Channel closure in large sand-bed braided rivers

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Channel closure in large sand-bed braided rivers

by

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An electronic version of this thesis is available at http://repository.tudelft.nl/.
Front cover: Photo of the braided Brahmaputra River in Assam, India.
Downloaded from: http://floodlist.com/asia/10000-in-relief-camps-assam-floods
Photo by: Ashwin Kumar
This thesis marks the end of my Master study of Hydraulic Engineering at Delft University of Technology. Except for the initial stage, the study was carried out in Deltares, which facilitated the process significantly. It was a challenging and interesting period, and I would like to use the opportunity to thank everyone that contributed along the way.

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Abstract

In large braided rivers, river training is often required to protect the banks against erosion, to improve navigability and for land reclamation. Closing one of the channels is a promising option to achieve these goals. However, there is a lack of systematic research on channel closures and no guidelines for their use exist. In the few documented cases, the river reopened the closed branch by eroding a channel across the island that separated the channels. The goal of this study is to analyse the consequences of closure, find the variables that affect channel reopening and provide guidelines for channel closures. The problem is studied with a numerical Delft3D model. A simplified reference case is set up, with two branches separated by an island. It is based on typical reaches of large braided rivers. Initially, one of the channels is closed with a combination of a weir in the channel and a short embankment on the island. A bypass channel is eroded around the weir in the first weeks of the wet season. A sensitivity analysis of different physical properties is performed in order to determine how general the simplified case is. Quantitative results vary, but the qualitative morphological response to closure remains similar. The largest part of the study consists of analysing simulations with various interventions. Combinations of a weir in the channel and embankment on the island, multiple weirs, roughness elements, vegetation and partial closures with bandals are tested in different positions along the channel. Analysis is extended by including simulations with higher water levels, four additional geometries and some longer-term simulations. Finally, aggregated results are analysed to find connections between variables. Channel reopening due to formation of channels on the island is the main cause of reduction in closure effectiveness. Bypass channels of varied depth form around the intervention in most cases. Channels across the island mostly occur when longer embankments are used. Their extent is less predictable and increases in time, so they should be avoided. The type of channel on the island that will most likely develop can be predicted from the initial hydrodynamic conditions after closure. Correlation between erosion of channels on the island and the initial hydrodynamic conditions is found. The water level gradient is the most important parameter that determines the location and degree of channel erosion. Water depth on the island plays a role when water levels are relatively low. Higher water levels cause more erosion, which can be mostly prevented with the use of submerged weirs. Flow patterns on the island determine the exact position of the eroded channels and directly contribute to erosion. Sediment supply to the newly formed channels reduces their growth. Deposition in the closed branch improves conditions over time, especially with interventions that do not block the channel fully. Length and width of the island play a role in the extent of erosion on the island, whereas channel and bifurcation asymmetry mostly do not. The best overall solution is found to be a combination of a weir with a long embankment or roughness elements. Further details, such as position of the interventions and weir crest height, depend on goals of closure and water levels in the system.
Summary

In large braided rivers, river training is often required to protect the banks against erosion, to improve navigability, for flood protection and land in large dynamic rivers. Closure of one of multiple channels is a promising cheaper and more adaptable alternative. However, there is a lack of systematic research on channel closures and no guidelines on their use exist. In the few documented cases, the river reopened the closed branch during a flood by eroding a channel across the island separating the two channels. The goal of this study is to analyse the consequences of closure, find the variables that affect channel reopening, try to relate the morphological response to the initial hydrodynamic conditions and use them to predict the response. Final objective is to provide guidelines for closing channels in large braided rivers.

The problem is studied with two-dimensional simulations using the numerical Delft3D model. A simplified reference case is set up with two branches separated by an island, based on typical reaches of large braided rivers. Initially a channel is closed with a combination of a weir in the channel and a short embankment on the island. Changes during one dry and one wet season are simulated. A bypass channel is eroded around the weir in the first few days of the wet season. It significantly reduces the effectiveness of closure.

A sensitivity analysis of different physical properties is performed in order to determine how general the simplified case is. Results are analysed qualitatively and quantitatively. Most important quantitative variables are reduction of discharges and near-bank velocities in the closed channel. The effects of sediment transport formulas, sediment size, turbulence, bed slope, helical flow and roughness are assessed. The largest quantitative difference is found for sediment transport formulas, whereas bed slope effect, eddy viscosity and sediment size play a role as well, when certain thresholds are reached. The qualitative morphological response to closure remains similar in all simulations.

The largest part of the study regards the simulations of various interventions and their analysis. First, a simple combination of a weir in the channel and an embankment on the island parallel to its banks is used. The effect of embankment length, crest height and position in the channel is analysed first. Bypass channels develop in most cases. With long embankments, the water level gradient can be reduced sufficiently and the branch can be almost completely closed. Channels across the island are eroded if the branch is not closed in the entrance. Combinations of multiple weirs are found to be a viable alternative that reduces the water level gradients at any single location. Additional weirs can be replaced with roughness elements for the same effect. Partial closure using bandals or groynes causes the largest reduction of near-bank velocities in the closed branch, up to 75%.

The analysis is extended with longer-term simulations, simulations with higher water levels and of four different geometries. Channels crossing the island are dangerous on the longer term, as they do deepen and widen and significantly change the island topography. Higher water levels cause faster erosion of the island. The best solution for high water levels is found with submerged weirs, which can prevent island erosion almost completely. If the island is normally not submerged, closure can cause flooding, but erosion problems are minimal. Length and width of the island play a role in the extent of erosion on the island. At least on the short term and in a simplified case, channel width and bifurcation asymmetry do not.
An analysis of aggregated results is performed to find the hydrodynamic variables that influence branch reopening. A connection of erosion depth of channels on the island to both average velocities and water level gradient at their location is found. Correlation with water depth is weaker, but still present. An approximate prediction of the type of channel that will form can be made from initial hydrodynamic conditions. Channels across the island become the dominant cause of branch reopening when the water level gradient across the island reaches approximately the same values as the gradient around the structure. Prediction of erosion based on initial hydrodynamic properties is not successful, but relative consequences of various interventions can be assessed. A relation between average erosion depth of channels on the island and discharge reduction in the closed branch is shown. Reopening due to formation of channels is the main cause of a drop in closure effectiveness. Increase in water depth in the open branch during the dry season is mainly determined by discharge distribution between the two branches.

Main variables influencing channel reopening are identified from simulations. Water level gradient plays the most important role in determining the location and degree of channel erosion. Water depth on the island is relevant when water levels are relatively low (water depth on the island below 2 m), as it can reduce capacity of flow for erosion. Flow patterns on the island determine the exact position of the channels and directly contribute to erosion. Sediment supply to the eroded channels reduces their growth, while sedimentation in the channel improves conditions over time, possibly leading to gradual closure. Erodibility of the island should affect the rate of channel erosion on the island. The report is concluded by answering the research questions and providing recommendations for closing channels in large sand-bed braided rivers. The best overall solution is found to be a combination of a weir with a long embankment or roughness elements. Further details such as position of the interventions and weir crest height depend on goals of closure and water levels in the system. This study is the first step in understanding the potential and consequences channel closures, and its findings can be used as background for further research and as guidelines when considering such interventions in braided rivers.
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- $\alpha$: Calibration parameter in sediment transport formulas
- $\Delta$: Relative submerged mass density
- $\eta$: Water level
- $\eta_{up}$: Water level upstream of the weir
- $\eta_{down}$: Water level downstream of the weir
- $\eta_{weir}$: Water level at the weir position
- $\Delta \eta_{up,\text{end}}$: Increase in water level upstream at the end of the wet season
- $\Delta \eta_{up,\text{in}}$: Increase in water level upstream at the beginning of the wet season
- $\kappa$: Von Karman constant
- $\theta$: Shields mobility parameter
- $\lambda_p$: Bed porosity
- $\lambda_{lin}$: Linear flow resistance coefficient
- $v_h$: Horizontal eddy viscosity
- $\rho_w$: Mass density of water
- $\rho_s$: Dry mass density of sediment
- $\tau$: Bed shear stress
- $\phi_t$: Bedload transport direction
- $\phi_s$: Final bedload transport direction
- $A_{\text{shield}}$: Calibration parameter for bed-slope effect
- $B$: Channel width
- $B_{\text{shield}}$: Calibration parameter for bed-slope effect
- $b$: Degree of non-linearity of dependence of sediment transport on depth averaged flow velocity
- $C$: Chézy roughness coefficient
- $C_b$: Chézy roughness coefficient due to bed only
- $C_d$: Drag coefficient for vegetation
- $C_{\text{shield}}$: Calibration parameter for bed-slope effect
- $c_{\text{loss,u}}$: Energy loss coefficient for porous plates in x-direction
- $c_{\text{loss,v}}$: Energy loss coefficient for porous plates in y-direction
- $D$: Sediment particle diameter
- $D_H$: Horizontal eddy diffusivity
- $D_i$: Particle diameter of fraction i
- $D_{\text{shield}}$: Calibration parameter for bed-slope effect
- $D_{\text{scour}}$: Depth of the eroded bypass channel
- $D_{50}$: Median particle diameter
- $E_{\text{spir}}$: Calibration parameter for spiral flow
- $E_{\text{up}}$: Energy head upstream of the weir
- $E_{\text{down}}$: Energy head downstream of the weir
- $\Delta E_{\text{weir}}$: Energy loss due to a weir
- $\Delta E_{\text{car}}$: Energy loss due to a weir with the Carnot equation
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g$</td>
<td>m/s²</td>
<td>Gravitational acceleration</td>
</tr>
<tr>
<td>$h$</td>
<td>m</td>
<td>Water depth</td>
</tr>
<tr>
<td>$\Delta h_{\text{end}}$</td>
<td>m</td>
<td>Increase in water depth in the open branch</td>
</tr>
<tr>
<td>$%h_{\text{end}}$</td>
<td>%</td>
<td>Relative increase in water depth in the open branch</td>
</tr>
<tr>
<td>$h_v$</td>
<td>m</td>
<td>Vegetation height</td>
</tr>
<tr>
<td>$I_s$</td>
<td>m/s</td>
<td>Spiral flow intensity</td>
</tr>
<tr>
<td>$i$</td>
<td>-</td>
<td>Bed slope</td>
</tr>
<tr>
<td>$k_s$</td>
<td>m</td>
<td>Nikuradse roughness height</td>
</tr>
<tr>
<td>$L$</td>
<td>m</td>
<td>Length of the river reach</td>
</tr>
<tr>
<td>$M_\xi$</td>
<td>kg/m s</td>
<td>Momentum loss due to a weir</td>
</tr>
<tr>
<td>$m$</td>
<td>-</td>
<td>Bar mode</td>
</tr>
<tr>
<td>$n$</td>
<td>-</td>
<td>Manning coefficient</td>
</tr>
<tr>
<td>$n_{\text{veg}}$</td>
<td>-</td>
<td>Vegetation density</td>
</tr>
<tr>
<td>$Q$</td>
<td>m³/s</td>
<td>Discharge</td>
</tr>
<tr>
<td>$Q_{\text{crit}}$</td>
<td>m³/s</td>
<td>Discharge over the weir when critical flow is reached</td>
</tr>
<tr>
<td>$Q_{\text{cl, end}}$</td>
<td>m³/s</td>
<td>Discharge in the closed channel at the end of the wet season</td>
</tr>
<tr>
<td>$%Q_{\text{cl}}$</td>
<td>%</td>
<td>Relative reduction of discharge in the closed channel at the end of the wet season</td>
</tr>
<tr>
<td>$s$</td>
<td>kg/m s</td>
<td>Sediment transport rate per meter width</td>
</tr>
<tr>
<td>$u$</td>
<td>m/s</td>
<td>Flow velocity in x-direction</td>
</tr>
<tr>
<td>$U$</td>
<td>m/s</td>
<td>Depth averaged flow velocity</td>
</tr>
<tr>
<td>$U_{\text{down}}$</td>
<td>m/s</td>
<td>Velocity downstream of the weir</td>
</tr>
<tr>
<td>$U_{\text{weir}}$</td>
<td>m/s</td>
<td>Velocity on top of the weir crest</td>
</tr>
<tr>
<td>$v$</td>
<td>m/s</td>
<td>Flow velocity in y-direction</td>
</tr>
<tr>
<td>$v_{\text{nb}}$</td>
<td>m/s</td>
<td>Average near-bank velocity in the closed channel</td>
</tr>
<tr>
<td>$%v_{\text{nb}}$</td>
<td>%</td>
<td>Relative reduction of near-bank velocities in the closed channel</td>
</tr>
<tr>
<td>$z_b$</td>
<td>m</td>
<td>Bed level</td>
</tr>
<tr>
<td>$z_{\text{crest}}$</td>
<td>m</td>
<td>Weir crest level</td>
</tr>
</tbody>
</table>
1. Introduction

1.1. Large braided rivers and the dangers they pose

Braided rivers are made up of a network of wide and shallow channels flowing around braid bars or islands. They occur across a variety of different scales and with different sediment sizes. The focus of this study is on large sand-bed rivers. They occur in gentle slopes, due to fine sediment and easily erodible banks that pose little width restriction and high sediment load (Jagers, 2003). Examples are the Brahmaputra-Jamuna River in Bangladesh, the Ayeyarwady River in Myanmar and the Upper Yellow river in China. They can have a combined channel width of a kilometre or more.

The rivers provide water and nutrients for agriculture, transport routes and support various ecosystem services. The livelihood of many people depends on them in some way. However, they are geomorphologically active, with rapid planform changes that are difficult to predict (Figure 1.2). Large hydrological variations between the dry and wet season lead to floods and navigability problems. This dynamic nature can be a major threat to the surrounding population.

The largest rivers may have bank line shifts of hundreds of meters per year (Baki & Gan, 2012). Bank erosion leads to loss of homes and whole villages, amenities and fertile agricultural land, destruction of infrastructure and flood protection (Figure 1.1). Resulting flooding can lead to damage that is even more extensive. Usually the poorest parts of the population are affected most severely, as they live in erosion prone areas. They are left with little choice but relocating to slums of large cities or try surviving on unstable islands (Rahman, 2010). Prevention or mitigation of bank erosion can help avoid these issues.

In floodplains that have experienced significant erosion in the past, land reclamation can return the riverbank to past conditions. Displaced people can resettle and valuable agricultural land is retrieved. Land increases in value, as it becomes erosion and/or flood risk free. In addition, narrowing the river corridor is expected to make the river less dynamic and easier to manage (FAP21/22, 2001).

