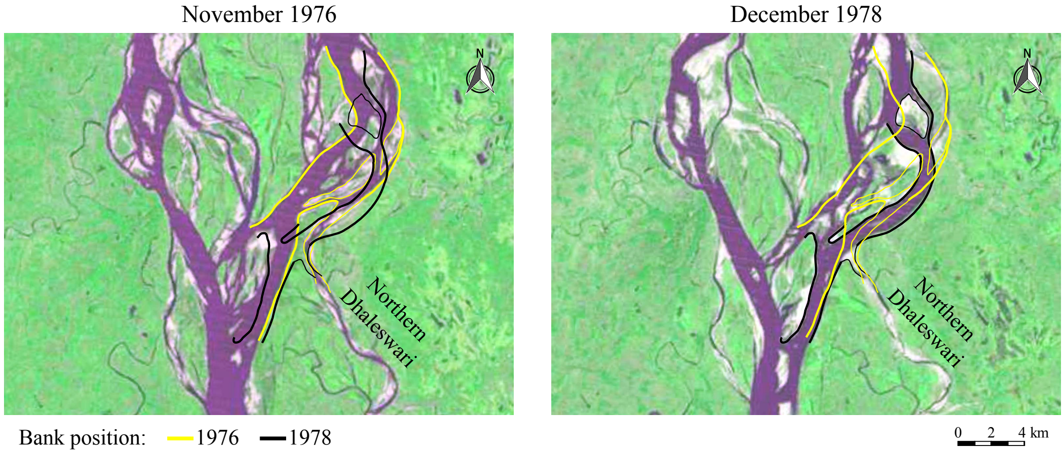


**Figure 3.1:** Transition of the Northern Dhaleswari offtake from an outer bend configuration (left, 1976) to an inner bend configuration (right, 1978) because of planform changes of the Jamuna River. Flow is from top to bottom. Note the decrease in channel width of the Northern Dhaleswari with the new configuration. Imagery source: Landsat (USGS).

stable—outer bend—offtake can change to an inner bend configuration in just a few years. An example of this behaviour is the case of the Northern Dhaleswari offtake between 1976 and 1978, shown in Figure 3.1. In 1976 the Northern Dhaleswari offtake was located at an outer bend of a Jamuna anabranch, but after just 2 years this anabranch moved more than 2 km southwards positioning the offtake at the inner bend. After this change occurred, flow into the distributary was significantly reduced, as can be appreciated in Figure 3.1 by the reduction in channel width of the Northern Dhaleswari in that period.

### b) Angle of approach becomes less favourable

One of the main causes of sedimentation in offtakes—and in general at bifurcations—is an unfavourable angle of one of the branches with respect to the main flow. Klaassen and Masselink (1992) and Klaassen et al. (1993) used the angle between the upstream channel and the downstream bifurcated channels as one of the main variables to predict planform evolution of the braided Jamuna river. They found, from the analysis of satellite images, that an angle lower than 30° had no influence on the probability of channel abandonment; but for larger angles (between 30° and 60°) it was a dominant factor. For angles larger than 60° the probability of abandonment remains at around 40 %. As described in Section 2.2.4, the Bulle effect and flow separation are physical processes dependent on the offtake angle that can increase the sediment load in the distributary channel as the approach angle increases.

There are two mechanisms by which the angle between the main flow of the parent river and the flow at the distributary channel can change. The first one is a change of the planform of the parent river, changing the orientation of the deepest channel (which concentrates the largest flows) with respect to the offtake. A clear example of this situation is the Gorai offtake in the 1970's. In 1973 the main branch of the Ganges was located at the north-east

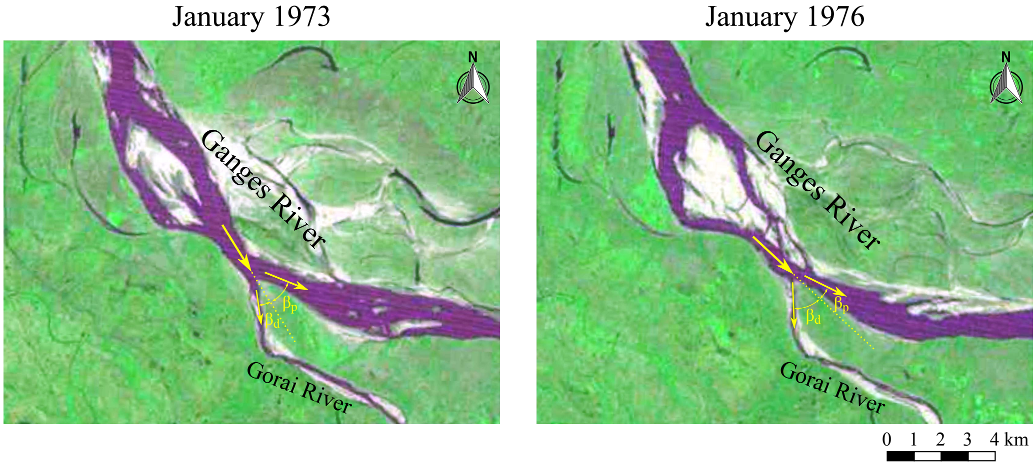


**Figure 3.2:** Transition of the Gorai offtake from a favourable offtake angle configuration (left, 1973) and an unfavourable offtake angle (right, 1976). $\beta_p$ and $\beta_d$ are the angles of the parent branch (Ganges) and distributary branch (Gorai) with respect to the flow upstream of the bifurcation. Flow is from top left to bottom right. Imagery source: Landsat (USGS).

side of the mid-channel bar, upstream of the offtake. This alignment was favourable for the flow diversion into the Gorai as the offtake angle was similar to the parent river bifurcation angle: 24° and 36° respectively (see Figure 3.2 left). However, in the satellite image from 1976 the Ganges main branch switched to the south-west side of the mid-channel bar, increasing the offtake angle, now 45°, and reducing the parent river bifurcation angle to 17° (Figure 3.2 right). This asymmetry steers relatively more flow toward the parent river, but an increased sediment load into the offtake.

The second mechanism that can modify an offtake angle is a planform change of the distributary channel near the offtake, which can lead to a larger angle with respect to the parent river. Examples of such a configuration can be found at the Old Brahmaputra offtake (see Figure 3.3 left) or the Dhaleswari offtake downstream of the Jamuna bridge.

### c) Main channel of the parent river moves away from the offtake

Another driver for excessive sediment load into offtakes comes from the large planform changes that occur in the major rivers of Bangladesh—which have been briefly described in Section 2.1.1. Some of these planform changes are triggered by a general sustained tendency of lateral shifting of the river or by anabranch avulsion, in which case large lateral movements of the channel feeding an offtake can occur. If this movement is in the direction away from the offtake, there will be a sustained increase of sedimentation around the offtake's bank—counteracting the erosion of the bank opposite to it. This process will not only increase the sediment load into the offtake but also increase the distributary channel distance to the parent river.

Some remarcable examples of channels moving away from offtakes can be found in the case of the Old Brahmaputra (Boskalis-GRC, 2000; ISPMC, 2016) and the Arial Khan (ISPMC, 2016) offtakes. Figure 3.3 shows how the main channel of the Jamuna River in

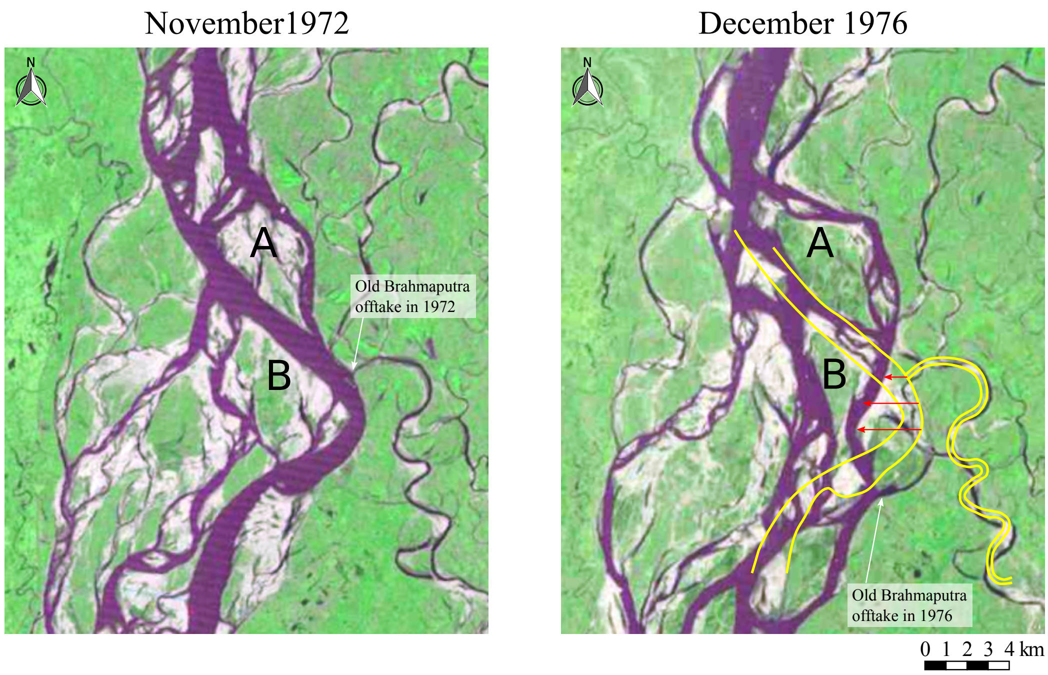


**Figure 3.3:** Example of channel moving away from the offtake location: the Old Brahmaputra offtake between 1972 and 1976. The old offtake was abandoned and a new one was opened naturally at a more favourable location. Bank position of the Jamuna branch in 1972 is shown in yellow. Red arrows indicate movement of west bank and letters A and B identify two mid-channel bars. Imagery source: Landsat (USGS).

1972 was partially abandoned in favour of a channel to the west of the char (mid-channel bar) marked with the letter B. After this, the channel feeding the Old Brahmaputra offtake started shifting westwards (red arrows in the figure) depositing a large quantity of sediment in front of the offtake. Because of this unfavourable condition, a new offtake was developed further downstream, as seen in the satellite image from 1976.

### d) Presence of chars in front of the offtake

Unfavourable conditions for an offtake can also occur with the presence of chars—fluvial islands—in front of the offtake. When these chars grow or migrate too close to the offtake location they can reduce the flow velocities, pushing faster flows away from the offtake bank. The effect of this reduction in flow velocities is an increase of sedimentation near the offtake.

An example of such a situation occurred in 2002 at the Arial Khan offtake (ISPMC, 2016). Despite the movement of the Padma river towards its right bank (where the offtake is located), a series of chars growing in front of the offtake reduced significantly the percentage of flow towards the Arial Khan from the Padma River (see Figure 3.4).

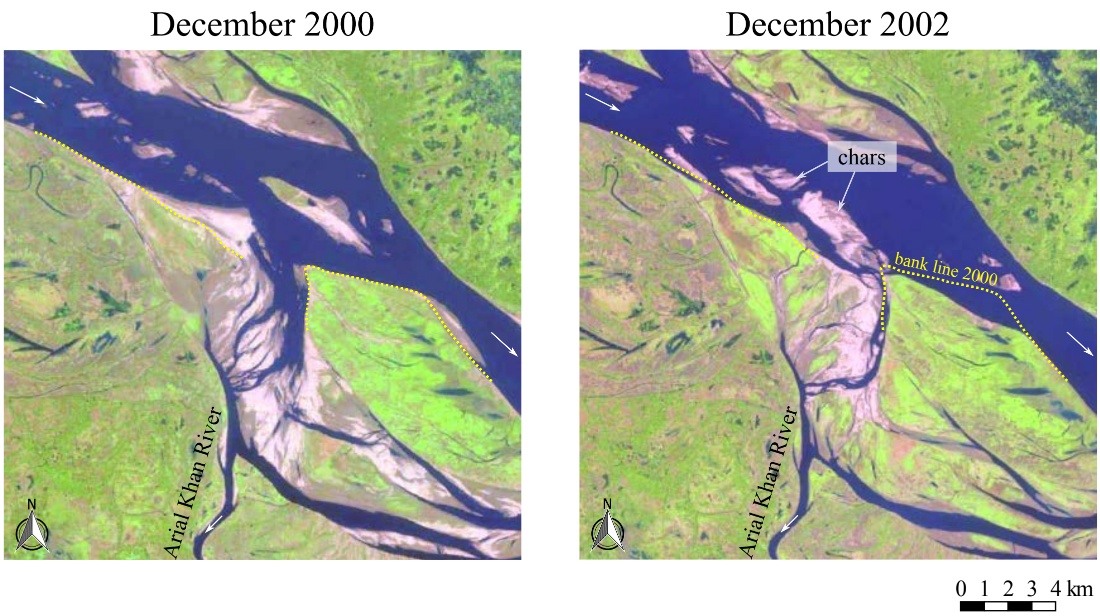


**Figure 3.4:** Example of chars in front of the Arial Khan offtake. Despite the bank erosion occurred at the right bank of the Padma River—see yellow lines for comparison—the chars in front of the offtake reduced the discharge diverted to the distributary river. Imagery source: Landsat (USGS).

### 3.2.3 Erosion at the distributary becomes insufficient

#### a) Reduced duration of recession period after monsoon

Although most morphologic changes in the Bangladeshi rivers occur during peak discharges, the recession period after the monsoon season also plays an important role in the river morphodynamics because of the occurrence of retarded scour—explained in Section 2.2.3.

As the discharge carried by the rivers decreases, water levels also decrease leaving the shallower parts of the river bed dry. Flow is then concentrated in the deeper parts only, reducing the cross-sectional area for conveyance. This can be sufficient to keep velocities high enough to continue eroding the river bed for an extended period of time. Because the erosion capacity of the flow under these conditions is much lower than during peak flows, the amount of time before before velocities get too low is very important, specially at offtakes and distributary rivers. This retarded scour process, if maintained long enough, is able to erode the additional sediment deposited during high discharges—for example under the situations presented in the previous section.

As mentioned in Section 3.2.1, changes to the hydrology of the rivers—including duration of the recession period—occur naturally and are difficult to control. But—as also mentioned before—there is one situation in which the hydrological regime can be altered: with the operation of retention hydraulic structures. The clear example in Bangladesh comes—again—from the operation of the Farakka Barrage in the Ganges river. The FAP24 study (Delft Hydraulics and DHI, 1996a) and later also CEGIS (2012b) point

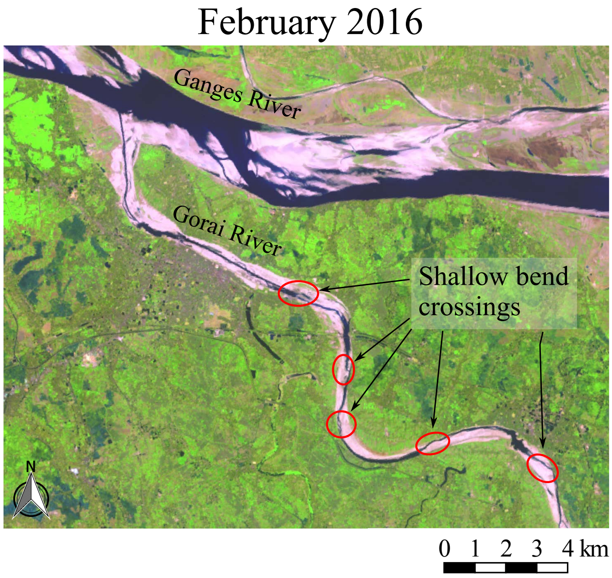


**Figure 3.5:** Example of shallow bend crossings in the Gorai River. Imagery source: Landsat (USGS).

out how the duration of the recession period near the Gorai offtake—calculated as the time required for the water level to lower form 11 m PWD to 7 m PWD in that particular case—was reduced by half: from approximately 5 months before the construction of the barrage to only 2.5 months afterwards.