Figure 1.2: Successive river courses in the Jamuna river between years 1973-1992. Each color indicates one year (Mosselman, 2006)

Figure 1.1: Bank erosion along the Jamuna river in Bangladesh [https://www.thethirdpole.net/2013/05/28/villages-swallowed-as-river-erosion-accelerates-in-bangladesh] (7.2.2017).
Rapid planform changes and wide but relatively shallow channels also pose problems for navigation. Unknown thalwegs, shallow areas, obstacles in main channels and an absence of fixed points on the banks all hinder efficient use of the river. During the dry season, water depth may be too low in multiple places. Vessels may be required to travel longer distances or even become stranded along the way (Jibon, 2013). During the wet season, high velocities cause hazardous situations. Channel shifts result in unknown positions of the main navigable channel after each monsoon season (van der Velden, 2015). The problem is more crucial in light of the fact that navigation is often the most important mode of transport where these rivers are present (Karmaker & Dutta, 2016).

1.2. Problems with river training in large braided rivers

The described problems can be mitigated by river training. However, in such large and dynamic rivers, this is usually difficult and expensive. Conventional river training structures such as groynes were developed in smaller watercourses. Scaling them up can lead to a disproportional increase in costs. Moreover, most large braided rivers are located in developing countries, possibly lacking required resources. Upscaling may not be correct from the process point of view as well. For example, due to an increase in size, additional processes occur around groynes (Figure 1.3). Conventional permanent interventions are also problematic due to their inflexibility and can sometimes be completely bypassed if the channels shifts their position (Nakagawa et al., 2013). A large river is powerful enough to destroy training measures (Rahman et al., 2004). Finally, interventions are often need driven and lack appropriate knowledge of long-term and large-scale consequences. Due to these considerations, gradual and adaptive river training is preferred, building upon the increased understanding of the river behaviour and its response to various measures.

More adaptable, smaller, cheaper and less disturbing alternatives using local materials are sought to replace conventional measures. In a study about river training in the Jamuna river (FAP21/22, 2001), recurrent measures were found to be about 50% cheaper than permanent ones. The most efficient solutions are often combinations of permanent and temporary measures. For that, novel approaches to river training are sought. For example, bandals were found to be a promising way to divert flow from the banks, induce aggradation and stabilize a channel gradually (Nakagawa et al., 2013). A larger-scale river training scheme can be designed with a combination of local permanent hard points and temporary or permanent closures of problematic channels (FAP21/22, 2001). Many river training projects are currently underway in large braided rivers, both on a local (Ko, 2016) and large scale (NHC Northwest Hydraulic Consultants & Mott MacDonald, 2014; Directorate of Water Resources and Improvement of River Systems, 2016). They all propose the use of novel and adaptable river training solutions to some degree.
1.3. **Channel closure as a river training measure**

Closure of one of the channels is one of the possible river training solutions to the problems described above. It can be used to divert flow from an aggressively eroding branch. Routing more water towards the main channel and stabilizing the planform can solve navigability problems. Land reclamation can start by closing secondary channels and forcing deposition within them.

Channels can be closed with low-cost recurrent measures made out of local materials. This provides the flexibility required in such dynamic and complex rivers. On its own, closing a channel provides a temporary and local solution. When long-lasting improvements are required, permanent closures can be combined with other conventional measures along the river. Examples of those are hard points upstream, which prevent eventual migration of the main channel into the closed branch, and bank protection to prevent erosion of the reclaimed land.

Based on a multi-criteria analysis, Hooning (2011) proposed that the most promising way of managing the braided Koshi River is narrowing it by closing some of its channels. The Brahmaputra-Jamuna River has widened significantly in the past four decades, but this process has now stopped (Takagi et al., 2007). The current river training paradigm is gradually narrowing it back to its previous width. Channel closures are to be used as supporting temporary measures. Once the required width is achieved, its course can be fixed with permanent training works (NHC Northwest Hydraulic Consultants & Mott MacDonald, 2014). In the Ayeyarwady River, a project is underway, where a channel will be closed in order to keep the main navigable channel next to the port of Mandalay (Directorate of Water Resources and Improvement of River Systems, 2016).

Despite mentions of channel closures in various projects, little is written about their consequences and processes that cause them. Channel closures done so far have not been well documented and no guidelines on their use exist. The few documented cases were only partially successful. During the wet season, the closed branch reopened, as the river eroded a new channel across the island separating the channels (Figure 1.4). The causes behind this and ways to prevent it are not well understood (Mosselman, 2006). Deltares is a project partner in river training projects in both Brahmaputra-Jamuna and Ayeyarwady River (NHC Northwest Hydraulic Consultants & Mott MacDonald, 2014; Directorate of Water Resources and Improvement of River Systems, 2016). Both projects involve channel closures and would benefit from understanding the processes involved better.
1.4. Previous research

Braided rivers in general have been extensively researched in the past concerning various subjects (Bristow & Best, 1993). Research into braided river morphodynamics has been largely focused on scale experiments representing gravel-bed rivers. This was able to provide understanding of various isolated processes such as initiation of braiding and its further development (Ashmore, 1982), bar formation and shape (An et al., 2013), or channel avulsions (Ashworth et al., 2007). There have been some scale experiments designed to explore sand bed rivers (Klaassen, 1987), but usually scaling problems are too large. It is difficult to fulfil scaling laws satisfactorily in rivers that are multiple kilometres wide but transport sediment that is less than a millimetre in diameter.

Studies on large sand-bed braided rivers were mostly focused on field measurements, satellite observation, and some numerical modelling. General behaviour and planform changes of sand bed braided rivers were studied (Coleman, 1969; Bristow, 1987; Thorne et al., 1993; Sarker et al., 2014) as well as development (Ashworth et al., 2000) and flow patterns around braid-bars (McLelland, et al., 1990) and bankline shifts (Takagi et al., 2007; Baki & Gan, 2012). Various models were developed to predict morphological evolution of braided rivers. First attempts were made with predictive models based on probabilities of certain morphological changes (Klaassen & Masselink, 1992; Klaassen et al., 1993) supported by observations and later results of numerical modelling (Jagers, 2003). Reduced-complexity models (e.g. cellular models) are able to reproduce large-scale morphological development to a certain degree, but fail when channel details are required (Ziliani et al., 2013).

Finally, physics based numerical models are starting to be used more extensively in the study of braided rivers (Williams et al., 2016a). Schuurman et al. (2013) and Yang et al. (2015) used a numerical model to simulate a self-formed braided river and study the processes involved in braiding. Wang et al. (2008) and Williams et al. (2016b) modelled real rivers and compared model results with measurements to assess the effectiveness of the models. Nicholas (2013) used a numerical model that incorporated bank erodibility and vegetation establishment to study the causes of various river planforms. Numerical models show promising results when used to analyse braided rivers, but there are still problems with accurate flow and sediment transport prediction, scaling in space and time and particularly with calibration and validation of models with actual rivers (Williams et al., 2016a). Lack of data is the largest reason for the latter.

Research has been done on training large sand-bed braided rivers as well. It can be separated into two categories, investigations focused on particular measures and those studying short or long-term morphodynamic effects of river training. Examples of the first are studies of groynes (Nakagawa et al., 2013), bandals (Zhang et al., 2010; Rahman & Osman, 2015) or porcupines (Tang et al., 2009; Lu et al., 2011; Aamir & Sharma, 2015). These studies focus mainly on local hydrodynamic properties. Schuurman et al. (2016) used a numerical model to study larger reach-scale effects of river training measures in a self-formed braided river. Karmaker and Dutta (2016) made a short-term simulation of a smaller braided reach in the Brahmaputra River in order to compare different river training measures. The general problem of river-training related studies is that little or no data exists to calibrate and validate the models. On the other hand, models often remain the only option, as pilot tests are expensive and often unwanted by the local authorities.

Finally, almost no research exists on closure of channels in braided rivers. The only case study found was described in a paper by Mossleman (2006) on the Jamuna-Brahmaputra River. The rest of were performed with numerical models (Hooning, 2011; Karmaker & Dutta, 2016; Schuurman et al., 2016) and were not focused on channel closure specifically.
1.5. **Problem definition and objectives**

Closing one of the channels of a braided river is a promising way of training large braided rivers. It can be used to prevent erosion of aggressive outflanking channels, improve navigability or reclaim land. For land reclamation, the closure has to be permanent, whereas for protection against erosion, one flood season could be enough and the measures repeated next year at a different location. A reduction of near-bank velocities in the closed channel could be achieved without closing it off completely. For navigability improvement, water depth in the open branch is important.

There has been no systematic research into this type of interventions and no guidelines or recommendations exist on their use. In the few documented cases, the closed branch reopened, as the river eroded a new channel across the island separating the two branches. The mechanisms causing this and the processes involved are not well understood, neither is the exact effect of it on closure effectiveness.

Smaller-scale and short-term consequences of channel closure have to be understood first and are the focus of this initial study. This will already produce knowledge that can be used in designing such interventions. Longer term and larger scale morphodynamic predictions are generally uncertain in dynamic braided rivers. Moreover, on a larger scale, closures should be considered together with other river training measures, as they would likely not be used alone. This makes predicting specific larger scale (spatial and temporal) response to channel closures difficult, but some understanding of possible development is beneficial.

A two dimensional numerical model including morphology is to be used in this study, as it allows simplification and multiple tests without large expenses. Similar models are used in most projects related to channel closures. However, numerical models can be time consuming, especially when morphodynamic modelling of real rivers is involved. It would be useful if predictions regarding closure consequences could be made based only on initial hydrodynamic conditions after a channel is closed. This would enable a quick first assessment and comparison of different options.

To solve the problems defined above, multiple interventions should be tested in various conditions, their consequences and the processes involved thoroughly analysed. The objective of this study is to find and define effective river training measures to close channels in a braided river and prevent reopening of the closed branch. Different possible goals of closure should be taken into account. To do this, the mechanisms of channel reopening and the variables that influence it have to be found. The focus should be on short term and small-scale response. An effort should be made to find relations between hydrodynamic conditions and the morphological response to closure and use them to establish a predictive model that would allow a quick assessment of various interventions.

The final goal is to find an effective way of closing channels in large sand-bed braided rivers. The channel should remain closed during high flow and at least the subsequent dry season. The results should be generally applicable. This can be achieved by focusing on discovering key processes related to channel closure, without delving into details of possible local situations. Various situations should be tested to obtain a thorough understanding. The results should provide a foundation on which to build with further studies, as well as basic guidelines for channel closures. It is expected that before actual implementation in river training projects, further case specific analysis will be unavoidable due to large differences both between and within braided rivers.
1.6. Research questions

Based on the analysis above, the problem can be summarized in a research question:

**How to use river training measures in order to close channels of large sand-bed braided rivers in a way that remains effective during and after high flow?**

Answering this question leads to the following sub-questions:

- *What are the causes by which channel closure measures in braided rivers fail in the short term?*
- *Which variables affect reopening of the closed branch and which are the mechanisms of channel formation?*
- *What are longer-term trends in the response to channel closure and how long can closure remain effective?*
- *How is the morphodynamic response to channel closure (island erosion) related to the initial hydrodynamic conditions after closure and how well can the response be predicted from them?*
- *To what degree can the results obtained with a numerical model be generalized to large braided rivers?*

1.7. Methodology

The methodology needs to reflect the research objectives and provide an answer to the research questions. Testing closure measures in the prototype would be time consuming and expensive and various processes would be harder to study. Physical modelling is beyond the scope of this study due to both time constraints and facility requirements. A physics based numerical model is used. This way it is possible to run many simulations, to control the boundary conditions and to analyse the results thoroughly in the time available. A Delft3D model is chosen, because of software availability, previous experience, available support and its previous use and validation on modelling braided rivers and river morphology in general.

No exact measured data on channel closures is available, only some reports that describe the general developments. Moreover, the problem has not been studied before, so it is beneficial to start with a simple case that can isolate the most important processes. A simplified symmetric reach with two branches separated by an island is set up. One of the channels is closed with a combination of a weir and a short embankment on the island parallel to the channel. This case is used perform an initial analysis of the processes and morphological changes (channel reopening) that take place after a channel is closed.

Model results could depend strongly on the choice of input parameters. A sensitivity analysis is performed around the reference case in order to generalize the results that are similar in all cases and understanding of physical processes that cause the differences when they are not.

The sensitivity analysis is followed by simulations of various interventions. Weirs combined with embankments or vegetation, roughness elements and groynes or bandals are tested. The measures are tested in different positions, with varying water levels and in five different geometries. Select simulations are extended for an additional wet season to assess the morphological trends on the longer term. Performance is assessed based on discharge and
velocity reduction in the closed channel and increase in water depth in the open branch (measure of navigability improvement).

The output data of the many simulations is combined and used to analyse the relations between erosion of new channels on the island and effectiveness of closure as well as initial hydrodynamic conditions during the wet season. The relations with hydrodynamic conditions are sought at each numerical cell and at the location of eroded channels. An attempt is made to also predict erosion and closure effectiveness from initial hydrodynamic conditions based on knowledge obtained in previous steps.

It has to be kept in mind that this is a model study. An attempt is made to relate the results as much as possible to real rivers. However, the reality is more complex and additional processes likely play a role in the river response. Further research will be required once basic knowledge is obtained from this study.

1.8. Thesis outline

The thesis is divided into 9 chapters. In the current chapter, the introduction to the problem is presented and research questions are defined. The next chapter deals with a review of the most important morphodynamic processes in braided rivers and variables that play a role in them. The third chapter describes river training in large braided rivers, starting with various possible measures followed by an analysis of channel closure. The fourth chapter presents the choices for the model set up and describes the reference case. In the fifth chapter, the sensitivity analysis to assess the importance of various parameters is presented. In the sixth and largest chapter, the results of modelling various interventions in different conditions are shown and compared. In the seventh chapter, analysis of results with a goal of finding relations between variables is shown, and various attempts to derive simple predictions for island erosion are presented. The eighth chapter contains the discussion. It is mainly focused on the different variables that play a role in channel reopening, based on the results shown in previous chapters. The final chapter presents the conclusions and answers to the research questions. Recommendations and guidelines for channel closure are given. The thesis is concluded with recommendations for further studies.
2. Braided river morphodynamics

2.1. Introduction

To model the problem and interpret the results, hydro- and morphodynamic processes related to braided rivers and channel closure need to be understood well. Complex and larger scale processes are described, followed by more elementary aspects. First, a short discussion on the positioning of the study within the field of river engineering is appropriate. This work deals mostly with river morphodynamics. Prediction of planform changes, erosion and deposition is based on sediment transport, which depends on hydrodynamics, which again depends on even more fundamental processes. It is last in a chain of calculations, and thus accumulates the largest error and is most uncertain. Knowledge of lower-level processes is required to make accurate predictions, however integration from lower levels is only useful to a certain extent. For example, small variations in hydrodynamics can be less important in comparison with uncertainty inherent in predictions of sediment transport. Often improving accuracy of modelling more fundamental processes brings bring only little improvement of the results. Therefore, the focus of this chapter and the study in general is on processes directly affecting the morphodynamic response to channel closure.