### b) Shallow bend crossings at distributary river

When analysing offtake closures, it is not only important what happens at the parent river and at the offtake location, but also what happens further downstream in the distributary channel. One important factor that determines the flow velocity—and thus sediment transport capacity—in a channel is its hydraulic gradient—or slope of the water surface. Shallow sections on a channel can reduce this hydraulic gradient and are therefore not desirable if erosion capacity is important. Moreover, these shallow sections can be an important obstacle for flow during low discharge situations. Such shallower sections usually develop at the transition between consecutive bends (bend crossings) or when the channel width is suddenly increased (e.g. downstream of river training structures or bridge abutments).

During the Gorai River Restoration Project (GRC, 2002) the development of shallow bend crossings during the monsoon was identified as one of the causes of this distributary not being able to transport water during low discharges (de Groot and van Groen, 2001). This problem is still visible in recent satellite images (Figure 3.5).

There is also a close relation between the problem with shallow bend crossings and the reduction of retarded scour (Section 3.2.3.a): these shallow sections develop when the rivers are more morphologically active—i.e. during peak flows—and can only be partially eroded during the recession period with the retarded scour mechanism.

#### c) Presence of stronger sediment layer at the offtake

A final driver that can contribute to insufficient erosion capacity is the presence of a stronger sediment bed layer, usually clay, at the offtake location. This layer can appear after an offtake switches location or when the bed levels are lowered. Such a clay layer has been found for example at the bed of the Gorai offtake (CEGIS, 2012b; Hore et al., 2013). As described by Hore et al. (2013), this strong layer cannot be eroded by the flow, restricting the freedom of the offtake to respond to the seasonal variation in flow conditions.

## 3.3 Possible remedial measures

After the most relevant causes of offtake closure have been analysed in the previous section, we now propose possible remedial measures that may help prevent the discontinuation of flow in distributary rivers. This section conceptually describes some possible measures, classified by the causes of offtake closure that motivate them. The list of measures in this section is, naturally, not exhaustive and only pretends to serve as an orientation of the typology of interventions that would be interesting to assess in the context of offtake maintenance. For this reason, only some general characteristics of the measures are described, without going into further design details or considerations.

### 3.3.1 Increase of dry-season water levels

#### a) Barrage in the parent river

A possibility to increase dry-season water levels is the construction of a large barrage across the entire width of the parent river downstream of the offtake location. By regulating the flow through this barrage, it would be possible to accumulate water before the dry season and raise the water levels behind the structure. Due to the very mild bed slopes of the rivers of Bangladesh, backwater effects produced by the barrage would extend far upstream even for a small water level increase, which allows for some flexibility in choosing an appropriate location for such infrastructure.

A barrage with these characteristics does already exist in the Ganges River: the Farakka Barrage—already mentioned in Sections 2.1.1 and 3.2.1—which was precisely build to achieve this effect on the Hoogli River in India (Mirza, 2004). And the Government of Bangladesh is planning to build a Ganges Barrage downstream of the Gorai offtake to increase dry-season water levels at this distributary, for which there are ongoing feasibility studies.

However, changing the flow regime of the untrained rivers in Bangladesh will have a large impact on their morphodynamics both upstream and downstream of the barrage, which can affect other distributary rivers, existing structures and bank erosion processes along the entire river. These impacts were not properly assessed for the Farakka Barrage and are still very difficult to predict with the current advancement of research. Before a new barrage is build, extensive analysis of its impact on the morphological development of the river system is required, which is out of the scope of the present study.

#### b) Erodible submerged weirs

On a much smaller scale, another measure that can increase dry-season water levels at an offtake is the construction of temporal weirs at the parent river, downstream of the offtake location. These temporary weirs should be constructed at the beginning of the dry season and be able to withstand the whole dry season without being eroded. However, in order to not increase maximum water levels and thus flood risk, these structures should also be weak enough to be eroded before the peak flows of the monsoon.

Submerged weirs can be build out of sediment from dredge spoil (earth dams). Since sediment available in Bangladesh is rather fine, a protective layer could be implemented with the use of fascine mattresses together with sand bags or clay bricks (rock is not easily available in Bangladesh).

### 3.3.2 Reduction of sediment input into the offtake

#### a) Offtake regulator

An offtake regulator is a structure similar to the barrage described before, but on a much smaller scale limited to the entrance of a distributary river. The operation of an offtake regulator, by means of gates or other similar systems, allows to regulate the amount of flow into the distributary river, and specially to limit the peak discharges during the monsoon season. The mere presence of this structure, together with the limitation of peak discharges will reduce the sediment input into the distributary channel, which is one of the identified drivers for the closure of offtakes. Regulation of flow throughout the year will also help stabilise the planform of the distributary river downstream.

However, the main difficulty for the design of an offtake regulator is, again, the dynamics of the river system. If the planform of the parent river is not stable enough, and large bank erosion or migrating bars are expected to affect the offtake area, a hard structure like an offtake regulator can become useless and an important waste of resources.

#### b) Flow divider

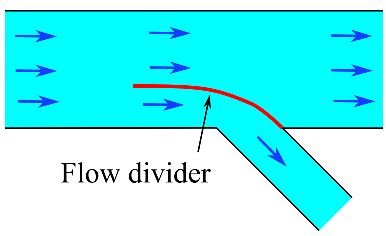


**Figure 3.6:** Schematisation of a flow divider.

The main function of a flow divider is to reduce the bifurcation angle between the parent river and the distributary channel by creating a longer transition between the two. This measure consists of a longitudinal groyne that extends from the bifurcation point upstream in the parent river (see Figure 3.6). By aligning this groyne with the main flow of the parent river it is possible to effectively reduce the offtake angle. This measure was proposed for the Gorai offtake by DHV-Haskoning & Associates (2001) and later on also recommended by CEGIS (2012b).

For a flow divider to function correctly, the alignment of the parent river should be fixed as much as possible. This is because this structure should always be parallel to the flow, and it is not possible to modify it once constructed.

#### c) Major dredging at the parent river

Improvement of the alignment of the parent river is possible by dredging the main channel and placing the dredge spoil in such a way to produce a more favourable orientation with the offtake, i.e. reducing the offtake angle. Given the dimensions of the major rivers of Bangladesh, this measure will always require a large volume of sediment to be displaced. The implementation of this measure is simple, as such projects are common around the world. However, in order to choose the correct alignment, a lot of morphodynamic modelling is required to anticipate the behaviour of the system after this intervention.

#### d) Width reduction of the parent river around the offtake location

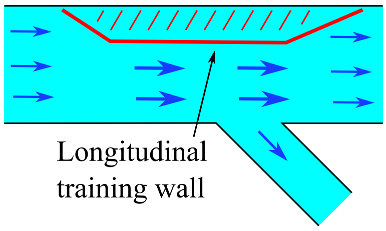


**Figure 3.7:** Schematisation of a longitudinal training wall to reduce the width of the parent river around the offtake location.

A reduction in the width of the parent river around the offtake location may prevent the formation of bars and chars next to the offtake by locally increasing flow velocities and thus sediment transport capacity. This reduction in width can be achieved with the construction of longitudinal training walls (see Figure 3.7) or with land reclamation and bank protection.

Degradation of the river bed is expected to occur around the offtake, as well as planform changes in the river system after this measure is implemented. For this reason, such an intervention needs to be carefully designed to account for these morphological changes.

### 3.3.3 Increase of the erosion capacity at the distributary

#### a) Dredging of the distributary dry-season channel

A direct measure to assure flow in a distributary is dredging its dry-season channel to increase the conveyance capacity and remove shallow bend crossings. This is already a current practice in some distributaries of Bangladesh, including the Gorai (GRC, 2002) and Dhaleswari rivers (IWM, 2015). The dimensions of the distributary rivers, much smaller than their parent rivers, makes this measure more cost-effective than other larger interventions.

Dredging has to be done during the recession period of the monsoon, while water levels are high enough to allow dredging equipment to operate easily and to take advantage of the effects of retarded scour. The drawback of this measure is that it does not contribute directly to the stabilisation of the offtake in the long term. Dredging of the distributary channel needs to be performed recurrently, presumably each year.

### b) Dredging of top clay layers

If clay layers were present at the offtake, dredging of these top layers would give the river system more flexibility to adapt to flow variability. This would be a one-time measure, as the situation would not revert. Only some distributaries present these clay layers, and this remedial measure would not be extensible to the others.

# Chapter 4

# Modelling of the no-intervention scenario

## 4.1 Introduction

Here we will focus on answering the 4th research question:

> *What is a suitable tool and approach to assess the effects of remedial measures for offtake stabilisation, given the dynamics of the system and the scarcity of available data?*

A first step towards assessing the effects of engineering interventions in a river is to reproduce, to the extent possible, the behaviour of the system in its current state—without implementing any measure. This chapter is dedicated to develop such a model and to check how well it reproduces the behaviour and characteristics of the rivers in Bangladesh.

First, the choice for a specific (numerical) model is justified in Section 4.2.1. The most important aspects of the model setup are then presented in Section 4.2.2 to 4.2.5. A comparison of the model results with available data is presented in Section 4.3, where we focus on answering the 5th research question:

> *How well is this tool able to reproduce the morphological evolution and offtake closure processes observed in Bangladesh?*

This chapter ends with a discussion of the model results, with special focus on the causes of offtake closure discussed in Section 3.2.

## 4.2 Approach and model setup

### 4.2.1 Choice of model

Physical processes described in Section 2.2 show how three-dimensional effects are of major relevance for the morphodynamic evolution of offtakes. 1D numerical models can incorporate some of these three-dimensional processes in the form of a nodal point relation. 1D models require less computation time than more complex 2D or 3D models, allowing to run more simulations or look at longer-term scenarios. However, nodal point relations in 1D models present a number of problems: 1) they require extensive calibration and validation which, given the available data for the offtakes in Bangladesh described in Section 1.4, would not be feasible in this case; 2) nodal point relations are usually case-specific making results difficult to generalise; 3) they do not provide enough insight into the underlying processes (van der Mark and Mosselman, 2013); and 4) most recent developments in nodal point relations still do not perform well for wide and shallow rivers (Kleinhans et al., 2008). Given the above problems, the use of a 1D model is discarded for this study.

On the other end, 3D numerical models are able to compute explicitly three-dimensional processes such as helical flow or transport of sediment in suspension. However, they are computationally very demanding, specially with morphodynamic models, as a new computation of the flow field is required after each time step of bed changes (Sloff and Mosselman, 2012). 2D (depth averaged) models—also referred as 2DH models—incorporate some of these three-dimensional processes in a parametrised form, and provide a trade-off between 1D and 3D models. Also, as discussed by Sloff and Mosselman (2012), the use of a 3D model, given the large uncertainties in sediment transport predictors and the effect of transverse bed slopes on sediment transport, can only provide minor improvements to the simulation of river bifurcations compared to a 2D model with parametrised 3D processes. Given this fact and the speed up of morphodynamic computations, the use of a 2DH model is selected for the present study and in particular the package Delft3D by Deltares. Delft3D has been applied in a large number of scientific river projects (e.g. Crosato et al., 2012; Schuurman, 2015) as well as in a wide range of river engineering projects, being one of the most used morphodynamic numerical models in the industry. Delft3D has also been validated with a large set of flume experiments and well-documented cases (Mosselman, 2004).

There are several examples of the use of 2DH models to study of bifurcation and offtake development, including the Pannerdense Kop in The Netherlands (Struiksma, 1998; Sloff and Mosselman, 2012) and some examples in Bangladesh for the Gorai (Delft Hydraulics and DHI, 1996c), Dhaleswari (IWM, 2015) and Old Brahmaputra (Noor, 2013) offtakes. In all those cases, models were calibrated and validated with data from field surveys, which—in principle—increases their prediction capabilities by confirming consistency with present and past observations (Oreskes et al., 1994). However, the dynamic nature of large deltaic rivers limit the applicability of those models in practice to specific locations and time frames.

As stated before, a proper calibration and validation of a numeric model is not possible for the present study. To overcome the lack of available data on the evolution of bed topography, it is decided to use a simplified geometry for the development of the numerical model. This geometry is based on the observed characteristics of the offtake locations of interest in Bangladesh described in Section 2.1 and will be described in Section 4.2.2. The approach is then to start with a flat bed and use the morphodynamic module of the numerical model to obtain the bed topography.

### 4.2.2 General setup

The model's simplified geometry is loosely based on the Ganges River and Gorai offtake. This selection has been made because of the relevance of the Gorai offtake for the south-western region of Bangladesh (summarised in Section 1.2) and because of the availability of more data on this location from previous projects (CEGIS, 2012b; Delft Hydraulics and DHI, 1996c; DHV-Haskoning & Associates, 2001; GRC, 2002). This allows to compare the results of the present study with observations from those projects.

The basic geometric characteristics needed for the model are the bank-full width of the parent river and distributary channel, bend radius of the parent river and development angle of the bends. These characteristics are roughly estimated from satellite images of the Gorai offtake during the monsoon season (Figure 4.2). The values used are 2000 m and 400 m for the channel widths of the parent and distributary rivers and 60° bends of 14.0 km radius. Initial simulations with a single bend and a total length of 30 km show that this domain is too short, as boundary conditions affect significantly the location of the offtake. It is then decided to extend the parent river using three consecutive bends with a total length of 100 km along the centreline of the channel.

The offtake is located at the outer bend with an offtake angle of 60°. This is selected based on the findings from Section 3.2.2.b, which corresponds to a favourable position along a bend with an unfavourable angle configuration and is also close to the present conditions of the Gorai offtake with the Ganges River. The distributary river is defined as a straight channel, with a length of 20 km to also reduce the influence of the downstream boundary condition at the bifurcation region. The decision for a straight channel is justified considering the overall reduction of complexity of the model and because, based on the findings in Section 3.2, the position of the offtake along a bend of the parent river is considered as much more important (see Section 3.2.2.a in particular) than the planform of the distributary river downstream of the offtake. A scheme with the layout and dimensions for the numeric model can be found in Figure 4.1. A comparison of this geometry with the Ganges and Gorai rivers can be seen in Figure 4.2, which clearly shows how the model is only representing the most general characteristics of the river system.

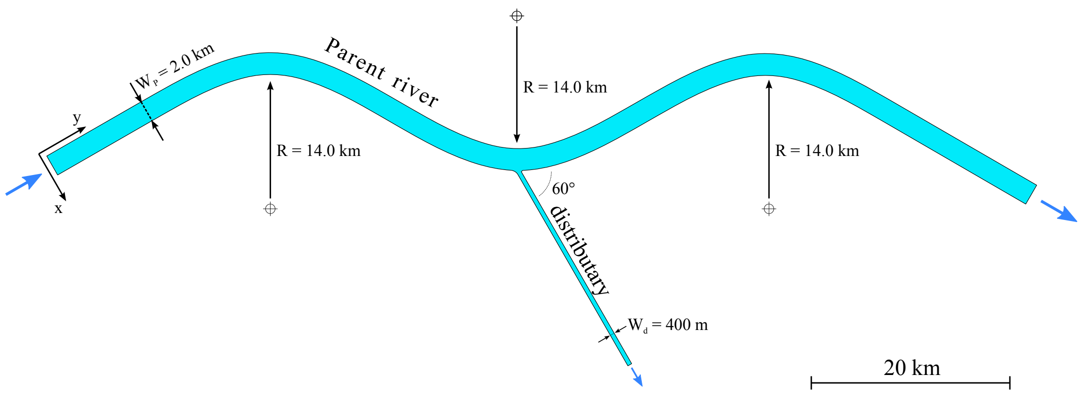


**Figure 4.1:** Main geometric dimensions of the numerical model.

In order to reduce the computational time required for the simulations, a morphology ac-

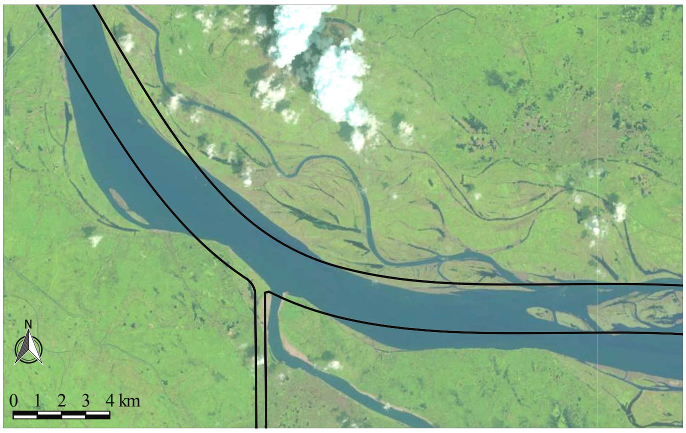


**Figure 4.2:** Overlay of the model geometry (black lines) with the real geometry of the Gorai offtake from satellite imagery showing bank-full conditions. Flow is from top left to bottom right. Satellite imagery from Landsat (USGS) acquired on 29th of September, 2014.

**Table 4.1:** Characteristics of the two phases of numerical simulation used in this study.

| Concept | Phase 1 | Phase 2 |
|---|---|---|
| Model geometry | only parent river | parent river + distributary |
| Inflow boundary conditions | constant discharge $Q = 20000\,\mathrm{m}^3/\mathrm{s}$ | variable discharge |
| Morphological acceleration factor ($MF$) | 5 | 2 |
| Computational time step ($\Delta t$) | 2 min. | 1 min. |
| Total (morphological) simulation time | 4 years | 6 years |

celeration factor ($MF$) is used. Morphological changes occur at a time-scale much longer than typical flow variations and for this reason an acceleration factor that speeds up bed level changes can bring both processes to a closer time-scale, reducing the computation time required for a specific morphological simulation. However, the use of a high $MF$ can decrease the accuracy of the model and amplify numerical instabilities. After a number of test simulations with different morphology acceleration factors, it is decided to split the simulation into two different phases in order to further reduce computation times. A first spin-up phase starts with the flat bed, only considers the parent river and is run with a constant discharge. These simplifications allow for the use of a $MF = 5$ to speed up the formation of an initial bed topography. The resulting bed topography from this 1st phase is used as starting conditions for the 2nd phase, which then incorporates the distributary channel, a variable discharge hydrograph and is run with a lower morphological acceleration factor of $MF = 2$. Table 4.1 summarises the main differences between the two phases.

### 4.2.3 Grid generation

A structured curvilinear grid is used for the model, which is generated from the geometry described in the previous sub-section and in Figure 4.1. A different grid is generated for each phase of the simulation, with the first grid only containing the parent river and the second one, more complex, including the offtake and distributary river.

For the 1st phase, the grid dimensions are M×N = 20 × 400 cells (8000 grid cells in total), where M and N are the directions across and along the channel respectively. The average width of the grid cells ($\Delta m$) is 100 m and the average length ($\Delta n$) is 250 m (with a maximum of 273 m at the outer bends and a minimum of 223 m at the inner bends). The difference between width and length of the grid cells (aspect ratio) is justified because flow in the model is predominantly in the longitudinal direction.

For the 2nd phase, the distributary branch is incorporated and a new grid is generated. This grid has to be split at the offtake location between the two downstream branches.The resolution of the downstream branch of the parent river is kept the same as the grid of the 1st phase (20 grid cells in cross-channel direction), while the distributary branch contains 10 grid cells in the cross-channel direction. An additional 2 grid cells are not active at the bifurcation point because of the grid definition[1]. Adding up these numbers, the parent river upstream of the offtake needs to be 32 grid cells wide. Figure 4.3 shows a detail of the computational grid around the offtake location. The total dimensions of the grid are: M×N = 32 × 310 cells for the parent river upstream of the bifurcation, M×N = 20 × 225 cells downstream and M×N = 10 × 225 cells for the distributary channel. This makes a total of 16 670 grid cells, which is slightly more than twice as much as for the grid of the 1st phase—and justifies in part the choice for a simplified 1st phase of the simulation to reduce the computational times required.

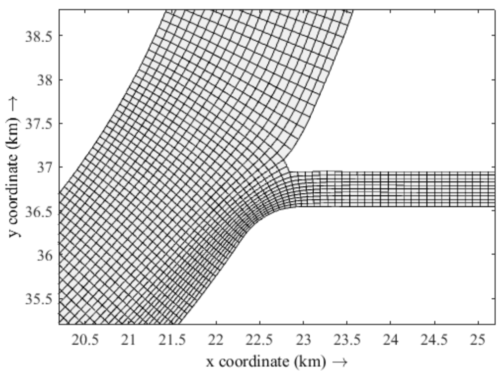


**Figure 4.3:** Detail of the computational grid around the offtake.

The transition between the grids for the three branches is progressive, as can be seen in Figure 4.3, in order to fulfil the requirements of orthogonality and smoothness for stability and accuracy of the model.

[1]Related to the use of a staggered grid by Delft3D in the numerical scheme to solve the shallow water equations, in which boundary conditions are defined on an additional cell outside the defined grid (Deltares, 2014).

### 4.2.4 Boundary conditions

The inflow boundary condition for the model consists of a discharge time series (hydrograph) that repeats for each year. The hydrograph used in the model is obtained from an average of the time series for the Ganges River at the Hardinge Bridge gauging station maintained by BWDB. Figure 4.4 shows the discharges used in the model (black line) compared to the measured discharges at the Hardinge Bridge between the years 1980 and 2006 (colour lines).

For the outflow boundary conditions, a stage-discharge curve is applied at both the parent river and the distributary. The stage discharge curve for the parent river is obtained from the same dataset at the Hardinge Bridge from BWDB, and presented in Figure 4.5. In order to use this curve without corrections for the elevation, the initial bed level at the downstream end of the parent river is defined as +4 m, to match the average bed level at the Hardinge Bridge, located at +4 m PWD. This also defines the reference level for the model.

The stage discharge for the distributary river is obtained from GRC (2002) at the Gorai offtake and adapted vertically according to the length and slopes of the parent and distributary rivers in the model.

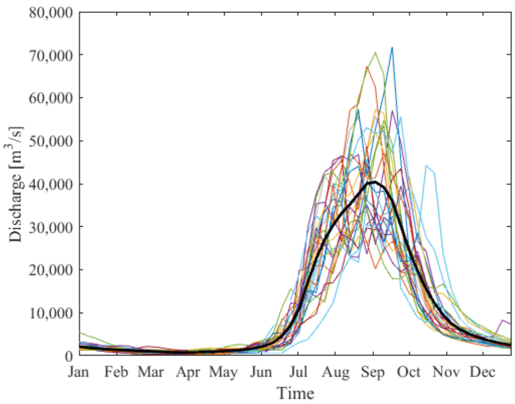


**Figure 4.4:** Colour lines: discharge time series from BWDB at the Ganges River (Hardinge Bridge) between 1980 and 2006. Thick black line: average weekly discharge used as upstream flow boundary condition in the numerical model.

Because there is no data is available on the instantaneous sediment transport, a simplified boundary condition for sediment and morphology is applied at the inflow boundary with the assumption of a fixed bed level and sediment inflow equal to the sediment transport capacity of the flow.

### 4.2.5 Physical processes included in the model

#### a) Sediment transport

The sediment transport formula of van Rijn (1993) was used for the initial test simulations. This formula distinguishes between bed-load transport and suspended load transport. However, after some years of simulation the model develops very deep channels

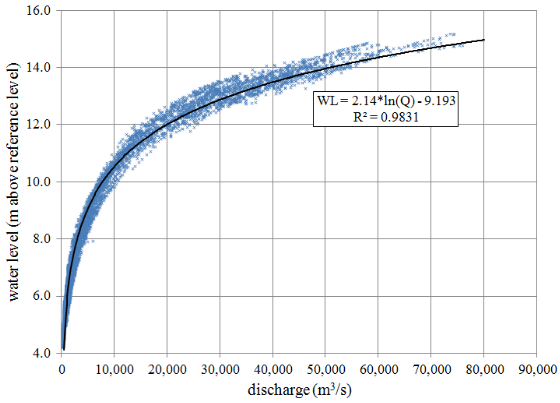


**Figure 4.5:** Stage-discharge curve computed from the discharge and water level data from BWDB at the Ganges River (blue dots).

that concentrate all the flow, leading to unrealistically elongated bars in the model (see Figure 4.6, left). Strange behaviour when using the van Rijn (1993) sediment transport formulation in river bend models has already been documented (e.g. Melman (2011)). Arailopoulos (2014) attributed this strange behaviour to the way Delft3D computes suspended sediment transport (and not specifically to the formulation from van Rijn, 1993), in which secondary flow is not taken into account. An alternative is to use a formulation which considers bed-load and suspended load together (in what is called a total sediment transport relation). Using the sediment transport formula of Engelund and Hansen (1967) (which is a total sediment transport relation) significantly improves the stability of the morphological development, as seen in Figure 4.6, right. Consequently, this formulation is used for the simulation in this study.

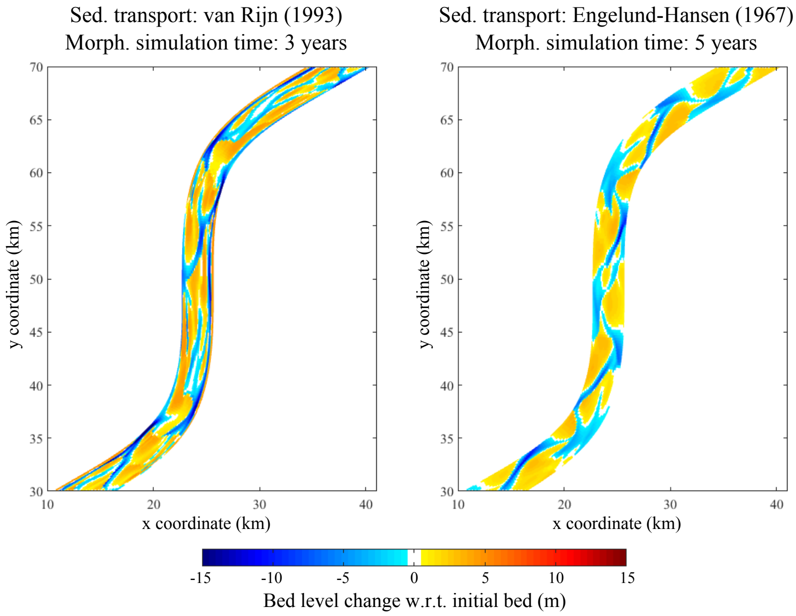


**Figure 4.6:** Comparison of bed level changes using van Rijn (1993) and Engelund-Hansen (1967) sediment transport formulas.

### b) Helical flow

In 2D depth-averaged simulations, Delft3D computes helical flow (see Section 2.2.2.a) assuming its distribution over the vertical to be a universal function multiplied by a helical flow intensity ($I_{hf}$) as described by Kalkwijk and Booij (1986). Apart from the shallow water equations described in Section 2.2.1, an additional advection-diffusion equation is solved to account for the generation and adaptation of the spiral motion intensity (Deltares, 2014). The effect of helical flow to the direction of bed-load sediment transport is taken into account with the angle $\phi_T$ between the depth-averaged flow velocity and sediment transport directions, determined by

$$\tan(\phi_T) = \frac{v - \alpha_I \frac{u}{U} I_{hf}}{u - \alpha_I \frac{v}{U} I_{hf}} \tag{4.1}$$

in which

$$\alpha_I = \frac{2}{\kappa^2} E_s \left(1 - \frac{1}{2} \frac{\sqrt{g}}{\kappa C}\right) \tag{4.2}$$

where $U$ is the magnitude of the depth-averaged velocity (m/s), $\kappa$ is the von Kármán constant (-), $C$ is the Chézy roughness ($m^{0.5}/s$) and $E_s$ is a calibration parameter ranging from 0 (for no effect of helical flow on sediment transport) to 1. $E_s = 1$ is used for the simulations in this study.

### c) Transverse bed-slope effects

Different formulations for the effect of transverse bed slopes on sediment transport (see Section 2.2.2.b) are available within Delft3D. The formulation by Koch and Flokstra (1980) is used for this study, where the direction of bed-load transport is adjusted by the angle $\phi_S$, which already includes the effect of helical flow and is given by

$$\tan(\phi_S) = \frac{\sin(\phi_T) + \frac{1}{f(\theta)} \frac{\partial z_b}{\partial y}}{\cos(\phi_T) + \frac{1}{f(\theta)} \frac{\partial z_b}{\partial x}} \tag{4.3}$$

with

$$f(\theta) = A_{sh} \theta^{B_{sh}} \left(\frac{D_{50}}{h}\right)^{C_{sh}} \tag{4.4}$$

where $A_{sh}$, $B_{sh}$ and $C_{sh}$ are calibration parameters and $\theta$ is the shields parameter given by

$$\theta = \frac{\tau_b}{(\rho_s - \rho_w)\, g\, D_{50}} \tag{4.5}$$

where $\rho_s$ is the density of sediment ($kg/m^3$), $\rho_w$ is the density of water ($kg/m^3$) and $\tau_b$ is the shear stress at the bed.

Values for the calibration parameters in Equation 4.4 where chosen as $A_{sh} = 0.3$, $B_{sh} = 0.5$ and $C_{sh} = 0$ based on the findings of Talmon et al. (1995) and expert opinion.

## 4.3 Comparison of model with the real river systems in Bangladesh

In order to make any prediction with the numerical model, it is indispensable to assess how well it is able to reproduce the behaviour of the rivers for which it has been developed. In this section, the results of the last two years of simulation—which are later on used as base scenarios for the assessment of measures—are compared with the available data to check which physical processes can be reproduced with this modelling strategy and to which extent predictions made based on these results are reliable.