2.2. Bifurcations and confluences

Bifurcations and confluences are the basic components of braided rivers (Surian, 2015). This study is based on one bifurcation-confluence section. Understanding bifurcation-confluence dynamics is valuable in order to determine appropriate sites for channel closure. Bifurcation instabilities may sometimes result in a natural closure of a channel, which could be exploited by adaptive river training interventions. On the other hand, attempts to close a channel that is becoming dominant might prove futile. However, it must be emphasised that this is not a bifurcation study. During the wet season, the whole planform is submerged and the bifurcation disappears.

2.2.1 Bifurcations

At bifurcations, the flow and sediment are distributed between two or more channels. Ashmore (2013) describes symmetric and asymmetric bifurcations in braided rivers. In a symmetric bifurcation, the main flow direction changes as the two channels turn away from each other. Deposition occurs in the upstream part of the channels and propagates inwards. This development is countered by bar head erosion during floods. In an asymmetric bifurcation, one of the channels has more or less the same direction as the inflow. The other channel is smaller and usually temporary. An asymmetric bifurcation is usually characterised by a difference in bed levels between the two branches. As one branch grows, it becomes deeper and wider, while the other one slowly narrows from the entrance downstream.

In sand bed braided rivers, bifurcations often evolve towards symmetrical geometries (Surian, 2015). However, the other trend is possible as well. There are various possible reasons for a change from a symmetrical to an asymmetrical bifurcation. Examples of these are migration of a bar that deflects the flow towards one of the channels, formation of a bar in the entrance of one of the
branches, a shift of the inflow channel and a bar downstream in one of the branches that narrows the cross section and causes a backwater effect (Schuurman & Kleinhans, 2015). This type of processes could play both a positive and negative role during channel closure. Backwater effect can be caused by partial closure and resulting bifurcation asymmetry could lead to channel abandonment. On the other hand, a bar deflecting flow into the closed channel could reduce the effectiveness or even make closing it impossible (Figure 2.1).

Distribution of sediment at the bifurcation depends on its topography, mode of sediment transport and flow patterns. It determines the stability of the bifurcation. In 1D models sediment distribution is modelled with nodal point relations, (Wang et al., 1995; Bolla Pittaluga et al., 2003). However, Schuurman and Kleinhans (2015) argue that in large sand bed braided rivers, even when a constant hydrograph is used, these relations do not work properly due to non-linear processes, migrating bars and backwater effects.

2.2.2 Confluences

Confluence geometry is usually more complex. It depends on relative discharges and sediment transport rates in the two channels, bed shear stress, sediment grain size distribution and the angle of incoming channels (Ashmore, 1993). Behind the island, a region of slack water can be present. It usually disappears in a year due to accelerated deposition. On the other hand, scour holes are common in confluences of major branches due to concentration of the flow (Ashmore, 2013).

Confluences are usually more stable than bifurcations, as long as the two channels are relatively symmetric. When one channel becomes dominant, the confluence moves towards and into the smaller channel through deposition (Klaassen & Masselink, 1992). If the flow separates again after a confluence, a bar might start growing and a second bifurcation develops (Ashmore, 1982). The direction of the downstream channel usually adapts to flow upstream of the confluence (Ashmore, 2013). This can be further affected by the growing bar tail limb, directing the flow to one side, possibly affecting the next bifurcation (Schuurman & Kleinhans, 2015). This way, disturbances can propagate through the braided system (Schuurman et al., 2016).
2.3. Braided islands

Thorne et al. (1993) distinguish between two types of bars in large braided rivers, meta-stable islands and mobile braid bars. Islands scale with full width of the river and reach almost floodplain height, whereas bars scale with individual channels. They are flat and highest along the sides and at the bar head. Some large islands are permanently populated and support agriculture and vegetation. They are submerged only during floods. Often they are covered by a layer of cohesive silt, which makes them more resistant against erosion. Their movement is limited, but they are reworked by erosion, bar dissection and accretion. Smaller braid bars have a looser surface that is easier to erode, only seasonal vegetation and are not permanently inhabited. They are overtopped by regular wet season discharges and are more morphologically active. Usually they remain in the same place for a few years only. Even smaller bars emerge only during low flow. They scale with secondary channels and obey bar to channel width relations. They are highly mobile and can move as much as 100 m every day.

2.3.1 Island shape

In a study on scale invariance of braided planforms, Kelly (2006) describes that major and minor axis of braided islands scale with each other and with the total bar area and perimeter. The major axis is two to ten times larger than the minor one. He also argues that bars scale with channel width. This holds for smaller bars but does not seem to be true for large islands in large sand-bed braided rivers, which can be much larger than that. Sambrook Smith et al. (2005) drew the same conclusion about scale invariance with a dataset that included the largest braided rivers as well.

2.3.2 Bar development

Bars grow mainly during low flow by lateral, downstream and upstream accretion. The largest contribution is by lateral accretion. Most bars migrate downstream through upstream erosion and downstream deposition (Bristow, 1987). As mentioned before, the largest islands are more stable and their position is often determined by larger scale controls on river planform. The usual development is growth of an embayment in the island due to flow deflection caused by growth of a bar on the other side and dissection by smaller channels in low points during high and falling stages (Thorne et al., 1993).

Similar findings related to bar propagation and growth were found in a numerical model study by Schuurman and Kleinhans (2015). Unit bars propagated through the river with celerity of 1 km a month. Larger compound bars were more or less static. Partly, this was considered a consequence of constant discharge and a primitive bank erosion formulation in the numerical model. The island head is eroded by the flow and the eroded sediment deposits in the bar tail (Figure 2.2). The dominant channel can be recognized by a larger bar tail limb that grows at the end of the island erosion (Schuurman & Kleinhans, 2015).

Ashworth et al. (2000) describe a comprehensive survey of development of a bar in the Jamuna River throughout its lifetime. The bar was 1.5 km long and 500 wide. During high flow, the bar top
was eroded, with local erosion depths reaching 6 metres. The eroded material was deposited in the anabranches and eventually washed away. Bed forms were found to be important for bar growth. Dunes slowed down both on bar top and at its sides causing accretion. Bar growth caused incision and shifts of the surrounding channels. In the slack zone behind the bar, rapid deposition occurred. Due to a change in upstream conditions, one of the branches started to become dominant, whereas the other started to fill up with deposited sediment. A bar tail developed in the confluence.

2.3.3 Flow patterns and sediment transport around islands

McLelland et al. (1990) conducted a study of flow patterns and sediment transport for the same braid bar in the Jamuna River. They found that helical flow plays almost no part. The authors did not find any significant and consistent difference between flow directions at different levels in the water column. This could be due to high width to depth ratios, flow from the island top into deeper channels and relatively small curvature. The flow is characterized only by divergence at the bifurcation and convergence near the bar tail. The former causes a dune front to stall and accrete, whereas the latter causes confluence scour. The flow diverges and accelerates over the bar head. Water depth on top of a submerged bar is shallow and large concentrations of sediment are present.

2.4. Bank erosion and bed scour

Bank erosion is one of the main problems in braided rivers. Its prevention is an important goal of channel closures. Various mechanisms of erosion are possible. In non-cohesive sediments, bank erosion occurs in shallow slides and through fluvial entrainment of particles. When banks are somewhat cohesive, the main erosion process is undercutting by the flow, which destabilizes the upper part of the bank. Failed material deposits at the toe and is eventually washed away. Banks may collapse due to water saturation, especially after a water level drop in the channel (Jagers, 2003). Finally, outflow of subsurface water can destabilize the bank and cause undercutting as well. This process is called piping or sapping, depending on the extent of the outflow area (Hagerty, 1991).

In large braided rivers, undercutting by large near-bank flow velocities that entrain bank sediment is the most common erosion process. Banks are cohesive enough that almost vertical planes are possible. After bank failure, blocks break down quickly and are washed away, which means that no temporary stabilization at the toe is provided (Thorne et al., 1993). Uddin and Rahman (2011) found that in a bend in the Jamuna River, near-bank shear stresses were six times higher than the critical stress. All of this leads to rapid erosion. Bank protection can mitigate the problem, but may result in deeper bend scour near the banks (Mosselman et al., 2000). A better solution would be to reduce velocities altogether.

Subsurface flow is known to play a part in riverbank erosion. It usually follows bank recharge by high flow or rainfall. Due to the presence of a less permeable layer the outflowing water concentrates. If the gradient is sufficient, entrainment of particles and possibly larger scale erosion occurs (Hagerty, 1991). Bank erosion due to seepage is documented by Karmaker and Dutta (2013) in the Brahmaputra River.

In the Jamuna River, eroding banks cause bank erosion of up to 500 m or even 1000 m per year in extreme conditions (Klaassen & Masselink, 1992). The average erosion rates were found to be around 200 m per year by Baki and Gan (2012). Sharper bends were found to cause faster erosion.
Influence of vegetation is negligible, as its roots do not penetrate deep enough to have an effect on the undercutting process (Klaassen & Masselink, 1992). Erosion is not limited to extreme events and is common even during the dry season and in smaller channels (Sarker et al., 2014).

### 2.4.1 Bed scour

Jagers (2003) describes multiple types of scour in braided rivers. Bend scour results in a scour hole in the outer bend because of helical flow patterns in a bend. Scour develops downstream of a confluence due to flow concentration where two channels join. It is especially prominent if channels join at a large angle. When a channel is confined at sides by bank protection or non-erodible banks, constriction causes erosion of the bed. The last scour type occurs at flow obstructions such as groynes, bridge piers or closure structures (Figure 2.3). Scour is mostly a consequence of increased mean flow velocities. However, increase in turbulence plays a role as well and can deepen scour holes further.

![Types of scour after Jagers (2003): (a) bend scour, (b) confluence scour, (c) constriction scour, (d) obstruction scour.](image)

### 2.5. Channel shifts and channel formation

Channel shifting in braided rivers is a common but complex process. It is difficult to determine the exact cause of the shift in each particular case and even harder to predict it. Usually an abandoned or smaller channel is reclaimed, and takes over the main conveyance function. It usually happens due to an unstable bifurcation or migration of the upstream channel. Propagating sand bars can block the one of the channels and divert flow into the other, causing bifurcation asymmetry or complete channel abandonment (Leddy et al., 1993). In some cases with high water depths, the multiple channel pattern is washed away during a flood, and the planform develops anew during the falling stage (person. comm., Kees Sloff). Bend cut-offs occur at lower cut-off ratios than in meandering rivers. Few sharp bends are present in the river. Channel shifts also happen when overbank flow erodes a completely new channel across the bar separating two branches (Klaassen & Masselink, 1992).

The process of new channel formation in braided rivers is not completely understood. In meandering rivers, cut-off channels often form from the downstream side of the bar if the form of a headcut. The water plunges into the channel with. Low water depth at the edge of the bar causes flow acceleration and increased sediment transport. Turbulent eddies develop near the bank and can cause undercutting. As the headcut develops, flow converges. This further accelerates the erosion (Jagers, 2003). Erosion from upstream is also present in the form of...
embayment erosion, caused by high shear stresses on the channel floodplain boundary (Constantine et al., 2009).

In braided rivers, the mechanisms of channel formation seem to be different. In a study by Jagers (2003), he found that in the Jamuna River, channels often form from the upstream side. He explored mechanisms of channel formation with a numerical model to determine what causes each type of channel erosion. Most results showed erosion starting from upstream as a propagating expansion wave. Headcut erosion could be reproduced only by specifically adjusting the model. When a cohesive layer was modelled by using a high critical shear stress close to the actual, the former is exceeded only in several places. Erosion occurred there, which exposed a weaker sandy layer below. This enhanced the erosion and attracted more flow. The other situation that downstream erosion was low water levels downstream, that caused acceleration and an increase in sediment transport capacity at the end of the bar. This erosion mechanism was also observed by Leddy et al. (1993) in scale experiments.

For further comparison, Sloff et al. (2004) identify two types of channel forming processes in reservoirs. The first one is headward erosion that occurs due to lowering of downstream water level and is similar to meander cut-off formation described in first paragraph. The second is called degradation, and is caused by erosion from upstream due to sediment supply being lower than transport capacity.

The analysis above provides a possible explanation why rivers erosion usually starts from the upstream side in large sand-bed braided rivers. First, sediment has little cohesion and is easily erodible. When the river flows on the bar, transport capacity becomes larger than the low sediment supply. Finally, in braided rivers water levels during floods are usually much above island level, which prevents large local accelerations at the downstream side.

### 2.6. Effect of hydrograph stages on braided morphology

Four hydrograph stages can be distinguished in large braided rivers, low, rising, peak and falling stage. They are a consequence of the typical climate in regions where these rivers are located, with one dry and one wet season. They have different contributions to morphological development. Even during low flow, some aggressive channels can cause bank erosion. Bars grow by lateral accretion (Ashworth et al., 2000) and some smaller channels can be abandoned (Bristow, 1987). During the rising stage deepening and widening of the channels takes place, to provide room for increased discharge. Peak flow causes most bank erosion problems and can completely wash away some of the bed topography, including smaller bars (Ligthart, 2017). Observations of Coleman (1969) and results of a numerical model by Yang et al. (2015) indicate that new channels form in particular during the falling stage. Due to a rapid drop in velocities, there is a lot of deposition. Bars form and block or deflect the flow, causing erosion of new channels. Large velocities and low water depths are present on the islands and can cause rapid erosion for a short time (Jagers, 2003). Likelihood of bank failure also increases during the falling stage. Heavy saturated banks lose their lateral support by the water in the river. Outflow of subsurface water further reduces shear strength and causes undercutting by seepage (Hagerty, 1991).
2.7. Bed roughness

In large sand-bed braided rivers, the bed is usually covered by dunes. Bedform roughness dominates over grain roughness. Froude numbers are usually low and the bed is in the lower regime. During high-flow periods, dunes can locally be washed out as the bed reaches the transition phase. A result is a sudden drop of resistance and shear stress and a decrease of the water levels. Usually, roughness reduces with larger water depths. Growth of bed forms can reduce this effect. The roughness of the Jamuna River drops from $50 \; m^{1/2}/s$ to $70 \; m^{1/2}/s$ during high flow (Jagers, 2003). To include the effect of varying depth on roughness, the Manning or White-Colebrook formulas are often used in models:

$$C = \frac{\frac{1}{n}}{}$$  \hspace{1cm} (4.1)

$$C = 18 \log_{10} \left( \frac{12h}{k_s} \right)$$  \hspace{1cm} (4.2)

Where $C$ is the Chézy roughness coefficient [$m^{1/2}/s$], $h$ the water depth [m], $n$ Manning roughness coefficient [-] and $k_s$ Nikuradse roughness height [m].

Studies show that in large sand-bed braided rivers roughness depends more strongly on the water depth as is accounted for in the above equations. Ma and Huang (2016) found this for the lower Yellow river. The same holds for the Brahmaputra-Jamuna River in Bangladesh (FAP24, 1996), where the Chézy value was found to be proportional:

$$C = 25h^{0.5}$$  \hspace{1cm} (4.3)

Depth dependence may affect morphological development, as it can change the distribution of flow and sediment transport in favour of shallow areas. It has a twofold effect on sediment transport. Increase in roughness reduces flow velocities and subsequently reduces the sediment transport. On the other hand, it increases the forces on the bed. The combination of both can either reduce or increase total sediment transport, which cannot be easily predicted without detailed calculations (Jagers, 2003). Finally, roughness is usually used as a calibration parameter that takes into account sub-grid processes as well. Thus, the underlying formulation becomes somewhat less important after a calibration has been made.

2.8. Sediment transport and its prediction

In large sand-bed braided rivers, sediment transport is dominated by suspended load and bed form migration. Clays and silts are transported as wash load and deposit in slack water zones. Sediment transport is occurs throughout the year and dominant flow that transports most sediment cumulatively is usually below flood discharges (Thorne et al., 1993).

Sediment transport starts when flow bed shear stress exceeds a critical value. Shear stress is usually expressed with a Shields parameter, which is derived from force equilibrium on the whole bed:
\[ \theta = \frac{\tau}{(\rho_s - \rho_w)gD} \] (4.4)

Where \( \theta \) is the Shields mobility parameter [-], \( \tau \) bed shear stress [N/m\(^2\)], \( \rho_s \) density of sediment [kg/m\(^3\)], \( \rho_w \) density of water [kg/m\(^3\)], \( g \) gravitational acceleration [m/s\(^2\)] and \( D \) sediment particle diameter [m].

In large sand-bed braided rivers the sediment is fine, which means the critical shear stress can usually be neglected in sediment transport formulas. Multiple sediment transport predictors exist, the most common being Engelund and Hansen (1967), Meyer-Peter and Muller (1948) and van Rijn (1993). The Engelund-Hansen formula reads:

\[ s = \frac{0.05}{\sqrt{gC^3\Delta^2D_{50}}}U^5 \] (4.5)

Where \( s \) is sediment transport rate per metre width [kg/m\(^3\).s], \( U \) depth averaged flow velocity [m/s], \( g \) gravitational acceleration [m/s\(^2\)], \( C \) Chézy roughness coefficient [m\(^{1/2}\)/s], \( \Delta \) relative density [-], \( D_{50} \) median particle diameter [m].

The commonly used sediment transport formulas were derived from measurements in small rivers or from flume experiments. Molinas and Wu (2001) argue that they are not accurate in large and deep rivers. Indeed, after an extensive measurement campaign in the Jamuna River (FAP24, 1996), it was found that sediment transport is best predicted with the following formula:

\[ s \left( \frac{1 - \lambda_p}{\sqrt{g\Delta D_{50}^3}} \right) = 0.165 \left( \frac{U^2}{C} \right)^{1.83} \frac{C^2}{g} \] (4.6)

Where \( s \) is sediment transport rate per metre width [kg/m\(^3\).s], \( \lambda_p \) bed porosity [-], \( g \) gravitational acceleration [m/s\(^2\)], \( \Delta \) relative density [-], \( D_{50} \) median particle diameter [m], \( U \) depth averaged flow velocity [m/s], \( C \) Chézy roughness coefficient [m\(^{1/2}\)/s].

The formula has similar structure to the Engelund and Hansen formulation. The power on velocity is smaller. Predicted sediment transport in the deep channels is lower, whereas in the shallow areas with low velocities it is larger. This relates to the considerations on higher depth dependence of roughness in braided rivers mentioned in section 2.7. Ligthart (2017) shows a derivation of a sediment transport formula with a lower power on velocity by combining the Engelund-Hansen formula and a roughness predictor with a power of 0.5 on water depth. Such a formula showed the best results for modelling the braided Ayeyarwady River.

### 2.9. Spiral flow and bed slope effect

Spiral or helical flow is caused by flow curvature. Inequality of transverse forces in the cross-section forces flow towards the outer bend close to the surface and towards the inner bend near the bottom. Combined with primary flow downstream, this results in a helical flow pattern along the curved river course. Helical flow deflects the transported sediment. As higher concentrations of suspended sediment are found near the bottom, the total sediment load is deflected towards
the inner bend. This results in bend scour and possible bank instabilities in the outer bends and formation of point bars in the inner bends. Helical flow can have a large effect on channel migration, especially in rivers with rapidly erodible banks. Interestingly, McLelland et al. (1990) report that almost no secondary flow patterns were found in curved channels along a braid bar in the Jamuna River, which indicates that the process could be less important in large, deep rivers with low curvature. Schuurman et al. (2013) found that the secondary flow effect enhanced the development of the braided pattern in a self-formed braided river. The equations below are used to describe the deflection of sediment transport due to helical flow:

\[
\tan(\phi_s) = \frac{v - \alpha_I u}{u - \alpha_I v} l_s
\]

(4.8)

\[
\alpha_I = \frac{2}{\kappa^2} E_{\text{spir}} \left(1 - \frac{1}{2 \kappa C} \sqrt{g} \right)
\]

(4.9)

Where \(\Phi_s\) is the direction of bed load transport relative to primary flow direction due to secondary flow, \(v\) and \(u\) are flow velocities in y and x direction [m/s], \(l_s\) the spiral flow intensity [m/s], \(C\) the Chezy roughness coefficient [m\(^{1/2}\)/s], \(h\) the water depth [m], \(\kappa\) the von Karman constant [-], \(E_{\text{spir}}\) calibration coefficient of the spiral flow [-].

The effect of gravity on sediment transport (bed slope effect) has an important influence on morphological development. The component of gravitational forces downslope enhances or reduces sediment transport rates. The steeper the slope, the higher its effect is. Gravity affects the direction of sediment transport as well, by deflecting it downslope. This reduces sharp gradients in the bed and results in a flatter bed topography overall. There are various ways to parameterize the bed slope effect in numerical models. However, accurate representation of the bed slope effect in numerical models is difficult to obtain and the selection of calibration parameters is often arbitrary. Schuurman et al. (2013) found that varying the parameters for bed slope effect significantly influences braiding intensity, dimensions of the channels and bar heights. In this study, the method of Talmon et al. (1995) is used. The equations describe the deflection of the angle of sediment transport direction due to bed slope:

\[
\tan(\phi_s) = \frac{\sin(\Phi_s) + \frac{1}{f(\theta)} \frac{dz_b}{dy}}{\cos(\Phi_s) + \frac{1}{f(\theta)} \frac{dz_b}{dx}}
\]

(4.10)

\[
f(\theta) = A_{\text{shield}} \theta B_{\text{shield}} \left(\frac{D}{h}\right)^{C_{\text{shield}}}
\]

(4.11)

Where \(\Phi_s\) is the direction of sediment transport due to bed slope effect and \(\Phi_s\) direction of shear stress (sediment transport before the bed slope effect), \(z_b\) the bed level [m], \(A_{\text{shield}}, B_{\text{shield}}, C_{\text{shield}}, D_{\text{shield}}\) are calibration parameters [-], \(\theta\) is the Shields mobility parameter [-] and \(D\) the grain size [m].
2.10. Turbulence

Effects of turbulence can be found in all aspects of braided river morphodynamics. It plays a role in the flow around braided islands, in bifurcations, confluences and at bankline discontinuities. Turbulence plays a part in energy dissipation in flow expansion when water flows from the island back into the channel, and in eddies that occur contribute to bank erosion. Turbulent patterns are found around bed forms and play a crucial role in bed form sediment transport, affect the suspension of sediment, as well as transport of sediment across hydraulic structures. On a larger scale, it influences the dispersion of the flow patterns and consequently affects the erosion and deposition processes in a braided river. It enhances scour processes by locally increasing velocities, affecting the local morphological response to various structures.

2.11. Vegetation

Vegetation can be present on riverbanks and larger islands or point bars. With its root system, it may stabilize the banks and reduces the lateral mobility of the river (Gran & Paola, 2001). On the other hand, bed vegetation influences the flow pattern and sediment transport. It modifies the velocity field both in the horizontal and vertical direction. In the vertical, it pushes higher velocities away from the bed, reducing the shear stresses. According to Zong and Nepf (2010) flow in and around vegetation can be separated into three distinct horizontal regions. The first one is the diverging flow at the upstream edge, where water decelerates and diverts towards the open channel. The second is the inner developed region throughout the vegetated area, where velocity is uniform. Most of the sediment deposits as it enters the vegetated patch. The third region is the shear layer at the interface between vegetation and the open channel. Reduction of velocities inside the vegetated patch compared to the open channel can be significant (even more than 90% in some cases). With its roots, vegetation can increase resistance against erosion by increasing the critical shear stress. Finally, it plays a role in riverbank accretion as well, by stabilizing new deposits through vegetation establishment (Vargas Luna, 2016).
3. River training and channel closure

3.1. Introduction

The following chapter focuses on describing the studies and projects related to river training in braided rivers in general and specifically on closure of channels in braided rivers. Reasons for river training were already presented in the introduction of this thesis. Here, several commonly used river training structures are described. A summary of previous projects involving closures is given. Finally, channel reopening and failures of closures are analysed from a theoretical point of view based on currently available knowledge.

Multiple approaches to river training exist in large braided rivers. There is always an option to use hard permanent measures to stabilize the most important locations in the river and protect and manage the corridor between them with revetments and groynes, transforming the river from braided to meandering. However, this approach is not flexible, is expensive and can result in unexpected problems due to river size, its power and environmental disturbance. Straying from the traditional hard approach, combinations of permanent and alternative recurrent measures show promise. Ideas for closing aggressive outflanking channels that separate large islands from the floodplain, while maintaining the general river course with some permanent hard points have been present for decades (FAP21/22, 2001). However, their implementation has been limited. Newer river training proposals emphasise innovation by combining modern approaches with traditional techniques. For minor interventions, pilot measures are envisioned. Once new knowledge is obtained, projects can be refined, in line with the philosophy of learning by doing (NHC Northwest Hydraulic Consultants & Mott MacDonald, 2014).

3.2. River training measures

Various measures can be used to train a braided river and to close its channels. Permanent structures usually have lifespans of around 50 years, whereas recurrent structures could be used for a year only or up to approximately 5 years. The former are various types of groynes, spurs and weirs. Examples of the latter are high-flow bandals (fixed screens), floating screens, vanes, erodible cross dams and porcupines. They are commonly damaged by peak flows and may need to be repeated, but provide more flexibility and are usually cheaper. Often, they can be reused elsewhere with minor modifications.

3.2.1 Groynes or spurs

Groynes or spurs play an important role in conventional river training. They are used to maintain sufficient navigable depth and to protect the riverbanks against erosion. Knowledge and design rules about them mainly stem from laboratory experiments and use in smaller rivers. When such structures are used in large braided rivers, design rules are often just extrapolated. This results in inefficient, expensive and environmentally disturbing structures. They block the flow and redirect it parallel to the structure. This flow has high erosive potential. The process is not important in smaller rivers, but resulted in partial failures of multiple structures in large braided rivers (Nakagawa et al., 2013).
3.2.2 Weirs or dams

Weirs or dams block the entire channel. Dams can be either emerged or submerged. Such structures are the simplest form of channel closure. Flow over weirs depends on the water level difference across the weir crest, the downstream water level and the crest shape. If the properties of the weir are known, the flow can be calculated accurately.

Sediment transport across hydraulic structures such as weirs is not yet completely understood and remains difficult to predict. On the upstream slope, higher velocities and shear stresses are present, whereas the effect of gravity reduces transport (Vuik, 2010). Suspended sediment may be easily transported over a submerged weir. On the other hand, bed load may pile up behind it until deposition reaches the weir crest.

Besides permanent concrete or similar dams, erodible sand plugs can be used to close a channel. These temporary structures are submerged and eventually eroded by the river, but partially close the channel in the meantime and can cause sedimentation upstream (Figure 3.1).

3.2.3 Bandals or surface screens

Bandals are a traditional river training measure used in the Indian subcontinent where a number of large braided rivers are located. They are permeable structures usually built of a combination of piles, beams and bars made out of wood and bamboo. The upper part of the structure is made impermeable by bamboo thatch, while the lower part is left open (Figure 3.2). This allows sediment rich flow to pass underneath the structure, while the upper part of the flow is blocked. Due to flow acceleration, scour usually occurs in front and below the bandal (Nakagawa et al., 2013). All this results in rapid deposition downstream, which can cause gradual channel abandonment.

Bandals show promise, but currently no standardized design rules exist. Their use is based mostly on experience, with insufficient scientific backing. During high flow, they can be damaged if not designed properly, so their use in large and deep channels is not recommended. Even in shallower water, they are usually a temporary measure.
Bandals can be used as bank protection as well. They induce sedimentation around them and create stable new land. Nakagawa (2013) compared them with spur dikes in a laboratory experiment and found them superior in terms of navigability improvement, scour reduction, deposition and lower environmental impact. However, due to three dimensional flow patterns around them, they remain difficult to correctly scale in physical models.

### 3.2.4 Porcupine systems

Porcupines are tetrahedral frames made out of six members connected together, three on the bottom, and three forming a pyramid. They are usually made out of wood or reinforced concrete. Material and size depend on the design requirements. They are permeable structures that allow flow to pass through them. They work by increasing flow resistance and thus reducing the velocities (Aamir & Sharma, 2015). Lu et al. (2011) found that porcupines reduced boundary shear stress and sediment entrainment. Porcupines can be used to protect banks, reduce flow in channels, induce sedimentation and protect islands against erosion (Wang et al., 2012). They are usually deployed in rows, parallel or perpendicular to the flow. They were shown to capture sediment if the porcupine field was dense enough (Figure 3.3) (Aamir & Sharma, 2015). Other types of roughness elements such as piles can be used for a similar effect.

### 3.3. Channel closures

A channel can be closed completely or partially. It is almost impossible for no discharge to be present in the channel during the high flow period, due to transverse flow across the island separating it from the open branch. Therefore, the distinction between partial and complete closure is made based on whether flow is purposefully allowed in the closed channel, either across or around the structure. The simplest form of closure is using a weir to block the flow in combination with an embankment on the island parallel to the flow that prevents outflanking (erosion just around the weir). Various other options exist and some are explored as part of this study.