Hydrodynamics:

An important aspect when modelling the development of a bifurcation or offtake is the flow distribution between the two downstream branches. Data on the discharge distribution between the Ganges and Gorai rivers for the last decades is available from CEGIS (2012b), which is compared with the model results. Inflow discharge into the model is based on measured data (see Section 4.2.4). However, discharge into the distributary channel is not imposed beforehand, as the downstream boundary conditions are stage-discharge curves in both cases. Figure 4.7 shows the comparison between the discharge hydrograph for the Gorai River (at the Gorai Railway Bridge) obtained from CEGIS (2012b); and computed by the model for the last 2 years of simulation at the distributary river. Moreover, Figure 4.8 shows the discharge distribution between the parent and distributary rivers for the Ganges – Gorai system and for the model. Both hydrographs and discharge ratios for the model are all within the values measured for the real river system, and therefore the model is able to reproduce a realistic flow distribution.

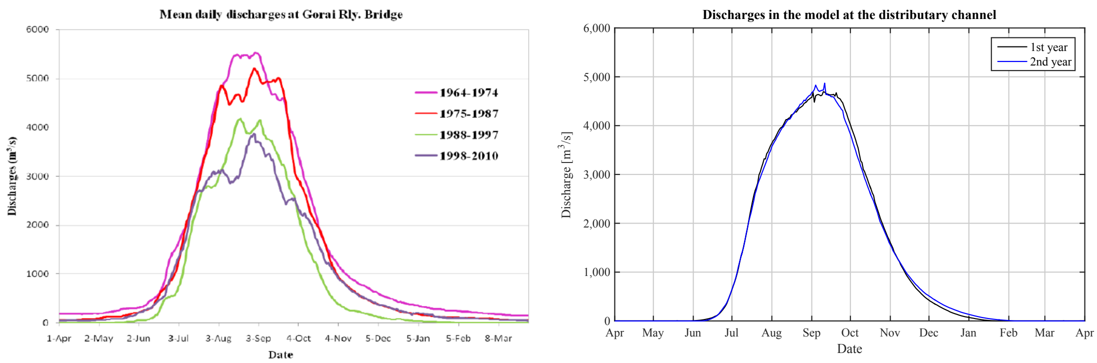


**Figure 4.7:** Discharge hydropgraphs for the Gorai River (left, from CEGIS, 2012b) and the distributary river in the model (right) for the last 2 years of simulation.

CEGIS (2012b) also performed a series of float tracking campaigns around the Gorai offtake to measure flow velocities. These measurements showed flow velocities during the recession period (late October, 2011) between 0.85 and 1.35 m/s at the main channel of the Ganges River and between 0.6 and 1.1 m/s at the entrance of the Gorai. Measurements during the dry season (early January, 2012)—before flow in the Gorai is discontinued—show smaller flow velocities, between 0.65 and 1.15 m/s for the Ganges and 0.15 to 0.65 m/s for the Gorai. Flow velocities observed in the simulations are on the same orders of magnitude as the velocities measured by CEGIS (2012b).

Sediment transport

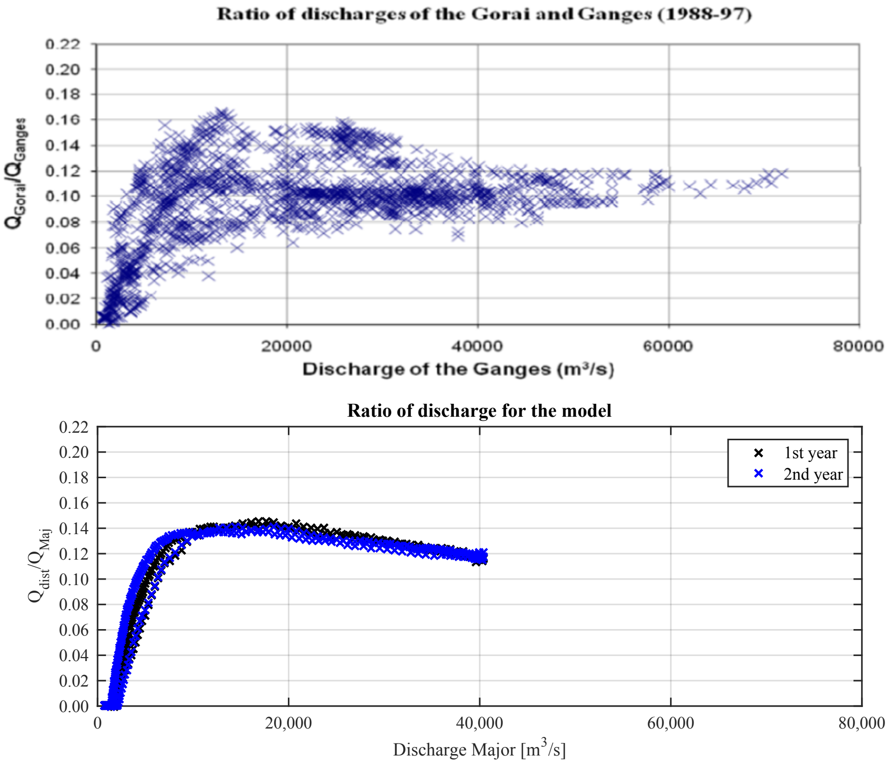


**Figure 4.8:** Discharge distribution ratio between the Gorai and Ganges rivers (top, from CEGIS, 2012b) and between the distributary and parent rivers in the model (bottom) for the last 2 years of simulation.

Only yearly sediment transport rates are available for the rivers of Bangladesh, which have already been summarised in Table 2.3. Yearly bed material sediment transport (excluding wash load) computed by the model for the parent river is around $24 \times 10^6$ T/year, while measurements for the Ganges river are on the order of $76 \times 10^6$ T/year (other sources give values up to $190 \times 10^6$ T/year). The difference in computed sediment transport compared to measurements could be in part caused by the combination of a fixed bed level at the inflow boundary and the assumption of inflow sediment load equal to the transport capacity of the flow.

Morphology

In order to compare the morphological evolution of the model with river data, bar dimensions and migration rates predicted by the model are compared with observations from recent satellite images of the Ganges River. Four images are used, all obtained from the OLI (Operational Land Imager) sensor on board of the Landsat 8 satellite:

- Monsoon 2014, capture day: 29th September 2014
- Dry season 2014, capture day: 5th March 2014
- Dry season 2015, capture day: 8th March 2015
- Dry season 2016, capture day: 10th March 2016

Figure 4.9 shows the location of 4 bars analysed along the Ganges River, together with the delimitation of the bar positions during the 3 consecutive dry seasons. The image from the monsoon season is used to define the position of both banks of the river. Dry-season images have been selected with similar dates so that water levels were approximately the same for each year. Table 4.2a shows the results after the processing of the satellite images. Bar dimensions are given as a non-dimensional width and length, scaled with the bank-full channel width. Bar migration rates are given in km of advancement for the upstream and downstream fronts separately.

To compare the bars visible from satellite images with the model predictions, the water level line at the beginning of March for the 3 simulated dry seasons is used to indicate the position of the bars. Non-dimensional width and length as well as migration rates are obtained for the two bars closer to the offtake in the numerical model (up- and downstream). These bars are selected because they are far from the boundaries, reducing the effects of boundary conditions on morphology development. These results are shown in Table 4.2b. Comparing both bar dimensions and migration rates obtained in the model with the values from satellite images it can be concluded that the model is able to reproduce the behaviour of the migrating bars in the real river system.

**Table 4.2:** Bar dimensions and downstream migration rates.

**a)** From satellite images in Figure 4.9.

| Bar number | Width ratio | Length ratio | Yearly downstream migration [km] | |
|---|---|---|---|---|
| | $W_{bar}/W_{total}$ | $L_{bar}/W_{total}$ | u/s front | d/s front |
| 1 | 0.70 to 0.87 | 1.28 to 1.81 | 0.35 | 1.00 |
| 2 | 0.40 to 0.79 | 1.30 to 2.44 | 1.75 | 1.15 |
| 3 | 0.77 to 0.85 | 2.31 to 3.26 | -0.20 | 0.55 |
| 4 | 0.67 to 0.74 | 2.33 to 2.70 | 0.60 | 0.40 |

**b)** From the numerical model.

| Bar | Width ratio | Length ratio | Yearly downstream migration [km] | |
|---|---|---|---|---|
| | $W_{bar}/W_{total}$ | $L_{bar}/W_{total}$ | u/s front | d/s front |
| upstream | 0.60 to 0.75 | 2.84 to 3.30 | 0.52 | 0.33 |
| downstream | 0.70 to 0.77 | 3.37 to 4.37 | 0.20 | 0.55 |

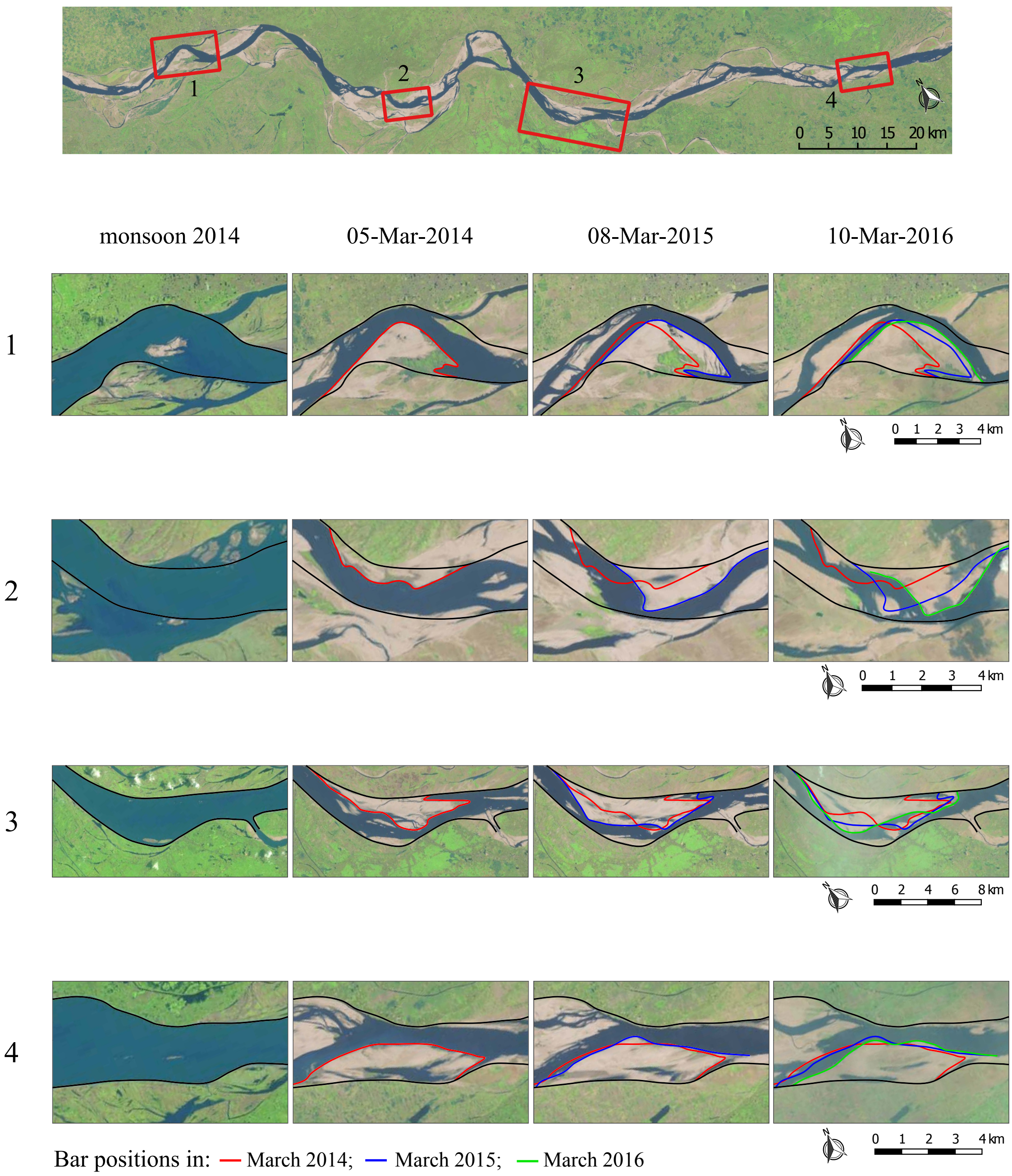


**Figure 4.9:** Estimation of bar dimensions and migration rates from satellite images at the Ganges River. Numeric values obtained from this analysis can be found in Table 4.2. Imagery source: Landsat (USGS)

## 4.4 Discussion of model results: morphologic evolution of the river and offtake closure process

As described in Section 4.2.2, the simulation is divided into two phases. The first phase starts with a flat bed topography with a uniform slope of $5 \times 10^{-5}$. Figure 4.10 shows the evolution of the bed levels after a simulation time of 2 to 5 years (taking into account the morphological acceleration factor of 5) with a constant discharge of $20\,000\,m^3/s$.

From the beginning of the simulation, an alternate bar pattern is formed because of the curvature of the flow at the consecutive bends. These bars migrate downstream while they get progressively shallower and the channel defined between them gets deeper. This effect can be appreciated with the difference in the colour bar limits in Figure 4.10 between 2 and 3 year simulation results.

Bars in the first 30 km from the inflow boundary present a shallow and elongated form, which may be caused by the fixed bed level at the inflow boundary limiting morphological development. Further downstream, and including the region of interest around the offtake, the bars simulated by the model present similar characteristics to the conditions observed from satellite images (see Section 4.3).

Between 3 and 4 years of simulation, the cross-section profile of bars stabilises, with some of the highest points already above the water level ("dry points"), while they continue migrating downstream at slower speeds.

After 4 years of simulation, the bed topography presents complex bar geometries, with shapes similar to observations from satellite images as presented in Section 4.3. However, after this period some deep and narrow (1 to 3 cells wide) channels start to form from the outflow boundary, producing unrealistically elongated bars. This phenomenon has also been documented recently by Schuurman (2015) while simulating the evolution of braided rivers. Although the reasons for this behaviour are not yet clear, he suggests that a possible cause is the lack of a proper bank erosion algorithm. Allowing for floodplain erosion or with variable discharges that allow water to flow over the shallower bars may reduce this problem. Because of this, the bed topography after 4 years is used as initial bed for the second phase of simulation, which includes the distributary river and variable inflow discharge.

Figure 4.11a shows a detail of the initial bed elevation for the 2nd phase of the simulation, at the area of interest around the offtake. Bed topography for the parent river is obtained from the 4th year of constant discharge simulation in phase 1, resampled to the more complex grid that includes the distributary river. Initial bed topography for the distributary river consists of a flat bed with a constant slope of $1.4 \times 10^{-5}$ and an elevation of 4.5 m (above reference level).

Peak flows in this 2nd phase are much higher than the constant discharge of the 1st phase—slightly more than double—which produces flow over the shallow bars and a large movement of sediment. The effect of this is a series of sediment waves that move over the existing bars increasing their elevation and scouring of the deeper channels. This can be observed after the 1st monsoon season in Figure 4.11b. Because the duration of these high discharges is limited in time, it takes some years until these sediment waves reach the downstream end of the longer bars.