Pilot measures to close a smaller secondary channel were tested as part of the FAP22 project for the Jamuna River in Bangladesh. The channel was closed by a combination of a cross dam and bandals. The cross dam reduced flow and increased sedimentation, while the bandals in the entrance diverted part of the flow away from the channel and permitted sediment to enter. Significant deposition occurred at the entrance and the channel was closed for a while. During the flood, a new channel was eroded across the island just downstream of the structures and the closed channel was reopened (Figure 1.4) (Mosselman, 2006). The project is presented in more detail in Appendix A. Similar problems occurred in other closure attempts in the Jamuna River (person. comm. Sanjay Giri) and in rivers Ayeyarwady and Congo (NHC Northwest Hydraulic Consultants & Mott MacDonald, 2014). Partial channel closure with groynes was simulated in a numerical model by Karmaker and Dutta (2016). A large scour hole developed at the groyne tip. A similar problem occurred during numerical simulation of channel closures in the Koshi river by Hooning (2011).
Chapter 3: River training and channel closure

3.4. Channel reopening

Channel reopening is the main problem preventing successful channel closure. The primary cause is expected to be the water level difference and the resulting gradient around the closure structure and across the island between the two parallel channels. When a channel is completely closed, the water level downstream of the intervention drops to the level in the confluence, whereas upstream it increases to the level at the bifurcation. During the high flow period, the island is submerged, and a connection is established around the structure and across the island. The resulting gradients should force flow towards the closed channel. It is not yet known what determines whether a channel forms around the structure or across the island and neither how to prevent this from happening and close the channel effectively.

A similar process occurs naturally as well. When a branch is partially blocked, for example by a propagating bar, water levels are temporarily raised, causing flow over the island. This flow erodes a channel across the island and connects the two branches (Figure 3.4). The process can happen during floods or just high flow during the wet season. This process was observed both in natural rivers (Bristow, 1987), as well as in scale experiments (Ashmore, 1982; Leddy et al., 1993) and in numerical models of braided rivers (Schuurman et al., 2013; Schuurman & Kleinhans, 2015).

The process has not been thoroughly studied for natural conditions, and even less is known about consequences of channel closure. Moreover, no natural equivalent to erosion of channels around the closure structure was found. This process is likely to occur even more often than erosion of channels across the islands.

3.4.1 Contribution of subsurface flow

During preliminary literature review, it was speculated that subsurface flow could contribute to channel reopening by causing headward channel erosion due to geotechnical instabilities, as shown conceptually in Figure 3.5.

The process could be similar to seepage induced undercutting and erosion, as mentioned in Section 2.4. Water level differences cause a hydraulic gradient across the island. If it is large enough, entrainment of particles occurs downstream where the water flows out of the soil. In contrast to seepage bank erosion, the supply of water is constant, which could cause faster erosion rates. This process could contribute to the formation of the channel across the bar even when the island is not submerged. Such a situation has not been studied yet.
A preliminary analysis was performed using a mathematical model developed by Karmaker and Dutta (2013) based on a modified model for seepage erosion in almost vertical banks with non-cohesive sediment by Fox et al. (2006). The paper states that for example in the Brahmaputra River, the threshold gradient for seepage erosion is 0.015 m/m. With typical slopes of sand bed braided rivers less than 0.0001 and an island with a high aspect ratio (length of 5 km and width of 500 m), even complete closure upstream or downstream results in a gradient of only about 0.001. Based on this, it is concluded that seepage on its own does not significantly contribute to the formation of new channels across the island. It is omitted from further analysis.

Undercutting may not be the only way subsurface flow contributes to channel reopening though. Outflowing pore water loosens the soil and creates conditions that are more unfavourable for fluvial erosion, which could enhance regular erosion from the downstream side (section 2.5). Finally, subsurface flow might have a local effect at the structure, where the distances are much lower, but the water level gradients remain high. This bears similarities to piping. It goes beyond the scope of this study, but it should be considered when interventions are designed.

### 3.5. Upstream and downstream effect of closure

Closing a channel narrows the braided river. Short and long-term morphodynamic effects of river narrowing in general are well understood and predictive equations exist based on assumptions of quasi-steady non-uniform flow. On the short term, the narrowed section of the river shows incision due to an increase in sediment transport capacity. Deposition occurs downstream where transport capacity stays unchanged. Upstream of the narrowed section, there is deposition as well, due to a backwater effect that gradually reduces velocities and transport capacity as the flow approaches the bifurcation. The long-term effect of narrowing is slope reduction through erosion in the narrowed section and overall bed degradation upstream due to a lower downstream bed boundary condition.

With numerical simulations in a self-formed braided river, Schuurman et al. (2016) found that short-term effects of channel closure and river narrowing go beyond what is mentioned above. The reach can be separated into four distinct sections (Figure 3.6). The first one is the local section, where narrowing takes place and channel incision occurs. Upstream is the backwater section, where the backwater effect determines the morphological response. Downstream of closure is the compensation section, where the deposition occurs. The main difference is the existence of the fourth section further downstream, where effects are still felt. Closure affects the discharge and sediment distribution at the next downstream bifurcation and reshapes the mid-channel bar. This in turn affects the next bifurcation in the river. The perturbation travels downstream by altering the stability of bifurcations and the shape of mid-channel bars. It can amplify on the way. Hydrodynamic change is occurs immediately, whereas the morphodynamic perturbation travels with the celerity of a sand wave.

![Figure 3.6: Effect of interventions in a larger braided river reach. Due to disturbances propagating through the bifurcation confluence network, the effects are felt further downstream than in meandering rivers. Taken from Schuurman et al. (2016).](image-url)
4. Model set-up and reference case

4.1. Introduction

In this chapter, the methodology followed for the set-up of the model is presented. First, the choice of the reference case is presented. This is followed by a short description of auxiliary calculations used in the process of setting up the model. Various choices regarding the set-up of the numerical model are explained, from numerical schemes to choice of parameters. Finally, input conditions, simulation procedure and results are described. The equations behind various models, test runs and other details are presented in Appendix B.

4.2. Reference case

A simplified symmetric reach with two branches separated by an island and an inflow and outflow section is chosen as the reference case (Figure 4.1). Its properties are based on typical reaches of large braided rivers, such as the one shown in Figure 4.2. Each section spans 6 kilometres, with a combined length of 18 km. The maximum width of the island is about 1500 m and the width of the two branches is 350 m around the island and 500 m upstream and downstream. The section does not necessarily represent the full width of a braided river, but in that case, the interaction with the rest of the river is neglected. The full set of parameters is presented at the end of this chapter.

4.3. Auxiliary calculations

Since no hydraulic or topographic data is available and the model is made from scratch, some auxiliary models and calculations are set up. First, a one-dimensional model of the island reach based on the assumption of steady non-uniform flow is written. It enables calculation of backwater curves and sediment transport in a simple geometry. It is used to find width and depth of channels that are close to morphodynamic equilibrium and result in low backwater effects during the wet season. It can also be used as a means of spotting errors in the Delft3D model without interventions. This model is also used to provide the first assessment of the effect of vegetation on the flow over the island. Finally, its ability to predict the water levels in the closed channel during the wet season is assessed. The water level drop at the weir is not correctly represented because...
the model does not take into account flow across the island. The model is explained in more detail in Appendix B.1.

The second check during model set-up is made with the planform predictor of Crosato and Mosselman (2009). The channels in the model should lie in the transition from braiding to meandering and not be fully braided in themselves. The braided planform is imposed already by initial bed topography. Additional central bars in the channels would distort the results. The calculation is described in more detail in Appendix B.2.

4.4. **Numerical model**

The main part of the present study comprises of numerical modelling with the physics-based Delft3D model. A scale model was considered during the preparatory phase. Since little is known about the problem, many situations have to be tested. A numerical model is more suited for that. Additionally, practical constraints related to the size of the available flume limited the use of a scale model. A laboratory experiment can be used to analyse the problem in detail when more is known about it and provide validation of numerical results. Delft3D has already been used to study the morphodynamics of braided rivers, for example by Hooning (2011), Schuurman et al. (2013), Schuurman and Kleinhans (2015), Schuurman, et al. (2016), Williams et al. (2016b), and Ligthart (2017). Karmaker and Dutta (2016) used a similar numerical model MIKE to simulate a short braided reach and the effects of interventions in it. The results of the scenario without interventions were validated with measurements, showing that the model can be successfully used for such purposes. The Delft3D model is presented in Appendix B.3. In this section, the most important choices regarding model set up are discussed.

A two-dimensional model is chosen. The problem is inherently two-dimensional, with transverse flow over the island playing an important role, so a 1D model did not make sense. Most of the research up to date in braided rivers has been performed with 2D models. A two-dimensional model allows parameterization of 3D processes, such as suspended sediment transport and helical flow. 3D models are not inherently better than 2D, as they have their own problems with accuracy due to vertical cell size. Moreover, possible improvements that a 3D model would bring are minor when compared to uncertainties regarding effects of gravity on sediment transport and the transport predictor itself (Sloff & Mosselman, 2012).

A curvilinear grid that follows the shape of the channels and the island is used. A rectangular grid shows problems with a staircase pattern in bends, especially with smaller channels. Channels start closing rapidly near the entrance. Finally, a Delft3D module that allows better simulation of bank erosion by using a grid to adapt to the boundaries as they change was considered (Spruyt et al., 2011). However, the bank erosion module works only at the interface of wet and dry cells. This means that when the whole planform is submerged, the flow is resolved on a rectangular grid with no boundary adaptation. The choices of various numerical properties, such as grid size, time step and advection scheme are presented in Appendix B.4.

4.5. **Model set-up and properties**

Based on the insight obtained during preliminary simulations and data from typical large sand braided rivers, a reference case is defined. The aim is that the modelled river behaviour resembles realistic development as much as possible, but the exact representation of a particular river is not a goal. The influence of important variables is tested under more controlled conditions during the
sensitivity analysis. Conclusions drawn from it can be used to extend results of this study to a particular river. The reference simulation is set up with the following characteristics:

Table 4-1: Geometrical and topographical properties of the reference simulation

<table>
<thead>
<tr>
<th></th>
<th>Upstream</th>
<th>Upper branch</th>
<th>Lower branch</th>
<th>Downstream</th>
<th>Island</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width [m]</td>
<td>500</td>
<td>350</td>
<td>350</td>
<td>500</td>
<td>1500</td>
</tr>
<tr>
<td>Bed level* [m + datum]</td>
<td>-7</td>
<td>-5.8</td>
<td>-5.8</td>
<td>-7</td>
<td>0</td>
</tr>
<tr>
<td>Length [m]</td>
<td>6000</td>
<td>6250</td>
<td>6250</td>
<td>6000</td>
<td>6000</td>
</tr>
<tr>
<td>Bifurcation angle [°]</td>
<td>/</td>
<td>20</td>
<td>20</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Slope [-]</td>
<td></td>
<td></td>
<td></td>
<td>7 * 10^{-5}</td>
<td>7 * 10^{-5}</td>
</tr>
</tbody>
</table>

* without taking bed slope into account

Table 4-2: Physical properties of the reference simulation

<table>
<thead>
<tr>
<th>$D_{50}$ [mm]</th>
<th>n [-]</th>
<th>$v_h$ [m$^2$/s]</th>
<th>$D_h$ [m$^2$/s]</th>
<th>$A_{Shields}$</th>
<th>$B_{Shields}$</th>
<th>$E_{Spir}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.02</td>
<td>1</td>
<td>1</td>
<td>0.6</td>
<td>0.5</td>
<td>0.8</td>
</tr>
</tbody>
</table>

In the initial simulations and during the sensitivity analysis a constant discharge is used. Without data, the Q-h relation is established by trial and error. The boundary conditions are selected so that water depth on the island during the wet season is about 0.5 metres. Grid cell size varies from 10 to 40 metres.

Table 4-3: Hydraulic boundary conditions of the reference simulation

<table>
<thead>
<tr>
<th>Discharge [m$^3$/s]</th>
<th>Water level [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry season</td>
<td>3100</td>
</tr>
<tr>
<td></td>
<td>-2.76</td>
</tr>
<tr>
<td>Wet season</td>
<td>5900</td>
</tr>
<tr>
<td></td>
<td>-0.76</td>
</tr>
</tbody>
</table>

Table 4-4: Numerical properties of the reference simulation

<table>
<thead>
<tr>
<th>Grid size</th>
<th>Time step [s]</th>
<th>Morphological time step [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>72x780</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

The general formula for sediment transport from the Delft3D model with a power on velocity of four is used, as it results in the most realistic development of the island (see section 2.8). At the upstream boundary, equilibrium sediment inflow is prescribed, based on inflow velocities.

\[ s = 25D_{50}\sqrt{Ad_{50}\theta^2} \quad (4.1) \]

The lower channel is closed in its upstream part, about 1 km from its entrance. The closure is made with a weir that remains emerged even during the high flow period. It completely blocks the flow in the channel. Preliminarily simulations showed that if just a weir perpendicular to the channel is used, the water level gradient around it is so large that supercritical flow occurs. This is avoided by combining the weir with a 150 m embankment on the island, parallel to the island banks.
4.6. **Simulation procedure**

The simulation procedure consists of four steps:

1. An eight month morphological spin-up with low flow conditions to generate a more realistic bed topography than the initial uniform one
2. A reference simulation without interventions for four months during high flow conditions
3. Simulation of closure during four months of low flow conditions, when bed adaptation occurs in the open branch
4. Response to closure during four months of high flow

4.7. **Reference simulations**

In this section, the four reference simulations are described. The physical processes are explored and related to the morphological development. It serves as background for further analyses in this thesis, as many processes remain the same in further simulations.

4.7.1 **Initial Development**

The initial bed topography is generated in an eight-month simulation of low-flow conditions (Figure 4.3). In the upstream section, the bed remains flat. A perturbation in the bed or the boundary conditions would be required to force morphological change there (Schuurman et al., 2013). Submerged point bars develop next to the island due to channel curvature. The island section works as a disturbance and results in a pattern of erosion and deposition in the downstream section. Without the restriction of land boundaries, this could lead to growth of new bars downstream (Ashmore, 2013). Confluence scour due to flow convergence can be observed.

4.7.2 **Scenario without interventions**

Flow widening in the section with the island causes deposition in the reach and narrowing causes erosion downstream of the confluence. The island moves about a hundred metres downstream due to erosion of its head, but otherwise remains stable (Figure 4.4). The movement is slightly slower than for example in the Ayeyarwady River (Figure 4.5), but the simulated flood levels are lower as well. The water level at the island head is larger than in the two branches, which results in transverse flow of water from the island into the channels at that location. Flow velocities on the rest of the island are...
low and relatively constant, which means that little erosion and deposition occurs elsewhere on the island. Flow is equally distributed between the two branches. Average velocities near the banks are about 1 m/s.