The model reproduces the formation of a sand bar at the right bank of the offtake. This bar is visible in Figure 4.11b and can be found in almost all of the offtakes in Bangladesh. This is a clear example of the Bulle effect described in Section 2.2.4.a, produced by the curvature of the flow as it enters the distributary river with a large offtake angle. The growth of this bar reduces the offtake angle for lower flow regimes, but it also reduces the

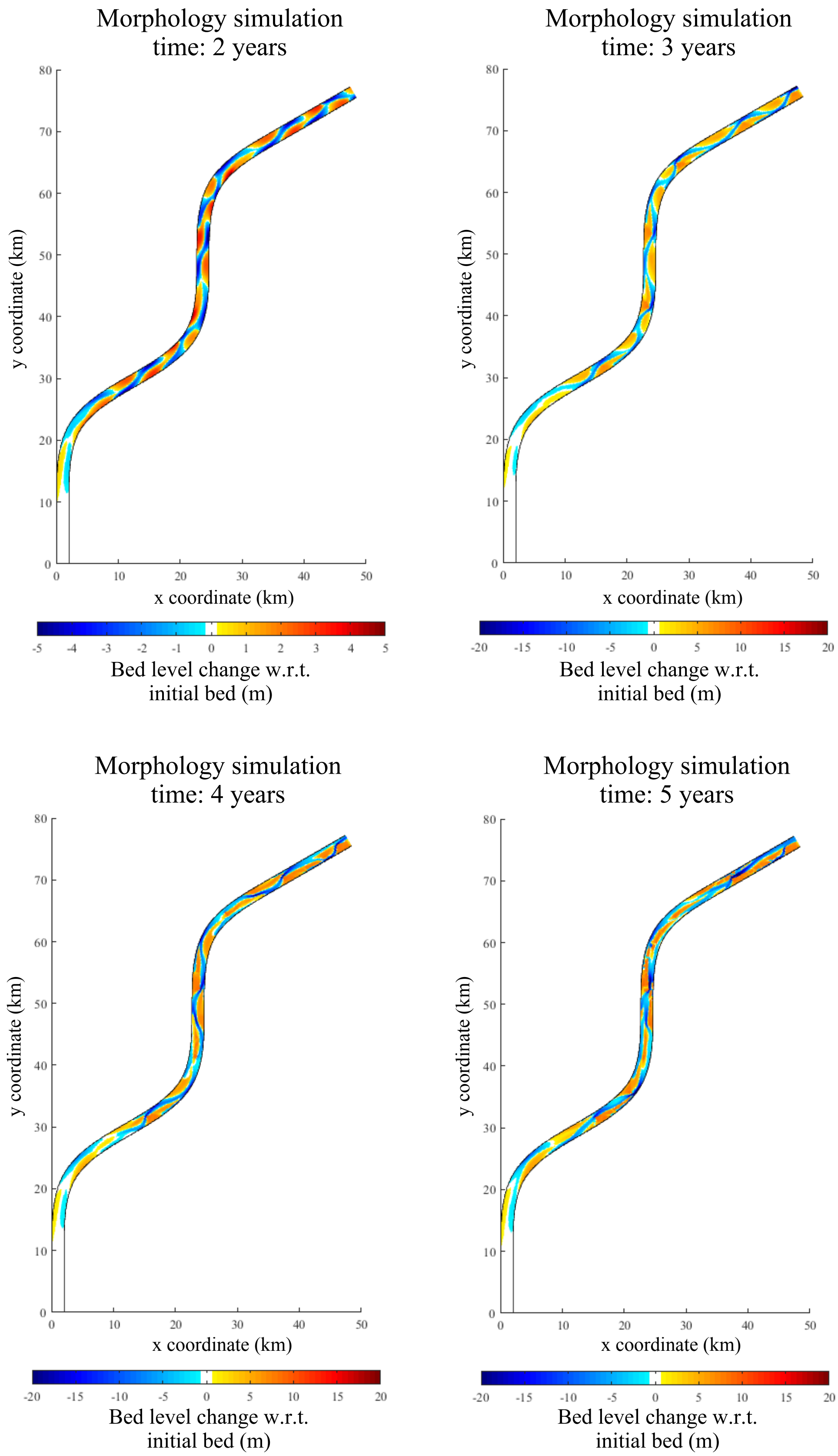


**Figure 4.10:** Bed level changes with respect to the original flat bed topography for the 1st phase of the numerical simulation.

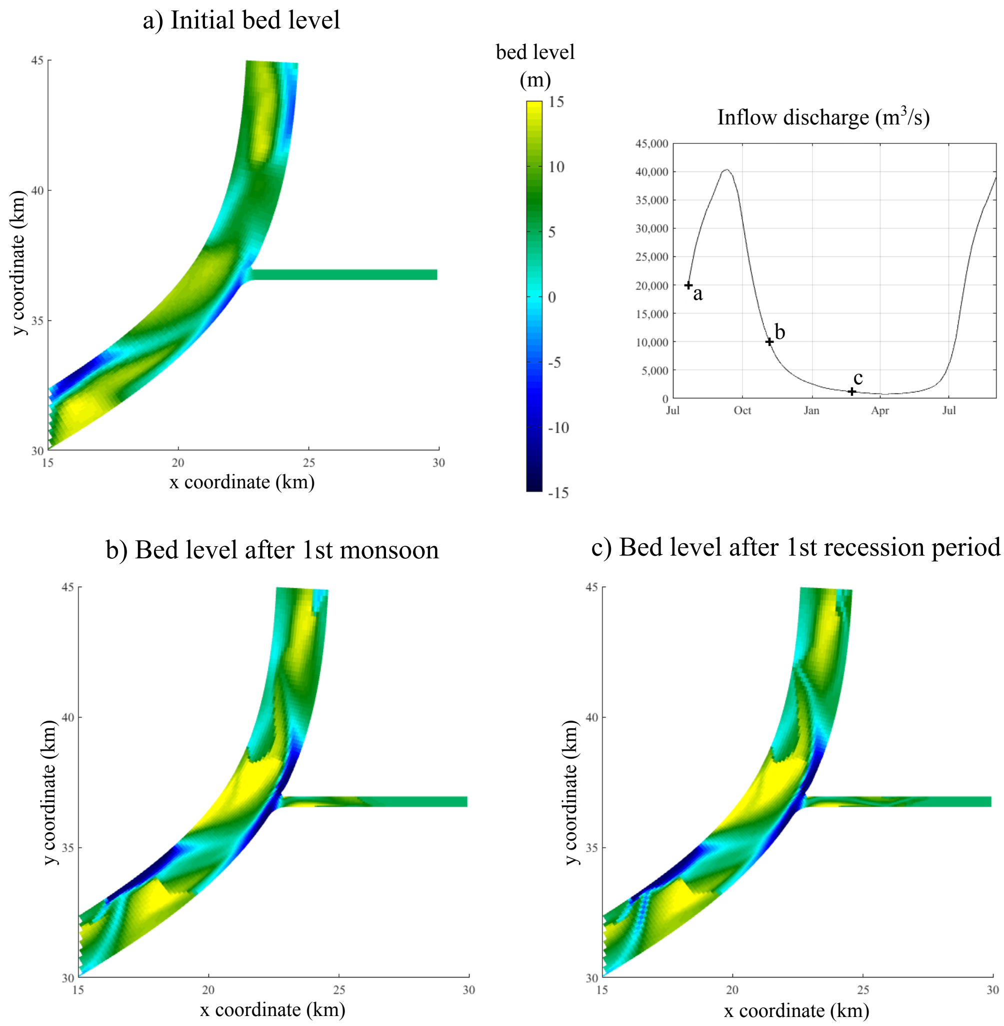


**Figure 4.11:** Evolution of the bed level for the 2nd phase of the simulation around the offtake. Elevation in metres above reference level of the model.

conveyance capacity of the offtake. Another effect of this entrance bar is that it induces the growth of a meandering planform at the distributary river (though limited by the fixed banks).

Most morphological changes in the model occur during the monsoon season, which is in agreement with observations of the river system (e.g CEGIS (2014), Delft Hydraulics and DHI (1996a) and Sarker et al. (2014)). For instance, Figures 4.11b and 4.11c look almost identical at first sight. Nevertheless, the model is also able to reproduce the importance of the recession period flows for erosion of the dry-season channels. Looking again at Figure 4.11c, the bend crossings of the parent river, at the bottom left corner of the figure and after the offtake, are clearly eroded in comparison with Figure 4.11b (up to 5 m of erosion) because of the retarded scour process described in Section 2.2.3.c. Even more important is, as will be seen later in this section, that this retarded scour phenomenon is also appreciable at the distributary river, which deepens most of the dry-season channel and was identified as one of the drivers preventing offtake closure (see Section 3.2.3.b).

Between Figure 4.11c and Figure 4.12a, separated by 3 years of simulation time, sediment waves reach the downstream end of the bars next to the offtake, while these bars keep migrating downstream with the celerities presented in Section 4.3 (Table 4.2).

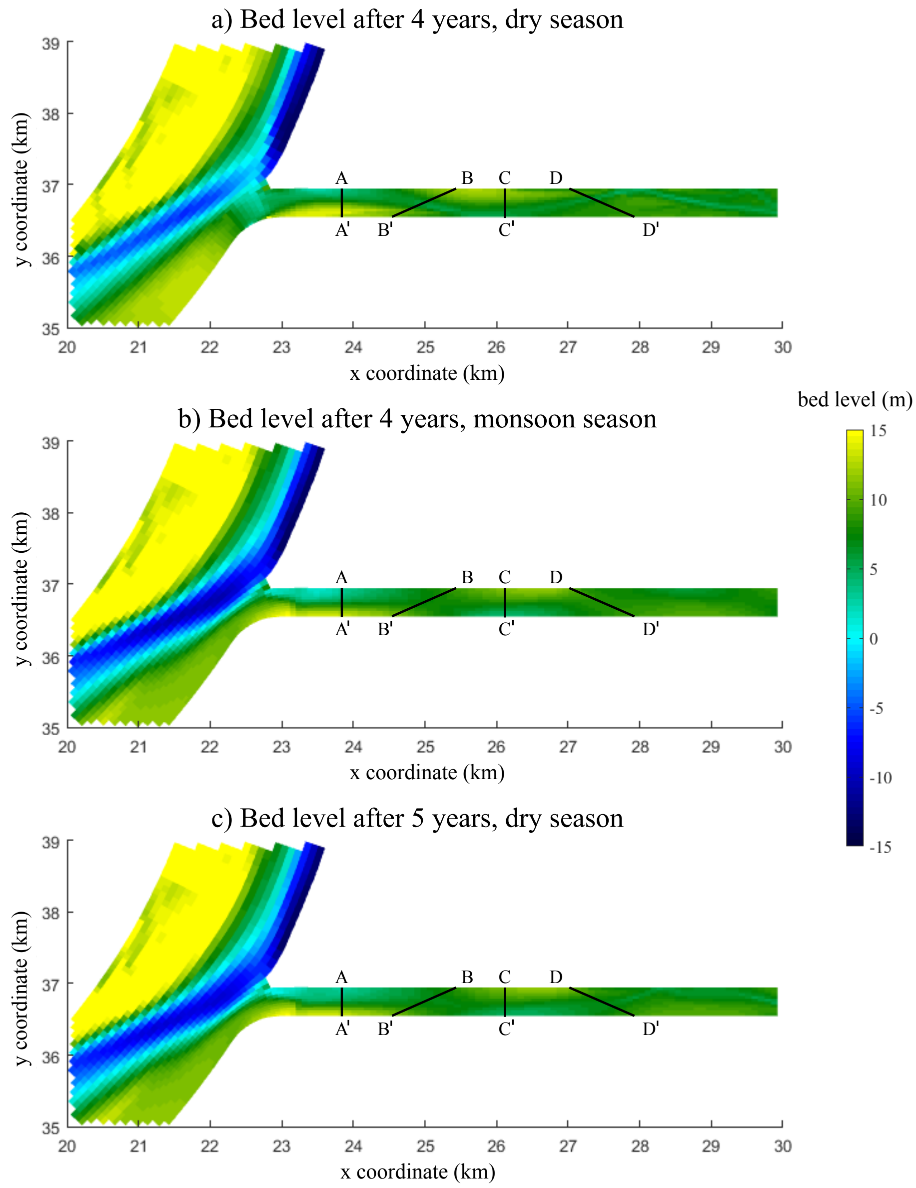


**Figure 4.12:** Evolution of the bed level after 4 years of simulation of the 2nd phase, including closure of the offtake. Elevation in metres above reference level of the model. Cross-sections A to D used in Figure 4.13.

Closure of the offtake occurs between the 4th and 5th year of the simulation, and is illustrated in Figures 4.12 and 4.13. A combination of two processes occur during the monsoon season of the 4th year (Figure 4.12b): on the one hand, the dry-season channel of the distributary river gets wider, but shallower at the bend crossings—as can be seen in the cross-sections B-B' and D-D' in both Figures 4.12 and 4.13. On the other hand, the bar upstream of the offtake reaches its entrance, significantly increasing the sediment

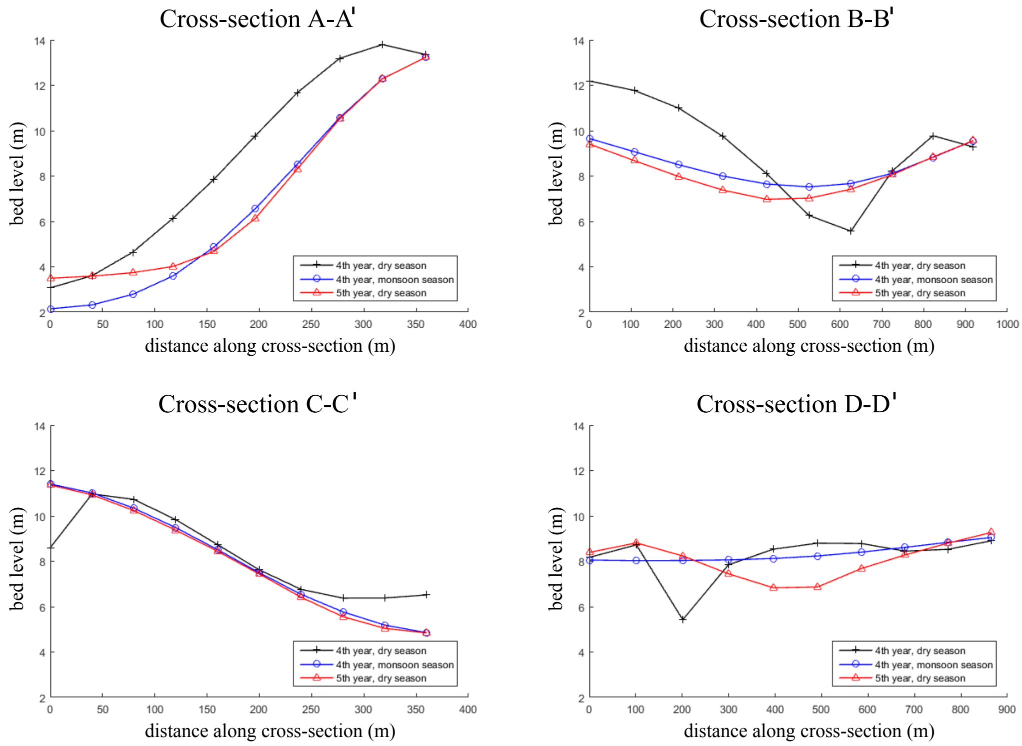


**Figure 4.13:** Bed level evolution after 4 years of simulation of the 2nd phase, for the cross-sections in Figure 4.12. Elevation in metres above reference level of the model.

load into the distributary river. During the recession period some retarded scour occurs at the bend crossings (compare the blue and red lines in Figure 4.13), but it is not sufficient to keep the offtake connected to the parent river, with flow in the distributary being discontinued on the 20th of January and until the 9th of June (140 days or 4.5 months). Both the dates of closure and reopening of the offtake, and the number of days without flow in the distributary are within the ranges found by CEGIS (2012) for the Gorai river.