### 4.7.3 Channel closure during low flow

The response during low flow is typical for river narrowing. Upstream of closure a backwater effect is present. The open branch experiences incision. Material is deposited downstream of the confluence and propagates further as a sediment wave (Figure 4.6). Immediately after a channel is closed, the water depth in the open branch increases by 20 cm (for the methodology see Section 5.2). With continuous erosion, this increases to 1.1 m, which is 25% deeper than the initial situation. Around the head of the island the flow contracts, which causes acceleration and high velocities. This results in a scour hole at the entrance of the open branch. Initially a backwater effect of 80 cm is present 2 km upstream from the island. This indicates that even during low flow such an intervention could cause flooding on lower islands in the upstream part of the river. After four months, the water level upstream drops by 40 cm. Just downstream of the confluence, the water no longer flows parallel to the banks, but is directed towards the south bank. This perturbation forces the formation of alternate bars.

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1 It should be kept in mind that if the reach were part of a wider braided river, the discharge at an upstream bifurcation (not included in the model) would adjust because of the backwater effect. This would mean lower discharges in the simulated part of the river and likely more favourable results.
4.7.4 Channel closure during high flow

The effect of closure during the wet season corresponds to that of channel narrowing as well. The water level 2 km upstream of the island rises by 30 cm. Differences are lower than during low flow. The river had already partially adjusted to the new conditions and the water flows over the submerged island. The water level difference causes flow around the intervention (a combination of a weir and embankment) and across the island as can be seen in Figure 4.7. Water levels in the closed channel upstream of the intervention are similar to water levels at the bifurcation, and downstream they are similar to the water levels at the confluence.

![Figure 4.7: Water levels and depth averaged flow velocities at the beginning of peak flow when the channel is closed by a combination of a weir and embankment. Flow on the island is concentrated around the weir.](image)

Immediately after the island is submerged, the discharge at the end of the closed channel is 1134 m$^3$/s (a reduction of 60 % compared to the simulation without interventions), whereas just downstream of the structure it is 600 m$^3$/s. This means that 600 m$^3$/s flows directly around the weir and the difference of about 535 m$^3$/s flows into the closed channel across the island. Initial average near-bank velocities in the closed channel are reduced significantly, to 0.3 m/s (reduction of 70%).

A high water level gradient around the structure causes concentrated flow with high velocities and a large sediment transport capacity. A bypass channel is eroded on top of the island around the weir (Figure 4.8). Erosion starts from the upstream side due to a difference between sediment transport capacity and supply. Scour depth reaches up to 8 metres in three weeks. Later erosion slows down due to larger input of sediment and lower velocities (Figure 4.9).

![Figure 4.8: Bed topography at the end of the wet season. A bypass channel is eroded around the weir and the branch reopens.](image)
The bypass channel draws more and more flow as it deepens. At the end of the wet season, the discharge in the closed channel increases to 1920 m$^3$/s (Figure 4.10). The branch effectively reopens. Average near-bank velocities rapidly increase, reaching 0.85 m/s after four months (Figure 4.11). The increase of discharge and velocities corresponds to the rate of channel erosion. The bypass channel is deep enough that even when the water level drops at the end of the wet season, flow through it remains.

The bypass enters the main channel under a large angle and the flow hits the outer bank, resulting in bank erosion in the model. Actual bank erosion would likely be even larger, as the current hits the bank itself, not just erodes the bed next to it. In a narrower channel, this erosion may be more significant.

Sediment deposits in the entrance of the closed branch. When the deposition reaches the entrance of the bypass channel, the sediment is transported through it, and deposition continues downstream of the intervention and propagates further downstream. Reduction of the cross section and water depth causes the depth-averaged velocities in the closed channel to remain high despite lower discharges.

Most of the changes related to channel reopening occur in the first few weeks. It is therefore considered sufficient to analyse the response to closure after four months, keeping in mind that the magnitude of changes could be different if the high-flow period is longer or shorter.
5. Sensitivity analysis

5.1. Introduction

A sensitivity analysis is made around the reference case described in the previous chapter. The purpose of the sensitivity analysis is twofold: it allows the generalization of results that are similar in all cases and enables understanding of physical processes when they are not. In this chapter, results are briefly described. Detailed values are presented in Appendix C, together with a description of previous sensitivity analyses in braided rivers.

The variables that are assessed in the analysis are chosen based on the theoretical considerations of most relevant processes. They can be separated into two categories, based on where in the process of calculation of morphological changes their main effect lies. These are variables that directly affect sediment transport (sediment transport formula, sediment grain size and distribution, bed slope effect) and those that affect hydrodynamics and indirectly affect the morphological development (turbulence, roughness, helical flow and water level). Duration of low flow period does not fall into these categories, but its importance is the reason it is included in the sensitivity analysis. For each of the variables several simulations are made spanning a realistic range.

5.2. Comparison criteria

Simulations are first evaluated and compared qualitatively based on morphological changes (such as erosion of new channels on the island). Comparisons are made during both the dry and the wet season. Furthermore, a large number of quantitative parameters are defined and compared. The most important are listed below and shown in Figure 5.1.

Dry season:
- Difference in water levels 2 km upstream from the island as a measure of bed adaptation $\Delta \eta_{upst}$
- Increase of the maximum water depth of the shallowest cross section in the open branch $\Delta h$ (4) and $\%h$

Wet season:
- Discharge in the closed channel at the end of the high flow period $Q_{cl}$ (2) and the relative change compared to the simulation without interventions $\%Q_{cl}$
- Near-bank velocities in the closed channel at the end of the high flow period $v_{cl}$ (3) and the relative change compared to the simulation without interventions $\%v_{cl}$
- Difference in the water level upstream compared to the simulation without interventions initially $\Delta \eta_{upst,ini}$ and at the end of high flow period $\Delta \eta_{upst,end}$ (5)

The maximum depth in the shallowest cross section is determined by finding the maximum depth of each cross section in the open branch and taking a minimum of among them. Its position
changes during the course of the simulation. The variable is considered as a measure of navigability improvement during the dry season. Average near-bank velocities are calculated by considering the three grid cell rows next to the floodplain in the closed channel. The discharge in the closed channel is measured in three cross sections (entrance, middle and end). The largest value is considered in the analysis.

Figure 5.1: The most important parameters that are used to compare simulations during the sensitivity analysis and the later analysis of different interventions.

1. QUALITATIVE

5.3. Sediment transport formulas

Based on preliminary results during model set-up, three sediment transport formulations are chosen. The first one is the Engelund-Hansen sediment transport formula, and the other two are based on the general formula implemented in Delft3D, but with varying coefficients. Each formula contains a calibration parameter. These are adjusted so that all of them result in similar transport rates for typical high flow conditions in the two channels.

The response during the dry season varies little, with the Engelund-Hansen formula resulting in slightly faster bed adaptation. The main differences are observed during the wet season. All three formulas result in similar sediment transport rates in the channels, but there is a difference in transport on the island. In the simulation with the Engelund-Hansen formula, erosion of the island is slower overall and the bypass channel is narrower but deeper (Figure 5.2). This results in lower discharge and velocities in the closed channel. The differences are caused by an additional dependence on roughness in the Engelund-Hansen formula (see Appendix B.3.2). Once a narrow channel starts developing, sediment transport rates in it increase due to not only higher velocities, but also lower roughness as well. It results in concentration of erosion and a narrower but deeper bypass channel. If constant roughness is used in the whole reach, the results of the simulation with the Engelund-Hansen formula differ little from the simulation using the general formula (with constant roughness also). The differences between the two simulations using a general formula are minor, with more erosion when the power of velocity is larger.

Figure 5.2: Bed topography at the end of the wet season when Engelund-Hansen formula for sediment transport is used (combined with depth dependent roughness).
5.4. **Eddy diffusivity and eddy viscosity**

Eddy diffusivity describes the effect of diffusion in the advection-diffusion equation for spiral flow intensity. It causes dispersion of spiral flow intensity, meaning smaller local values but larger extent of its influence. If eddy diffusivity is increased by an order of magnitude or more, discharge in the closed channel decreases. Both velocities and scour depths are slightly reduced.

Eddy viscosity represents the effect of turbulence on the distribution of flow velocities. Larger viscosity results in more uniform velocities, smaller local peaks, and more smooth morphological development (Williams et al., 2016b). An increase in eddy viscosity does not change the results, whereas a decrease by an order of magnitude or more reduces the discharges in the closed channel (Figure 5.3). Velocity profile is more concentrated, which causes peaks in sediment transport and concentration of erosion. This results in a narrower but deeper channel. Eddy viscosity thus affects the discharges in the closed channel by changing the morphological development. Even though lower eddy viscosity would be physically more realistic based on grid cell size, the value of 1 m$^2$/s is used in further simulations, as it smoothens the velocities and reduces numerical issues due to sharp gradients (such as wiggles).

5.5. **Bed slope and spiral flow effect**

Larger bed slope effect and a lower effect of helical flow lead to shallower and wider channels even in simulations without interventions. The same holds for the newly eroded bypass channel. A narrower and deeper bypass with steeper side slopes leads to a lower discharge in the closed branch. The differences between simulations are small. Only the last run with a low bed slope effect shows different results (Figure 5.4). The bypass channel is narrower but not deeper.

Discharges in the closed channel have a peak when the parameter for the effect of spiral flow ($E_{\text{spir}}$) is around one. The difference is less than 10% and can likely be attributed to non-linear processes related to channel formation. No satisfactory physical explanation for the peak is found.

5.6. **Roughness**

Simulations with different parameterizations of roughness are set up in such a way that water depth on the island is kept constant in the simulation without interventions. This means that
different discharges are imposed at the upstream boundary in each simulation. Only relative comparisons of results can be made.

A constant Chézy value of 60 m$^{1/2}$/s results in relatively rougher channels and smoother islands (in comparison with the depth varying roughness in the reference case). This causes more flow over the island and larger initial discharge in the closed channel. As roughness is not dependent on water depth, there is less preference for flow to concentrate in deeper sections, which results in a shallower bypass channel. A Manning parameter of 0.0023 increases the total roughness, resulting in lower discharges and velocities altogether and slower morphological changes. Lowering the Manning roughness parameter has the opposite effect. The effects are opposite to what was found by (Jagers, 2003), where he used a constant discharge and varying water depth. White-Colebrook formula with roughness height of 0.1 m results in slightly higher roughness in the channels and lower discharges on the island. This allows more water to flow around the structure and faster bypass erosion. Despite all this, the differences between simulations are small.

5.7. **Sediment size**

Discharges and velocities in the closed channel at the end of the wet season are lower when the sediment is smaller. Based on generally larger sediment transport rates the opposite would be expected. Partly, this can be explained by the faster bed adaptation in the open branch during low flow. It results in lower water depth on the island, which leads to less erosion. However, if the simulations start with the same initial bed topography, smaller sediment still results in lower discharges in the closed channel (Figure 5.5). Sediment transport in the closed channel and inflow of sediment into the bypass channel are larger when smaller sediment is used (compare Figure 5.6 to Figure 5.7). Since erosion does not depend only on sediment transport capacity, but also on sediment supply from upstream, this results in slower growth of the bypass channel. On the other hand, erosion of the island overall is faster when sediment is smaller.

![Figure 5.5: Relation between sediment grain size and the discharge in the closed channel at the end of the wet season for the simulations that share the same starting bed topography.](image)

![Figure 5.6: Sediment transport rates at the end of the wet season for sediment grain diameter of 0.1 mm. Note the higher transport rates in the closed channel upstream of the weir.](image)
A particular situation occurs when graded sediment is used. The bed is layered, with fine sand on top and coarser sediment below. The top layer is easily eroded, but erosion slows down when coarser sediment is exposed. This results in a shallower but wider bypass channel that conveys almost the same discharge as the reference situation.

### 5.8. Closure during the dry season

The importance of the bed adaptation when a channel is closed already during the dry season is assessed next. Three additional simulations are made, where the duration of low flow ranges from zero to eight months. The latter is not a represents the case where morphological adjustment is faster than the model predicts. Bed adaptation during low flow is important for the effectiveness of the intervention during the subsequent high flow period (Figure 5.8). It diminishes the backwater effect due to narrowing. This reduces water depth on the island and the water level difference between the two branches. If the channel is closed immediately before the wet season begins, the intervention is almost completely ineffective. A deep and wide bypass channel forms. Sediment deposits almost to the end of the closed branch (Figure 5.9). On the other hand, effectiveness after two months is only slightly reduced compared to the reference, whereas even longer adaptation increases the effectiveness of closure by 10% for both discharges and velocities.

Figure 5.7: Sediment transport rates at the end of the wet season for sediment grain diameter of 0.8 mm. Note the lower transport rates in the closed channel upstream of the weir.

Figure 5.8: Reduction of discharge in the closed channel related duration of the dry season after closure is made and before the island is submerged for the first time.

Figure 5.9: Bed topography after the wet season if the closure is made just before the island is submerged.
Timing of closure should be taken into account when planning to close a channel in a braided river. There should be at least some time for the bed adaptation in the open branch to occur, especially if the two branches are of approximately equal size. If the closed channel is smaller or the water levels higher, it is expected that this would be less important.

5.9. Water level

The simulations up to this point are all set up so that water depth on the island during high flow is 0.5 metres. This is not the case for all braided rivers. The islands can be submerged by as much as 5 m (in the Ayeyarwady river) or not at all (except during flood peaks). Two additional cases are analysed here. The first is with a higher water depth on the island. In the second case, the water levels are lower, so that the island is not submerged at all in the simulation without interventions. Due to large differences in morphological changes of the island and discharge reduction in the closed channel for higher water levels, water levels are varied in the analysis of different interventions; the results are presented in chapter 6.

In the case where the island is not submerged during wet season if the channel is not closed, the intervention causes a rise in water levels, which results in an average water depth on the island of 30 cm. Erosion is slower due to lower water depth. The water levels continuously drop during the wet season, as the river adapts. At the end of the wet season, the island is not submerged anymore. The reduction of discharges and velocities both reach 80% at the end of the wet season. Finally, the backwater effect is larger, with water levels 2 km upstream initially increased by 40 cm. It appears that the problem here is the increase in water levels, which could cause flooding, and not channel reopening.

The water level in the closed channel is barely higher than the island. The water flows from the island into the closed channel and accelerates near the edge of the island due to a rapid decrease in water depth. This results in erosion of channels starting from the downstream edge of the island (Figure 5.10), instead of from upstream as in simulations with higher water levels. As the water level drops, the flow concentrates in these channels.