As a summary to this section, it can be concluded that the following drivers of offtake closure are reproduced by the numerical model:

- Unfavourable offtake angle, contributing to the formation of a bar at the right bank of the offtake.
- Shallow bend crossings at the distributary, which retarded scour is not able to erode sufficiently.
- Unfavourable alignment of the main channel of the parent river, which also moves away from the offtake with the approach of a migrating bar from upstream.

Chapter 5

# Modelling and assessment of remedial measures

## 5.1 Introduction

This chapter presents the application of the numerical model developed in Chapter 4 to assess the effectiveness and the impacts of some of the measures proposed in Section 3.3, giving an answer to the 6th and last research question:

> *How effective are the remedial measures proposed in preventing offtake closure, and what impacts do they have associated?*

Based on the drivers of closure identified for the no-intervention closure scenario analysed in Section 4.4, five possible remedial measures from the options presented in Section 3.3 are selected to be implemented in the model. The following sections describe how each measure is implemented in the model and discuss the results obtained.

In order to compare the results of the measures with each other and with the no-intervention scenario, all simulations start on the dry season after 4 years of simulation of phase 2 (e.g. bed topography from Figure 4.12a). From that point, a total of 2.5 years of morphologic time are simulated including two monsoon seasons and three dry seasons.

## 5.2 Dredging of the distributary dry-season channel

One of the most obvious measures to keep flow in the distributary is to dredge the dry-season channel to a sufficient depth, removing shallow bend crossings. It is expected that, because of the small morphology changes expected during the dry season, this dredged channel may not silt up during this period. However, it is not clear whether this intervention can also improve the flow conditions after a monsoon.

Two simplified dredging strategies are implemented in the model by lowering the initial bed topography of the dry-season channel for a length of approximately 10 km. For the first strategy, the dry-season channel is dredged for a width of 120 to 160 m (3 to 4 grid cells across). The total volume dredged is $2.2 \times 10^6$ m$^3$, with an average dredge depth of 1.8 m and a maximum depth of 4.7 m. This layout is presented in Figure 5.1 a) and b).

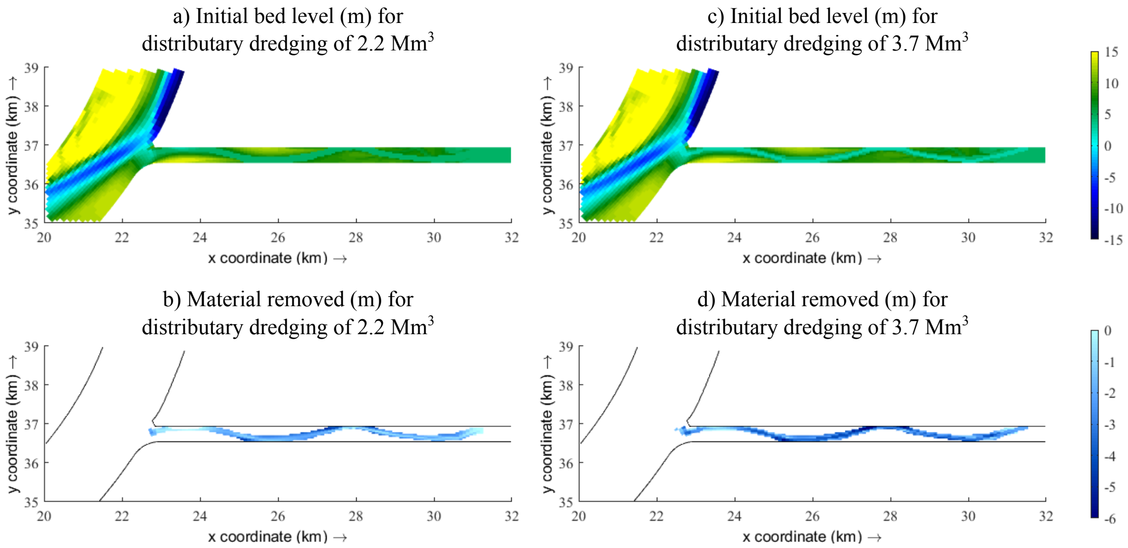


**Figure 5.1:** Layout of the two dredging strategies for the distributary river implemented in the model.

The second dredging strategy consists of removing an additional 2 m layer of sediment with a width of 80 m (2 grid cells) along the centre of the previous dredging layout. The total volume dredged in this case is $3.7 \times 10^6$ m$^3$, with an average dredging depth of 2.7 m and a maximum depth of 6.7 m, as shown in Figure 5.1 c) and d).

This measure, with both layouts, is effective in keeping a minimum discharge flowing in the distributary throughout the dry season after its implementation. Minimum discharges computed by the model are 17.4 m$^3$/s for the 2.2 Mm$^3$ layout and 33.5 m$^3$/s for the 3.7 Mm$^3$ layout, which is roughly a 2 % and a 4 % of the parent flow respectively.

During the monsoon season, the dredged dry-season channel experiences the behaviour described in Section 4.4: shallower bend crossings, deeper pools and widening of the channel. However, during the recession period retarded scour is able to erode the bend crossings more than in the no-intervention scenario. This is shown in Figure 5.2 for the 2nd dry season by comparing the changes in bed level shown in b) and c) with the bed level changes for the no-intervention scenario in a). From the same figure it is possible to see how this intervention has no impact on the parent river and only affects the distributary.

The improvement in flow conditions after the monsoon is able to maintain the offtake opened for a longer period of time also during the 2nd dry season, until it closes again as shown in Figure 5.3.

After another monsoon season reshapes the distributary channel again, the system comes back to the no-intervention scenario (compare Figure 5.2 e) and f) with d)), and dredging would be required again.

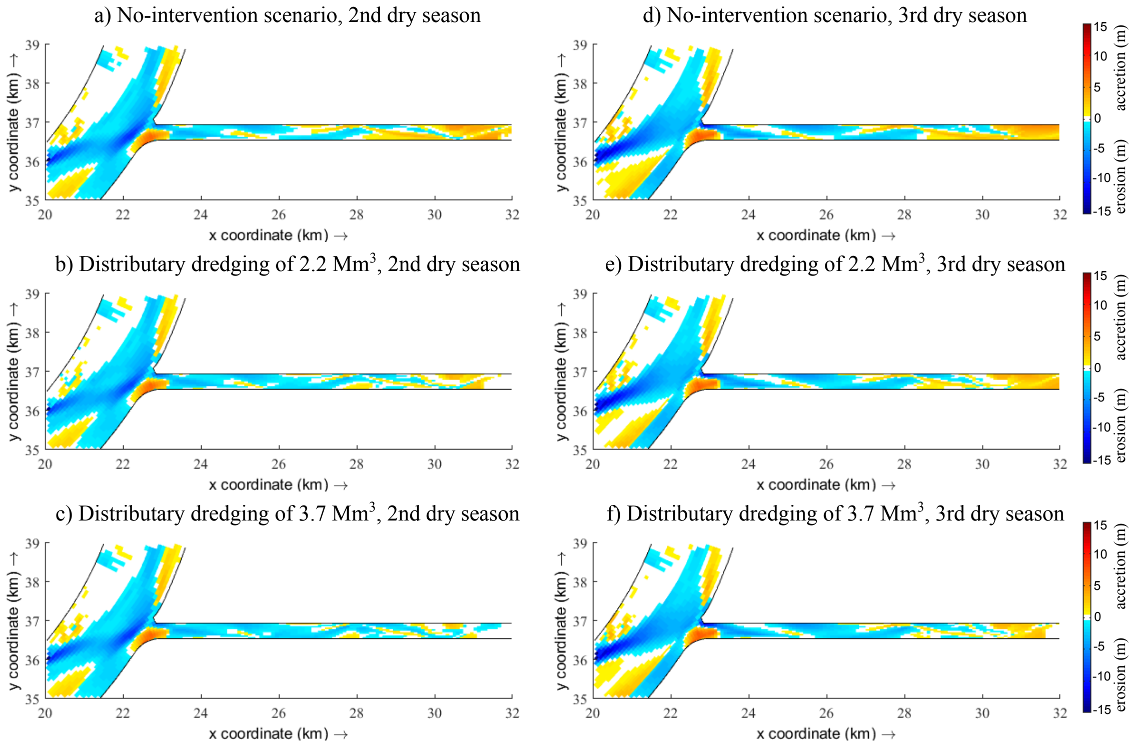


**Figure 5.2:** Erosion and accretion with respect to the initial bed level for the no-intervention scenario and for the two dredging strategies at the distributary. a), b) and c) show changes for the 2nd dry season (after 1.5 years of simulation). d), e) and f) show changes for the 3rd dry season (after 2.5 years of simulation).

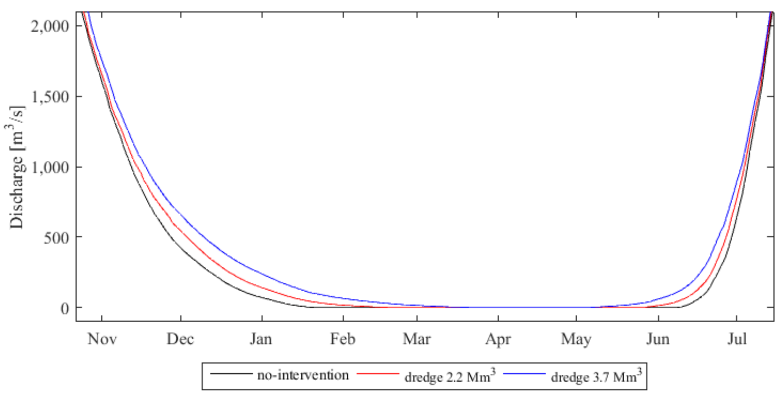


**Figure 5.3:** Comparison of discharges in the distributary channel during the 2nd dry season for the no-intervention scenario and the 2 dredging strategies at the distributary. No dredging is performed during this period. Disconnection with the parent river occurs when discharges are reduced to $0\,\mathrm{m^3/s}$.

Table 5.1 shows the summarises the dates of closure and reopening of the offtake for the no-intervention scenario and for the two dredging strategies2nd and 3rd monsoon seasons (during the 1st dry season it does not close). As stated before, both dredging strategies

**Table 5.1:** Offtake closure and reopening dates for no-intervention scenario and the two dredging strategies at the distributary.

| | | Model simulation | | |
|---|---|---|---|---|
| | | no-intervention | dredging 2.2 $Mm^3$ | dredging 3.7 $Mm^3$ |
| 1st dry season | date closure | 20–Jan | — | — |
| | date reopening | 09–Jun | — | — |
| | n. weeks with no flow | 20 | 0 | 0 |
| 2nd dry season | date closure | 22–Jan | 20–Feb | 24–Mar |
| | date reopening | 07–Jun | 28–May | 09–May |
| | n. weeks with no flow | 20 | 14 | 7 |
| 3rd dry season | date closure | 05–Feb | 05–Feb | 17–Feb |
| | date reopening | 04–Jun | 03–Jun | 09–May |
| | n. weeks with no flow | 17 | 17 | 14 |

also produce a reduction in closure duration in the 2nd dry season, while for the 3rd dry season only the strategy with a larger volume produces a small reduction.

In view of these results results, it is possible to conclude that this measure could be effective for the first year when implemented at the beginning of the dry season. In order to guarantee that there is no disconnection from the parent river in the following years, further dredging would be required at the beginning of each dry season.

The fact that during 2nd dry season flow conditions are better than initially indicates that dredging in consecutive years would require less volume to prevent the disconnection. This is in line with the observations by GRC (2002), who reported a reduction in the volumes dredged in consecutive years during the dredging works at the upper Gorai River.

## 5.3 Major dredging to improve alignment of parent river

In order to improve the alignment of the main channel of the parent river with the offtake, a capital dredging strategy is implemented in the model by lowering (dredging) the bed levels of the bar upstream of the offtake by 5 m and rising (dumping dredged material) the bed levels on the opposite bank by 10 m, while using the same volume of material: approximately $11.4 \times 10^6\,m^3$. The layout for the implementation of this strategy in the model is shown in Figure 5.4.

Figure 5.5 shows the evolution of the morphology after the 1st and 2nd monsoon seasons. The model shows how the sediment dumped at the bar opposite of the offtake is quickly eroded during the 1st monsoon season and the bed is almost back to the no-intervention scenario after the 2nd monsoon season.

Despite the large volume of sediment dredged (3 to 5 times larger than for the recurrent dredging in Section 5.2), the bed topography of the distributary river is not affected by this measure. There is only a small reduction in the size of the bar at the entrance of the distributary, but insufficient to improve flow conditions at the offtake.

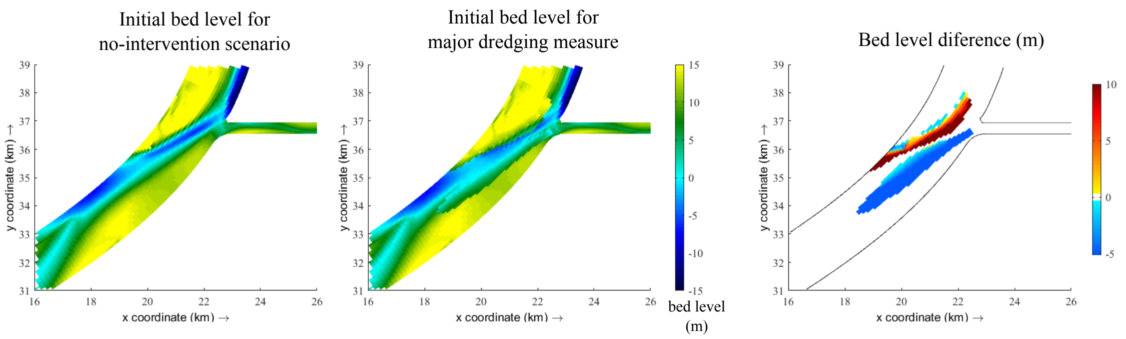


**Figure 5.4:** Layout of the dredging and dumping strategy implemented in the model to improve the alignment of the main channel of the parent river.

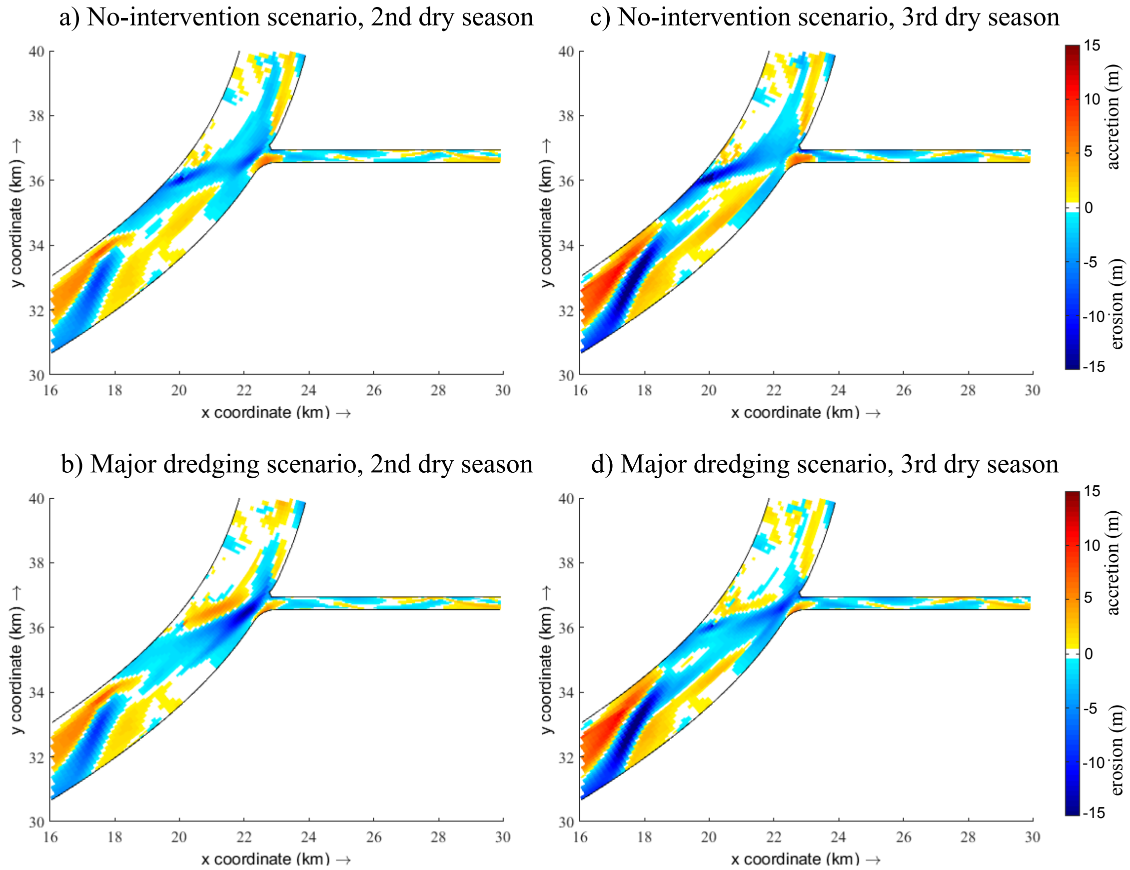


**Figure 5.5:** Erosion and accretion with respect to the initial bed level for the no-intervention scenario and for the major dredging strategy at the parent river. a) and b) show changes for the 2nd dry season (after 1.5 years of simulation). d) and e) show changes for the 3rd dry season (after 2.5 years of simulation).

## 5.4 Submerged erodible weirs

A submerged erodible weir is implemented in the model by raising the bed level of the deep channel of the parent river 1 km downstream of the offtake location, as shown in Figure 5.6. The total volume of sand required for the weir is around $1.4 \times 10^6\,\mathrm{m}^3$ and the crest of the weir is located at +4 m above the reference level of the model, 2.5 m below the minimum water levels of the parent river.

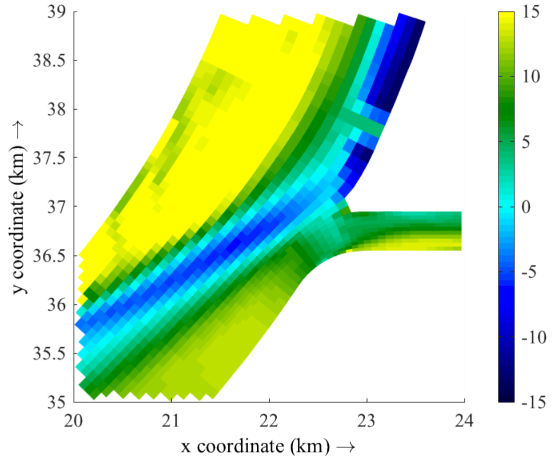


**Figure 5.6:** Location of the submerged erodible weir implemented in the model.

The results of the model show how this weir is only able to raise the upstream water levels by only a few centimetres, and is eroded rapidly before the monsoon season without any impacts on the monsoon flows.

The dimensions of the weir tested were clearly insufficient to produce any effect to the distributary river, despite the volume of the sand required being significant. A larger weir could produce a larger increase in water level, but this quickly becomes very expensive for a measure with such a short life span.

## 5.5 Flow divider

One of the drivers of offtake closure detected is the unfavourable angle of the offtake, which produces the growth of a sand bar at the entrance of the distributary channel. A possible measure to reduce this angle is the construction of a flow divider.

This structure is implemented in the numerical model with the use of elements called "thin dams" in Delft 3D. These elements are infinitely thin walls that prevent flow exchange between their two sides. They are typically used to represent obstacles in the model that have sub-grid dimensions (Deltares, 2014). It is important to note that these dams are infinitely tall, meaning that also peak flows in the model are completely blocked—which for a real structure may not be the case. Figure 5.7 shows the 2 geometries tested in the model, with both of them being around 1.3 km long but Flow divider 2 protruding more into the parent river than Flow divider 1.

Model results are shown in Figure 5.8, comparing bed level differences with the initial bed topography for both geometries. A clear impact of both structures is the deepening of the parent river channel and large sedimentation downstream of the flow divider.

In both cases, the flow divider produces the erosion of the bar located at the entrance of the distributary channel. However, when the migrating bar at the parent river reaches

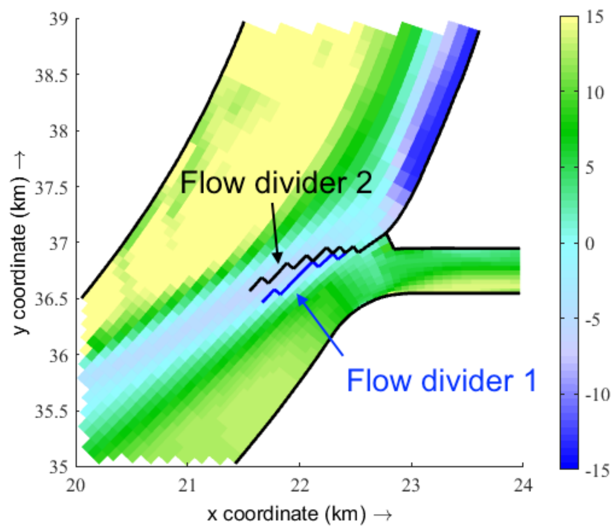


**Figure 5.7:** Layout of the two flow divider options implemented in the numerical model using "thin dams".

the location of the flow divider, the entrance to the distributary is blocked by this bar, and the main channel of the parent river moves even further away. Although with a very simplified representation of the structure, the model shows the problems associated with the construction of hard structures in dynamic river environments, which cannot adapt to changes in morphology.

Looking into the hydrodynamics, both flow dividers increase the discharge into the distributary river during the monsoon season. Also during the monsoon season, there is a small but appreciable water level difference between both sides of the flow divider, with the distributary side being around 20 cm higher than the parent river side during peak flows. These values are summarised in Table 5.2. During the dry season, water levels are the same at both sides of the flow divider, but they are 20 cm higher than the no-intervention scenario for the Flow divider 1 and 15 cm lower for Flow divider 2. Because of this difference, these results are not conclusive on the effect of the flow divider to the dry-season water levels.

Overall it can be concluded that, because of the migrating bar reaching the flow divider and the main channel of the parent river moving further away from the offtake, the layout for the flow dividers is clearly not beneficial for offtake maintenance and have a large impact on the morphology of the parent river.

## 5.6 Longitudinal training wall

The last measure implemented in the model is a longitudinal training wall with the objective of reducing the width of the parent river next to the offtake location and prevent migrating bars from reaching the entrance to the distributary river. This measure is implemented in the numerical model using thin dams again, with the layout in Figure 5.9.

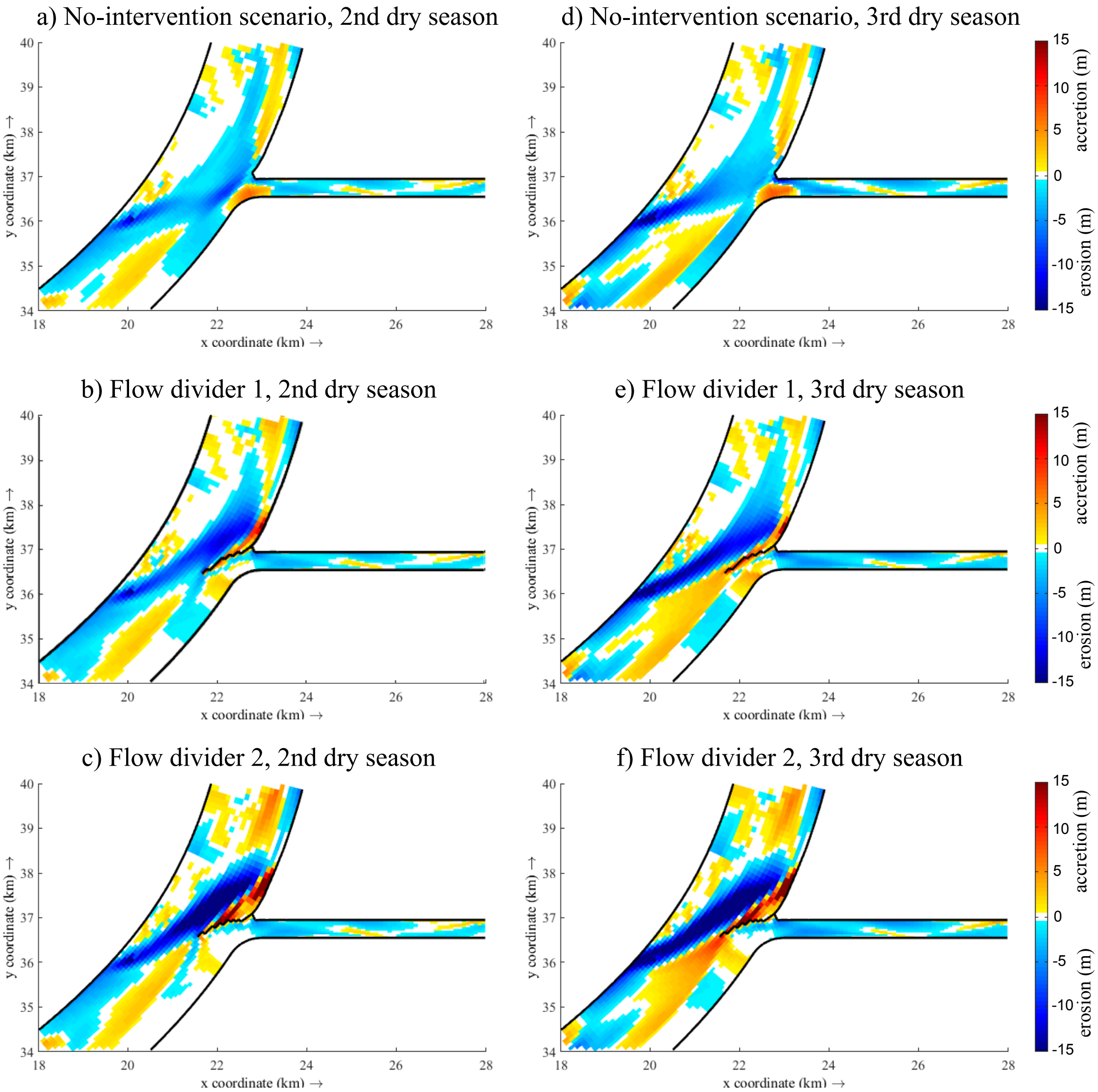


**Figure 5.8:** Erosion and accretion with respect to the initial bed level for the no-intervention scenario and after the implementation of two different flow dividers. a), b) and c) show changes for the 2nd dry season (after 1.5 years of simulation). d), e) and f) show changes for the 3rd dry season (after 2.5 years of simulation).

Morphological evolution after the implementation of the longitudinal training wall can be seen in Figure 5.10. Velocities at the main channel of the parent river increase because of the flow concentration over a smaller width. This produces the erosion of this channel next to the offtake, reducing the advancement of the migrating bar and bringing the channel closer to the offtake. The effect is a theoretical improvement of the alignment of the parent river, which effectively reduces the size of the bar at the entrance of the distributary river (compare Figure 5.10 d with c). However, this is not sufficient to improve the flow conditions at the distributary channel, which remains without flow for the same duration as in the no-intervention scenario.

Moreover, the reduction in channel width of the parent river causes a rise of 20 cm in water

**Table 5.2:** Water levels at the flow divider location (metres above reference level).

| Model simulation | 1st monsoon | | 2nd monsoon | | 1st dry season | 2nd dry season |
|---|---|---|---|---|---|---|
| | distributary side | parent side | distributary side | parent side | | |
| no-intervention | 17.90 | 17.90 | 18.00 | 18.00 | 5.40 | 5.45 |
| Flow divider 1 | 18.35 | 18.10 | 18.20 | 18.00 | 5.65 | 5.60 |
| Flow divider 2 | 18.35 | 18.05 | 18.10 | 17.90 | 5.26 | 5.30 |

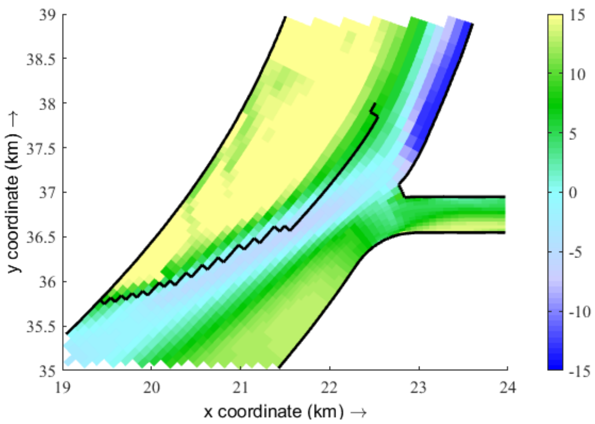


**Figure 5.9:** Layout of the longitudinal training wall implemented in the numerical model using "thin dams".

levels during peak flows to the entire domain upstream of the training wall. On the other hand, minimum water levels at the offtake location are lowered 20 cm during the 2nd dry season and 40 cm during the 3rd dry season, which worsens the flow conditions for the offtake.

In conclusion, the layout proposed for the longitudinal training wall shows a theoretical improvement of the alignment of the parent river with the offtake. But this improvement is not translated into a reduction of the closure time of the offtake and the structure produces an increase in peak water levels that affects all the upstream reach of the model. Other layouts with the training wall starting further upstream but blocking a smaller width of the parent river could show a larger effect on the distributary with a smaller impact on the parent river upstream. However, this would require a larger investment as a new channel should be dredged for the parent river following the alignment of the training wall.