![Figure 5.10: Depth averaged velocities and bed topography after one month of the wet season. Downstream erosion of the island and concentration of flow in the eroded shallow channels is visible.](image-url)
6. Interventions

6.1. Introduction

In this chapter, the results of numerical simulations of various interventions are presented. Initial tests are oriented towards influencing the water level gradient around the structure. The same combination of a weir in the channel and embankment on the island as in the sensitivity analysis is used. Embankment length and weir crest levels are varied. Several positions in the closed channel are explored. Simulations of combinations of weirs follow, including varying the crest levels. Closure using porcupines or other roughness elements is evaluated. Partial closure of the channel with groynes or bandals is assessed. Finally, the option of using vegetation on the island to improve channel closure is considered.

The first simulations are performed with water levels 0.5 m above the island during the wet season. This is only one possible scenario in large braided rivers, and it is not safe to generalize the results to situations with higher water levels. A number of simulations are repeated with higher discharges and water levels in order to assess the consequences of higher water depth on the island during the high flow period. The island geometry has to be adjusted in order for it not to be washed away by higher discharges. Relevant simulations for 0.5 m water depth on the island are repeated to provide a new reference.

In order to generalize the conclusions to various braided reaches and rivers, the interventions are tested in four additional geometries. The purpose of this is to understand how processes related to channel closure are affected by different reach size and geometry. One smaller scale and one larger scale case are set up, and two cases with an asymmetric channel configuration.

The chapter is concluded by presenting the results of extending several representative simulations over another wet season. This is done in order to assess how the response to closing a channel changes on a slightly longer term.

The purpose of the simulations is not to find exact values or definite predictions. In a simplified case without the possibility of calibration, this does not even make sense. The goal is to explain the processes that follow channel closure and to gain insight into how each intervention works, how various measures compare with each other. Because of this, specific quantitative values are rarely mentioned in the text. They are shown in figures for most representative cases.

6.2. Simulation procedure and method of analysis

The simulation procedure and analysis methodology remain more or less the same as during the sensitivity analysis. A few changes are made based on the insights obtained. As most cases start with a fully closed channel during the dry season, the low-flow simulations are not repeated. The model parameters (both physical and numerical) remain the same as in the reference case.

A time varying hydrograph is used instead of a steady discharge. The simulation lasts 6 months, with a one-month rising stage, four months of peak flow and a one-month falling period. The changes are linear. This is a simplified approximation of the hydrograph found for large braided
rivers like the Jamuna River (see Appendix A). During the dry season, the water likely falls even lower, but the morphological impact of that period on channel closure is assumed less important. There are two reasons to include an unsteady hydrograph. The first is that it allows inclusion and study of the effect of the rising and particularly falling period on the morphological response to closure. In most cases, additional incision occurs in the eroded channels during the falling phase. Second, this allows the assessment of effectiveness of closure during the next-year dry season. The focus of this is mainly on whether the channel remains closed and on the increase of minimum water depth in the open branch. Here it has to be taken into account that the water level during the dry season is likely even lower than at the end of the simulations. Lower water levels mean that even the deeper channels on the island would not transmit any flow.

6.3. Embankment length

The first tests were made by increasing the embankment length on the island. The weir is in the same position as in the reference case. The embankment in this study is a structure on the island, built parallel to the closed channel and the island banks, which prevents flow directly around the weir (shown in Figure 6.3 inside the red ellipse). The embankments are extended downstream in all cases to keep the situations comparable. The longer the embankment, the more effective closure becomes, as the water level gradient around the structure is reduced (Figure 6.2). The bypass becomes shallower and transports less water. When the embankment is long enough (1500 m), almost complete closure during both wet and dry season is possible. Velocities are kept low, reduced to almost 0.3 m/s. Some bypass erosion is visible, but it is shallow (Figure 6.3). Because of lower discharges in the closed channel, the water level difference between two channels increases. As a result, more water starts flowing across the island from one channel towards the other. This causes a channel across the island to start developing from the closed towards the open branch, upstream of the weir. The longer the embankment, the more prominent this channel is. Sedimentation both in the channel entrance and downstream of the closure structure is reduced when the embankment is longer, due to lower velocities in the closed channel and less sediment transport.

Figure 6.1: Bed topography at the end of the wet season after closure with a weir and a 1000 m long embankment. The black line inside the red ellipse indicates the embankment on the island. The structure perpendicular to the closed channel is the weir.
Figure 6.2: Influence of embankment length in combination with a weir 1 km from the channel entrance on the effectiveness of closure, represented by five different parameters.

The relative effectiveness of closure is better during the dry season. There is no flow across the island and over the weir, and flow through the bypass is the only mechanism of keeping the channel open. With a 1500 m embankment, it is possible to close a channel in such a way that it remains closed during the next year dry season. If the water level would drop even more during the dry season, conditions would be more favourable.

Figure 6.3: Bed topography at the end of the wet season after closure with a weir and a 1500 m long embankment on the island. The bypass channel is barely visible, instead a channel across the island is eroded.

6.4. **Weir crest level**

The crest level is varied for a case with a combination of a weir and 150 m embankment on the island in the same position as the reference case. Water can flow across the weir, meaning that the water level difference around the structure is reduced. This leads to less severe bypass erosion, lower combined discharge and lower near-bank velocities in the closed branch. There is a limit to how much wet-season conditions in this specific case can be improved by lowering the crest level, which can be seen in Figure 6.4 (crest level below -0.75 m). During the dry season, a lower weir is always more favourable, as long as it still fully blocks the flow.
Based on additional simulations, it can be concluded that for each different case an optimum crest level (or range) exists. The longer the embankment, the higher the optimum crest levels are, as bypass erosion is already diminished by reducing the water level gradient. Unless explicitly stated, emerged weirs are used in various figures in the rest of this report.

### 6.5. Weir positions

Five different positions of the weir and embankment are tested. Interventions are placed in the entrance, upstream part, middle, downstream part and end of the closed branch. The simulations for closure in the upstream part are already presented in the previous sections. In each position four simulations are analysed, combinations of an emerged or submerged weir with a 350 m or 1500 m long embankment and with an emerged or submerged weir. The island width is not constant, which should affect the erosion of channels across the island. Moreover, the water level difference across the island is expected to be smallest when closure is made in the middle of the island. The simulations with the 350 m embankment do not show large differences, as a deep bypass channel is eroded in all cases. The differences become pronounced when the weir is combined with the 1500 m long embankment on the island.

#### 6.5.1 Entrance

If the 1500 m long embankment is extended to the entrance, the channel across the island does not develop (Figure 6.5). Some traces of erosion can be seen, but a clear channel is not visible. The position of the weir within the bounds of the embankment does not matter. Closing a channel in the entrance is found to be the optimum position also in terms of quantitative parameters (Figure 6.6). The branch remains closed during the dry season.
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6.5.2 Middle

Closing the channel in the middle gives similar results to closing it in the upstream part, at the reference position. The flow crosses the island upstream of closure and erodes a channel connecting the two branches (Figure 6.7). The water level gradient between the two channels is slightly lower than with closure in the entrance, where such a channel does not occur ($1.4 \times 10^{-4}$ and $1.7 \times 10^{-4}$), so the explanation of this difference lies elsewhere. When closure is positioned in the middle, the water depth on the island upstream of the structure is about 40 cm higher than in the simulation without interventions. With closure in the entrance, the flow crosses the island only downstream of the intervention, where the water depth is lower. The combined difference in water depth is almost half a metre. This affects velocities and shear stress on the island. Channels are found to be more easily eroded from the closed towards the open branch, upstream of the intervention, where the water depth is larger.

Channels across the island are more problematic than bypass channels that form around the intervention. The location of the bypass channel can be predicted, although the magnitude of erosion is unreliable. The prediction of channels across the island is less reliable. In the course of a couple of years, the channels crossing the island could capture more water and completely change the local river topography. Formation of channels across the island should be avoided.
6.5.3 Weir in the downstream part of the channel

If the weir is placed further downstream, either in the lower half or at the end of the closed channel, its effectiveness reduces significantly. A deep channel connecting the two branches is eroded across the island (Figure 6.8). The largest gradient is no longer around the structure, but across the island, which is narrower towards its tail. Moreover, the water depth on the island in front of the structure is larger due to high water levels in the closed channel at that location.

The model indicates that the new channel across the island would likely cause bank erosion just upstream of the confluence (Figure 6.8). This can be deduced from the large scour depth in that area, which is most likely a consequence of the non-erodible land boundary in the numerical model, which prevents channel from widening. A simulation with a larger floodplain is performed to assess the importance of this bank erosion. Its results indicate that some degree of bank erosion would indeed occur, but would not change the consequences of closure. It must be noted that even this simulation might underestimate the degree of bank erosion due to the simplistic calculation of it in Delft3D (see Appendix B.3.4).

6.6 Multiple weirs

Multiple weirs separate the channel into three or more sections. 350 m embankments are used on the island next to each weir. The drop in water level occurs in multiple locations, which reduces the gradients at each one. The largest gradient is present at the most upstream structure (Figure 6.9). The dominant morphological response is still scour of bypass channels around the weirs (Figure 6.10). The channels are shallower and transport less water when compared to the case where only a single weir is used.
Figure 6.9: Water levels and depth averaged flow velocity at the beginning of the wet season after the channel is closed with three emerged weirs. The highest water level gradient and highest velocities are concentrated at the most upstream weir.

Figure 6.10: Bed topography at the end of the wet season after the channel is closed with three emerged weirs.

The most effective combinations of two weirs are in the entrance and in the middle or in the middle of the upper half and the lower half of the channel. During the wet season they are almost as effective as using a 1500 m long embankment. Interestingly, other combinations of upstream weirs are less effective. The likely reason is that the weirs are spaced further apart. The effectiveness of using various combinations of three weirs is similar for each combination, as long as none of them is positioned in the end of the closed branch. The results of select simulations using multiple weirs are shown in Figure 6.11.
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Figure 6.11: Comparison of effectiveness of different combinations of multiple weirs combined with 350 m long embankments. The legend indicates the position of each weir in the closed channel.

Using combinations of multiple weirs may still cause shallow channels across the island, usually at the location of the most upstream weir, where the water level gradient is the highest. Positioning the weir in the entrance instead of further downstream prevents this. Correct positioning of multiple weirs can mostly prevent transverse flow across the island (Figure 6.9).

From an economical point of view, building multiple weirs in a deep and wide channel does not seem to make sense, compared to building one structure and an embankment which shows the same effectiveness. However, the morphological response is more predictable and controlled when multiple weirs are used, as erosion is concentrated around the structures. This may play an important role in choosing an appropriate intervention.

### 6.6.1 Varied weir crest levels

In this section, the effect of varying weir crest levels is analysed. Lowering the crest level of all the weirs to island level increases the discharges in the closed channel. Bypass erosion is reduced, but there is little effect on the formation of channels across the island. Quantitative effectiveness of closure could not be improved by varying weir crest levels either, as combinations of multiple weirs are already effective. However, bypass erosion can be influenced by weir crest levels. For example, if one weir is higher than the others are, erosion is concentrated around it (Figure 6.12). This can be exploited, for example in combination with bed protection. Channels across the island cannot be prevented only by varying the weir crest heights.
6.6.2 Multiple submerged weirs

Reducing weir crest level improves conditions during the dry season. A combination of multiple submerged weirs without embankments is tested with an aim of completely closing the channel during the dry season, while still being reasonably effective during the wet season. A combination of three and five weirs is used, with crest levels 1 m below the island. Thus, the weirs allow significant flow across them during the wet season. The water level drop is achieved in multiple discrete locations, as well as continuously along the channel due to higher discharges. Local gradients around the weirs are reduced and almost no trace of bypass channels is observed (Error! Reference source not found.). During the wet season, the reduction of discharges and velocities is on par with a single emerged weir with a 350 m long embankment.

During the dry season, a combination of three low weirs can almost completely close the channel. Its effect is comparable to three emerged weirs with 350 m long embankments (Figure 6.14). The channel is not completely closed as some water still flows through the shallow bypass channels that deepen during the falling period. However, by adding short embankments or lowering the weirs further, these could probably be prevented. There is not much difference between using three or five weirs. This may depend on the length of the closed branch.
Figure 6.14: Comparison of effectiveness of closing a channel with three submerged weirs and with bandals (section 6.8) partially blocking the channel with two representative previously analysed interventions.

6.7. Porcupines and other roughness elements

Roughness elements like porcupines or piles can be used to increase roughness and cause energy losses in the closed channel. Their main advantage compared to weirs is they can be spread over a larger area. This means that the water level drop occurs over a longer distance, which could reduce erosion of the island. Moreover, their use is likely cheaper and less disturbing to the local river system.

There is no direct way of modelling porcupines in Delft3D, also because their effect on hydro- and especially morphodynamic processes is not exactly known. After discussions with Delft3D users in Deltares, an approach using the implementation of permeable structures in Delft3D is used. Permeable structures reproduce effects of roughness with an additional energy loss, without completely obstructing the flow. For more details, see Appendix B.3.7. Another option would be to use the parameterization of vegetation and model roughness elements as piles in the channel. Since calibration with measured data is not possible, the choice would likely not make a difference.

The reference simulation with porcupines is set up by comparing the discharge in the channel closed with four rows of porous plates spread over 400 m to the discharge in a channel closed by a single submerged weir (1 m below island level). This way, a direct comparison between the two interventions is possible. Various variations of this initial set up are simulated to assess their effect.

The porous plates perform as expected, causing an energy loss and reducing the water level in four steps over the distance of 400 m (Figure 6.15). A shallow bypass channel forms around the complete porcupine field (Figure 6.16). The discharge reduction is comparable to a single emerged weir combined with a 150 m embankment and the velocity reduction is comparable to the case with a 350 m embankment. Erosion is less severe than in those cases. The same comparison holds for the dry-season conditions, but now the water flows in the channel instead of through the bypass, making the situation more controlled. Using multiple porcupine fields causes an erosion pattern similar to multiple weirs. Porcupines cause the largest sedimentation in the channel entrance so far, due to higher discharges in the closed channel during the wet season. This may cause gradual closure of the channel over the course of a few years.
If the area covered by porcupines is smaller, the intervention is less effective, as the same water level drop occurs over a smaller distance. The opposite holds for a larger area, with the upper limit when the porcupine field no longer acts as a whole. Increasing the amount of permeable structures in the area improves the results. Placing the porcupine field upstream slows down the propagation of the sediment front. However, deposition around roughness elements is likely not correctly reproduced in the approximation with porous plates. It is possible that actual porcupines would capture more sediment (Aamir & Sharma, 2015) and improve conditions.