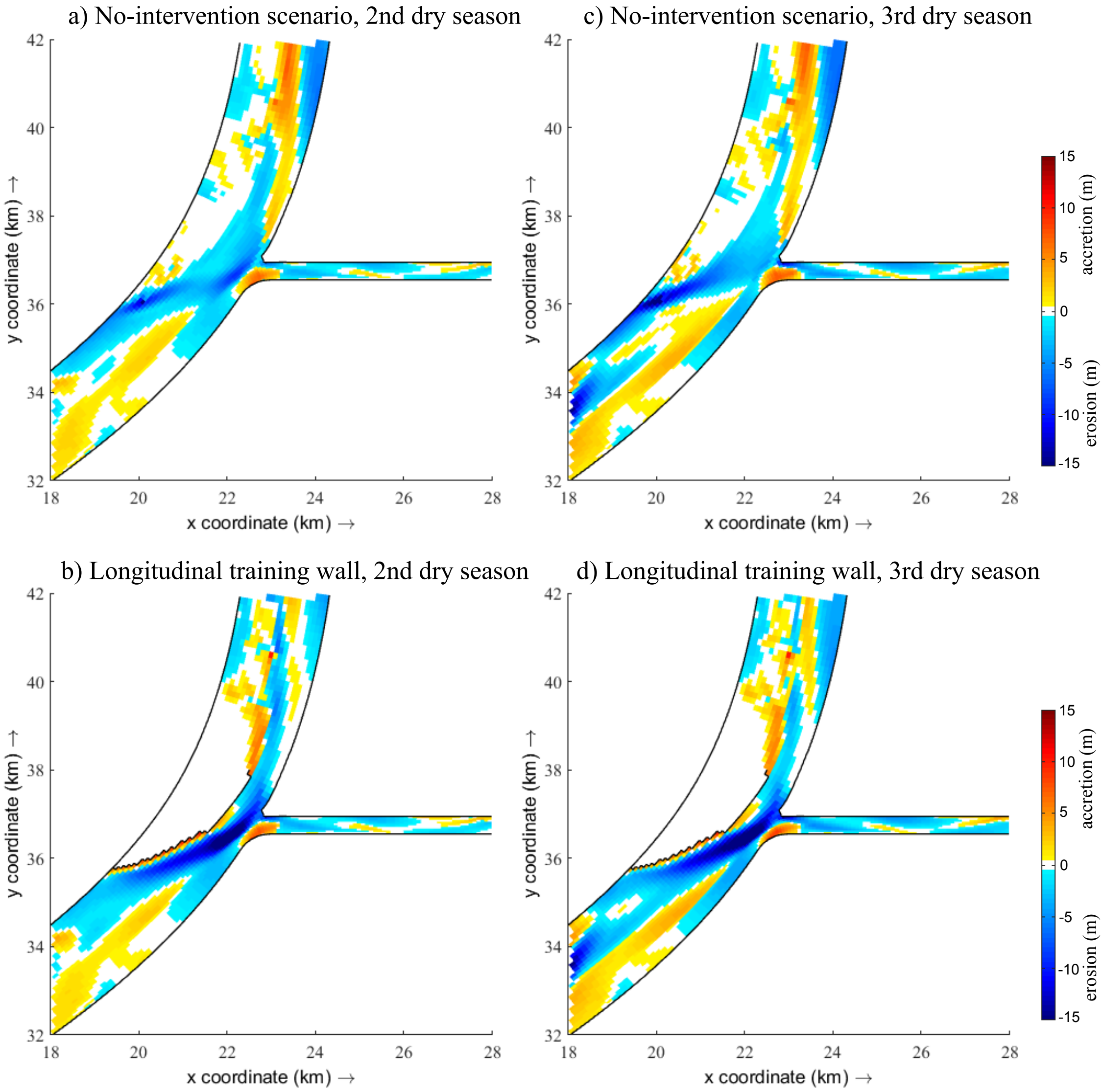


**Figure 5.10:** Erosion and accretion with respect to the initial bed level for the no-intervention scenario and after the implementation of the longitudinal training wall. a) and b) show changes for the 2nd dry season (after 1.5 years of simulation). d) and e) show changes for the 3rd dry season (after 2.5 years of simulation).

# Chapter 6

# Conclusions and recommendations

## 6.1 Conclusions

This section summarises the findings of the present study in relation with the research questions and objective described in Section 1.3. Given the scarcity of morphology data available for the rivers of Bangladesh, the overall objective of this study is:

> *Propose a method to assess the effectiveness and impacts of possible remedial measures to prevent the closure of offtakes in Bangladesh.*

To determine whether this objective has been reached, the different research questions are answered below:

1. **What physical processes are relevant for the morphodynamic evolution of offtakes?**

In offtakes, one branch is dominant—the parent river—over the other one—the distributary river. Offtake evolution is determined by processes at both local (around the offtake location) and regional scales, both upstream and downstream of the parent and distributary rivers. Because of the difference in magnitudes of the parent and distributary channels, morphodynamic changes at the parent river play a major role in offtake evolution.

Morphodynamics of large sand-bed rivers, and in particular for the large rivers in Bangladesh, are affected by deflection of sediment transport by helical flow and transverse bed slopes, and by bank erosion processes. Bedforms also affect sediment transport rates and bed roughness. The retarded scour phenomenon is also important for both the parent river and the distributary channel. Sediment sorting processes play just a secondary role because sediment grain size is found to be rather uniform in this case.

Physical processes at the local scale can also change the discharge and sediment transport distribution between the two branches. The most relevant processes around the offtake location are the Bulle effect, which depends on the offtake angle; flow separation at sharp edges; transverse slope which steers sediment transport towards one branch; and upstream asymmetrical approach conditions because of upstream bends.

Any kind of physics-based model has to reproduce as much of these physical processes as possible to simulate the behaviour of an offtake system.

2. **What are the main causes and drivers of offtake closure?**

Offtake closure processes are complex and often caused by a combination of factors. These factors can be grouped into three main causes of offtake closure: a too large difference in flow rate and water level between peak flow and dry-season flow, sediment load into the offtake increasing above the sediment transport capacity of the distributary or, vice-versa, sediment transport capacity reducing and being insufficient for this sediment load.

Low dry-season water levels can occur due to the natural hydrologic variability or because of the operation of retention hydraulic structures. However, bed accretion at the offtake or distributary channel seem to play a more important role than water levels.

Too high sediment load into an offtake can be caused by a number of drivers related to morphologic changes at the parent river leading to unfavourable configurations for the offtake. The most important unfavourable configurations are, in no particular order: 1) the distributary offtaking from an inner bend of the parent river; 2) an increase of the offtake angle enhancing the Bulle effect or flow separation; 3) the main channel of the parent river moving away from the offtake, increasing sediment deposited in front of the offtake; or 4) the presence of chars in front of the offtake.

Finally, the following drivers are identified in relation with a reduction in erosion capacity at the distributary river: 1) a reduction of the recession period duration, which reduces the time available for retarded scour; 2) presence of shallow parts in the distributary channel, mostly occurring at bend crossings, which reduce the available hydraulic gradient and therefore also flow velocities; and 3) the presence of a stronger—usually clay—layer at the offtake, decreasing the natural adaptation capacity of the offtake to changing conditions.

3. **What remedial measures can be defined which might prevent offtake closure?**

A list of possible remedial measures to prevent offtake closure has been elaborated taking into account the river system of Bangladesh. This list is not exhaustive and only pretends to serve as an orientation of the typology of interventions that can be implemented in the numerical model. For this reason it is not necessary to go into details of each measure.

A barrage across the entire width of the parent river, or smaller submerged erodible weirs can be constructed downstream of the offtake to increase dry-season water levels. While the first one will have a large impact on the morphodynamics of the whole river system, the latter presents the challenge of resisting during the entire dry season but being eroded before peak flows to not increase flood risk.

Reduction of sediment input into the distributary river can be achieved with the construction of an offtake regulator. Also, dredging at the parent river or constructing a flow divider can improve the configuration of the offtake; and narrowing the parent river around the offtake can prevent the formation of bars.

Finally, to increase the sediment transport capacity at the offtake and distributary river it is possible to deepen the dry-season channel of the distributary by dredging—which should be done regularly. Strong clay layers at the offtake can also be removed, if present, to restore the natural adjustment capacity of the offtake to changing hydrodynamic conditions.

4. **What is a suitable tool and approach to assess the effects of remedial measures for offtake stabilisation, given the dynamics of the system and the scarcity of available data?**

A two-dimensional, depth-averaged model is the best compromise between the reproduction of relevant physical processes and a reasonable computation time. Three-dimensional processes such as helical flow and the effect of transverse slopes on sediment transport can be included in a parametrised form; and there is no need to use an empirical nodal point relation for the discharge and sediment transport distribution between the two branches.

A physics-based morphodynamic numerical model with an initial flat bed topography is proposed to overcome the lack of available morphological data. A more realistic bed topography is then generated by simulation with a model including most of the relevant physical processes in the numeric scheme.

Variable discharges are included in the model to take into account retarded scour during the monsoon recession period as well as to estimate the time during which the distributary river is dry.

A limitation of the model used is that it does not consider bank erosion of the floodplains, as the computational grid is fixed during the simulation (which is common practice in state-of-the-art models). This limits the time-frame for which predictions of the model are reliable to a few years, which is sufficient to analyse the initial effects of measures on the river system.

5. **How well is this tool able to reproduce the morphological evolution and offtake closure processes observed in Bangladesh?**

Despite the limitations of the model, a comparison with available data shows that the discharge distribution between the two branches is well within the observed values for the Ganges and Gorai rivers, on which the model is roughly based. Flow velocities observed in the model also agree with the few measurements available.

Sediment transport in the model (around 24 million T/year) is lower than the yearly bed material sediment loads measured in the Ganges River (of, at least, 76 million T/year).

However, within the area of interest, roughly 10 km up- and downstream of the offtake, bar shapes, dimensions and migration rates are within the values observed from recent satellite images. With the above considerations, the model is considered to reproduce the behaviour of the river system with enough accuracy to obtain the correct orders of magnitude for the evolution of the offtake system and the effects of interventions.

Analysing the closure process of the offtake, the model reproduces the development of the distributary river described in project reports (Delft Hydraulics and DHI, 1996c; GRC, 2002), with the formation of a sand bar at the offtake entrance and the main channel getting wider and shallower during the monsoon season and then eroding again during the recession period.

The evolution of the parent river in front of the offtake also reproduces how the approach of a bar shifts the channel of the parent river away from the offtake, reducing the discharge and sediment transport capacity at the offtake and distributary river.

6. **How effective are the different remedial measures proposed in preventing offtake closure, and what impacts do they have associated?**

Five different remedial measures were assessed with the numerical model. These are:

1) Dredging of the distributary dry-season channel:

This measure was effective in maintaining a minimum flow in the distributary river for the entire duration of the dry season after its implementation. In the following year (without dredging) it was only possible to reduce the duration of no flow but the offtake closed again. Increasing the volume dredged (from 2.2 to 3.7 million $m^3$) allows a higher discharge during the dry season and delays the closure date of the 2nd dry season by several weeks.

After the 2nd monsoon season the conditions were back to the no-intervention scenario. This means that this measure should be repeated at the beginning of each dry season, with a possible reduction in dredging volumes for each campaign. This is in accordance with the observations of GRC (2002) at the Gorai offtake.

The impacts of this measure are limited to the distributary channel, with no significant effects on the parent river morphodynamics.

2) Improvement of parent river alignment with major dredging and dumping:

The channel alignment of the parent river was improved by dredging the bar next to the offtake and dumping this sediment at the opposite bank. Although large amounts of material need to be relocated, this measure was not effective, as the discharge and sediment transport distribution was not affected. After the first monsoon season the alignment presented no appreciable differences with the no-intervention scenario.

3) Submerged erodible weirs:

Bed levels in the parent river downstream of the offtake were increased around 10 m from the original topography creating a narrow weir. This measure was not effective, as water levels during the dry season were only increased by a few centimetres, which was not sufficient to reconnect the distributary. The large volume required to construct the weir was quickly eroded before the monsoon season.

4) Flow divider:

Two slightly different geometries were tested for a conceptual flow divider with a length of around 1.3 km. In both cases the distributary side of the flow divider was filled up with sediment after the first monsoon, becoming an ineffective measure and showing the potential risk of building hard structures in a dynamic river.

Moreover, this measure produced a deepening of the main channel at the parent river, sedimentation at the leeward side of the structure and an increase in peak water levels during the monsoon.

5) Longitudinal training wall to reduce width of parent river:

A longitudinal training wall was implemented in the model at the river bank opposite to the offtake to reduce the channel width of the parent river. The results of the model show an increase in flow velocities at the parent river with degradation of the parent river's channel and migrating bars. However, this was not sufficient to improve the flow conditions at the offtake or to reduce the closure duration.

The implementation of this measure had a significant impact on the parent river, initially increasing peak water levels by 20 cm over the entire reach upstream of the structure and reducing dry-season water levels at the offtake.

Summary:

In view of the conclusions from the different measures implemented in the model, dredging the distributary river at the end of the monsoon season is the only intervention that seems to be effective, with also a small impact on the river system.

## 6.2 Recommendations

### 6.2.1 On remedial measures for offtake maintenance

From the remedial measures that have been assessed in this study, a recurrent dredging strategy for the distributary rivers shows the most promising results to maintain flow in the offtakes during the dry season. This measure should be carried out each year during the recession period of the monsoon, in order to enhance the effects of retarded scour. Although recurrent dredging does not stabilise the offtake in the long term, this can be considered as a no-regret measure to be implemented as soon as possible because of its effectiveness and low impacts on the river system.

The construction of hard structures (e.g. an offtake regulator, a large barrage or a permanent flow divider) is strongly discouraged if the planform of the parent river is not stabilised around the location of such structures. This is because these structures cannot adapt to changing conditions in such a dynamic environment as the major rivers of Bangladesh.

Further research is needed to find more successful interventions to stabilise offtakes in a longer term. This research should be directed towards improving the local alignment of the offtake with the parent river to reduce the inflow of sediment during peak discharges. A combination of different remedial measures can also improve the results of the individual measures and provide valuable solutions in this direction. For example, the combination of a flow divider with the improvement of the alignment of the parent river with dredging could prevent the fast siltation of the offtake observed in the simulations of the present study.

### 6.2.2 On the approach followed in the present study

One of the most important outcomes of this study is that, even without bed topography data, it is possible to quantitatively reproduce the general evolution of an offtake with the use of physics-based morphodynamic numerical models. Following the approach of this study it is possible to assess the order of magnitude of effects that future river engineering interventions can have on an offtake system when available data is insufficient for the development of detailed models.

The first step should always be an analysis of the system to be modelled, with special attention to the relevant physical processes that need to be incorporated in the model. It is strongly recommended to incorporate field data as it becomes available in the form of more accurate boundary conditions or in the calibration of hydrodynamic and sediment transport processes.

To make a numerical model inexpensive and with reasonable computational requirements it is necessary to limit its extension. With the simplifications and assumptions used in the present study, the model developed is capable of generating possible scenarios to simulate the effects of engineering measures without the limitation to available measurements, which is extremely valuable for a preliminary research on engineering remedial measures or in the early stages of river engineering projects. One simplification applied to this study is that bank erosion of the floodplains is not taken into account, which limits the meandering and braiding behaviour of the rivers by confining them to the existing banks. If results on a longer term were required, an extension to this model would be to incorporate the floodplains and bank erosion mechanisms. The accuracy of the model for morphological predictions could also be increased with the development of a more advanced formulation for the effect of transverse bed slopes on sediment transport, as the current formulations available still present large uncertainties. These extensions to the model make it more complex, requiring more computational resources.

As the intent of this thesis is to develop a tool useful to prepare general guidelines to prevent offtake closure, variations in the geometry and input parameters of the model can be used to generate a whole range of closure scenarios to asses the effectiveness of measures under different river configurations.

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