### 6.7.1 Combination of a weir and porcupines

A porcupine field can be combined with a weir that completely blocks the channel. The weir is placed in the upstream part of the closed channel and the porcupines in its middle. The roughness elements increase the water level upstream and reduce the gradient around the weir. This reduces the bypass erosion (Figure 6.17). The channel is completely closed by the weir. It is found to be a successful strategy, even better than a combination of two weirs, especially during the dry season (Figure 6.18). This indicates that when multiple weirs are used, all but one can be replaced by porcupines, offering a cheaper solution with similar effectiveness.
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6.8. Partial closure with groynes or bandals

The channel can be closed partially by blocking only a part of the cross section, with a goal of reducing near-bank velocities or forcing gradual closure due to deposition in the closed channel. Multiple weirs or bandals could be used to narrow the channel and move the flow away from the bank. Narrowing causes deposition in the entrance of the closed channel and influences the upstream bifurcation, which could lead to a gradual channel abandonment.

The bandals are represented with submerged weirs in the numerical model. Bandals block the upper part of the flow, while they permit some water to pass below them, thus changing the flow profile and influencing deposition (see section 3.2.3). Regrettably, weirs in Delft3D cannot
reproduce local hydrodynamic and morphological processes around bandals. Three or five weirs are used and two levels of submergence are tested.

Even during the dry season discharges in the closed channel remain high (reduction of about 40%). However, near-bank velocities are reduced by more than 70% (Figure 6.14). During the wet season, this is one of the highest reductions found. The bandals divert the flow away from the bank and narrow the channel. Considering that sedimentation around the bandals and advancement of the bank line is not well reproduced in Delft3D, possible effects could be even more beneficial. An option that could improve the results is to use bandals alternately on the two banks of the closed branch, creating a narrower and longer channel within.

A negative consideration has to be mentioned at this point. All the simulations made in this chapter are run from an initial bed topography that is the result of four months of complete closure during the low flow period. If the channel is not completely closed, bed adaptation in the open branch is smaller, which increases the discharges in the closed channel (discharge reduction is 20% lower). The near-bank velocity reduction remains similar.

6.9. Use of vegetation

Up to now, the best overall solutions were found by using a single weir with a long embankment or multiple weirs in the channel. However, both interventions may be expensive. Using a combination of a single weir with vegetation on the island next to it could be an effective alternative. Vegetation increases roughness, slows down the flow, reduces the shear stresses near the bed and improves erosion resistance by binding the soil with its roots. Except for the latter, its effect can be modelled with Delft3D. The approach is described in more detail in Appendix B.3.8.

Since modelling of vegetation in this case is not based on measurements, the initial choice of parameters for the numerical model is made with the help of an analytical assessment based on the Matlab model used in the set-up phase. The model requires input of vegetation density, its height, drag coefficient and the Chézy roughness of the bed. Vegetation density is the only parameter that produced a variation in the results for a case with low water depth.

Based on the assessment, a vegetated area with a length of 1 km and width of 300 m next to an emerged weir in the middle of the channel is simulated. Vegetation height is 0.7 m, its density 0.5 m/m³, with a drag coefficient of 1.65 and Chézy bed roughness of 45 m⁻¹²/s. A sensitivity analysis is performed in the numerical model as well. The differences are even smaller, with vegetation density having little impact on model results as well. This is because the water mostly flows around the vegetated patch instead of through it.

Essentially, vegetation in this case performs a similar function as an embankment or a wall, blocking the flow through it almost completely. The velocities inside the vegetated patch are low, which is reasonable for shallow flow (see section 2.11). Quantitative results are similar to results when a longitudinal embankment of comparable length and position is used. Morphological response is more severe. A 300 m wide patch reduces the conveyance cross section in the middle of the island. This further increases the water depth upstream and the velocities on the island. This is sufficient to increase erosion of the island in the upstream section and causes the eroded channels across the island and around the vegetation patch to be deeper (Figure 6.20).
Figure 6.20: Cumulative erosion and deposition at the end of the wet season after the channel is partially closed with a weir and a vegetation patch on the island. Erosion of the island is larger than in comparable cases where an embankment is used.

The benefits of using vegetation in this case are related mainly to costs, environmental considerations and possible problems with embankment stability. Results could be improved if vegetation would allow more flow through it. This could reduce the erosion elsewhere, while the island bed would be better protected against erosion in the critical area of high gradients next to the weir. Finding such a configuration requires additional tests varying patch width, submergence and density. Finally, it needs to be considered that the vegetation can be fully submerged only for a limited period in order to survive.

### 6.10. Varied water levels

The simulations to assess the importance of various water levels are made with weirs and 350 m or 1500 m long embankments, positioned in the upper, middle or lower part of the closed channel, both submerged and emerged. In addition, a combination of two and three weirs is tested for each water level. During preliminary simulations, the island was partially washed out when the water level was higher than 0.5 m above the island. The solution is found by adapting the initial island geometry to the topography at the end of the preliminary simulations. The island is better adapted to high flow conditions and remains more stable (compare Figure 4.1 and Figure 6.21.).

Figure 6.21: New island geometry that allows simulations with higher water levels without the problem of the island being washed away. The figure shows the bed topography after a wet season with water levels 2 m above the island.

Relevant simulations for 0.5 m water depth on the island are repeated to provide a new reference. The simulations for the two different island shapes are qualitatively similar, whereas quantitative results sometimes vary, especially due to different grid cell locations for the extraction of near-bank velocities in and a different shape of the channel entrance. The relative differences between various simulations remain the same, so the conclusions drawn in the previous sections still hold.

Larger water depth means lower roughness and higher velocities, which in this case result in higher bed stresses and sediment transport. If the channel is closed with an emerged weir and a short embankment, it is found that higher water levels do not change relative discharge reduction
in the closed channel significantly, but that velocity reduction falls drastically or disappears altogether (Figure 6.22). This is likely due to a changed flow pattern, as the flow from the bypass channel hits the bank, and stays close to it downstream of the weir. Curvature of the bypass channel is lower with higher water levels. When two weirs are used, effectiveness falls with higher water levels as channels form across the island. For three weirs, effectiveness does not change significantly. Results of most simulations with longer embankments do not show large variations (compare Figure 6.23 to Figure 6.7). The relative effectiveness of different interventions compared to each other remains mostly the same for different water levels.

![Figure 6.22: Comparison of the effectiveness of closure in the middle of the channel with a 350 m embankment for varying water levels.](image)

When water levels are higher (more than 2 m above the island), the positive effect of placing the weir in the channel entrance disappears. In the simulations with lower water levels, a channel across the island was not eroded due to relatively lower water depth on the island downstream of the intervention. With higher water levels, the relative water depth difference is negligible and a channel develops between the two branches (Figure 6.24). Closure in the middle is more effective due to lower water level gradients across the island (Figure 6.25). However, channels across the island still develop in all cases.

![Figure 6.23: Bed topography at the end of wet season after the channel is closed with a weir and a 1500 m embankment in the middle of the channel with water depth on the island of 1m (left) and 4 m (right).](image)
Figure 6.24: Bed topography at the end of wet season after the channel is closed with a weir and a 1500 m embankment in the entrance of the channel for water depth on the island of 1 m (left) and 4 m (right).

Erosion of the island becomes more problematic when water levels rise. Complete closures become less viable. Using a combination of a submerged weir and emerged embankment is found to be beneficial in preventing erosion and improving conditions overall. When water levels are higher, a larger proportion of discharge flows over the weir during the wet season. This reduces the local water level gradient, which in turn significantly reduces or even prevents erosion of the island (Figure 6.26). Wet season discharges are not much higher, as water would otherwise flow into the closed branch across the island. Because of lower degree of erosion, dry-season conditions are improved and the results are more predictable. With high water levels (2 m or 4 m), three submerged weirs without any embankments also give better overall results than three emerged weirs with a 350 m embankment.

Figure 6.25: Comparison of the effectiveness of different interventions when water levels are 4 m above the island.

Figure 6.26: Bed topography at the end of wet season after the channel is closed with a submerged weir and a 1500 m embankment in the middle of the channel for water depth on the island of 4 m.
The water depth on the island of 4 metres is found to be the limit of applicability of these simulations. With even higher water levels, the island is partially washed out in the simulation with no interventions. In braided rivers, higher water levels are possible, but to test their effect a different configuration would need to be found, possibly including some cohesion of the islands or similar. However, it is likely that extrapolating the observed trends gives a good prediction of what would happen with even higher water levels.

6.11. Varied geometry

One smaller scale and one larger scale case are set up, and two cases with an asymmetric channel configuration. For each case, weirs with short and long embankments and a combination of multiple weirs, both emerged and submerged, are tested. Two different water levels are used. The properties of each case are presented in Appendix D.

6.11.1 Smaller-scale asymmetric reach (FAP22) – scenario 1

This scenario is based on the conditions in the Jamuna River during FAP22 channel closure pilot project (see Appendix A). This is the best-documented case of channel closure, and including a similar case in the analysis allowed for some degree of validation of results. The measured cross-sections are used to set up the initial river topography, so that water depths, island geometry and channel widths are approximately similar. In the project, the two channels were a part of a wider river, which is not modelled in the simplified case. Comparisons can thus be made only qualitatively.

During the simulation without interventions, the secondary channel is slowly closing, due to larger input of sediment than the transport capacity. This should make closure easier. The reach is shorter, so the water level difference around the structure and across the island is smaller. This makes bypass channels less problematic. However, the island is narrower, so the water level gradient across the island is slightly higher (1.4e^{-4} in the reference geometry and 1.8e^{-4} here). Channels across the island develop faster. Conditions cannot be further improved by increasing embankment length, as closures still fail due to erosion of a channel across the island (Figure 6.27). Even multiple weirs do not prevent this.

Figure 6.27: Bed topography at the end of wet season with water levels 0.5 m above the island. The channel is closed with a weir and a 350 m embankment (left) and a weir and a 1500 m embankment (right).

The exception is when the embankment extends to the entrance of the closed channel. Water depths on the island are relatively lower when water flows across the island downstream of the intervention. This way erosion is prevented (Figure 6.28). Using three submerged weirs also prevents erosion completely (Figure 6.29) and is especially effective during the dry season.
Due to smaller scale of the island, the highest water depth on the island is 1 m before the island is washed out. This increase is not enough to show the consequences of higher water levels discussed in the previous chapter, and results of the simulations with with 0.5 and 1 m water depth on the island are mostly the same.

A single weir in the entrance is used for a comparison (water depth of 1 m on the island) with the FAP22 pilot project (Appendix A). In the actual project two measures were used, but they were spaced close together. Moreover, bandals cannot be correctly modelled with a numerical model, so some differences are inevitable. Results show a similar morphological response. A channel is eroded across the island with its end just downstream of the closure structure (Figure 6.30). This shows that at least at the level of general morphological response to closure, results of simulations correspond with observations in the field.

In conclusion, closure is likely to be less effective when the island is smaller. Channels across the island are more likely to occur. It is not the size of the island is important, but the length to width ratio. It determines the water level gradient between the two branches when one of them is closed. Island length increases the water level difference across the island and around the structure, whereas the width reduces the water level gradient due to larger distance between the branches. Finally, even with a very different geometry, the general morphological response to closure is similar to the reference situation.
Figure 6.30: Bed topography at the end of wet season for the case with closure in the entrance that can be compared with the FAP 22 pilot project in the Jamuna river. The morphological response is similar in both cases. The channel is reopened by erosion of a channel across the island head downstream of the structure.

6.11.2 Larger-scale reach – scenario 2

The second scenario is made to assess the effects of closing a channel next to a larger island, with a similar width to length ratio. The simulations show an opposite result to what was described in the previous section. The water level gradients across the island remain more or less the same, whereas the gradients around the weirs increase due to longer channels. This causes less erosion across the island and more problems with bypass channels. However, bypass channels can be more easily prevented with longer embankments. A wider island also means that it takes more time for the flow to erode a channel across it, even when the flow has the same erosion capacity.

Successful closure can be achieved when a weir is combined with a 1500 m long embankment. This actually causes two times higher water level gradients around the intervention compared to the reference geometry. A channel across the island is present if the weir is positioned in the middle of the closed branch, but it does not reach the other side of the island (Figure 6.31 left). A further increase of the embankment length does not noticeably improve the situation. The position of closure plays an even more important role than in the reference geometry. Because the island is longer, water depth downstream of the weir with an embankment that extends to the entrance of the closed channel is even lower than in the reference situation. This retards the erosion of channels across the island even more. Even with water depth of 2 m, little erosion occurs (Figure 6.31 right).

When the island is larger, closing a branch may be easier, because problematic channels across the island are less likely. This is due to both larger volume of sediment that needs to be eroded and a more pronounced effect of water depth decrease downstream of closure on channel erosion. Bypass channels can be prevented with longer embankments. The general morphological response to closure for different interventions remains the same.
6.11.3 Asymmetric channels – scenarios 3 and 4

Scenarios 3 and 4 are set up to explore the effect of channel asymmetry. The length of the island is the same. In scenario 3, the closed channel is narrower, but the bifurcation configuration remains symmetric. In scenario 4, the closed channel is narrower and also straighter and shorter. The latter means larger bed and water level gradient in it. This is meant to simulate a case where the branch in naturally opening (Figure 6.32).

Despite the differences in geometry, results do not vary significantly (Figure 6.33). The morphological response to different interventions is similar. The best results are obtained when the channel is closed with a weir and embankment in its entrance. Most quantitative differences can be attributed to the way results are acquired from Delft3D output, especially when it comes to near-bank velocities. Scenario 4 results in slightly worse conditions and more erosion of the island. This may due to shorter length of the closed channel, but the difference is not conclusive.

Water level gradients and water depths on the island remain the same as in the reference case, so it is reasonable that morphological response remains similar. On the longer term, some differences might be present due to different degree of sedimentation in the closed channel. Based on the performed simulations, it seems that even if one branch shows a tendency to open, it can still be successful closed and the change prevented. This might not be the case if the opening is caused by upstream developments such as propagating sand bars that deflect the flow towards the closed channel, which is not accounted for in the current simplified model.
6.12. **Longer-term simulations**

Several representative simulations are extended for an additional year. Results of most interventions do not significantly improve or deteriorate. Bypass channels usually deepen. On the other hand, there is more sedimentation in the closed branch, which likely balances the conditions. Improvement is the most pronounced in partial closures with submerged weirs, porcupines or bandals, especially during the dry season. This is likely a consequence of larger sedimentation in the closed channel that increases roughness. Over a longer period it could cause gradual channel closure (Figure 6.34).

There is a large discrepancy in the durability when the channel is closed with a weir and a long embankment. In those cases, channels across the island are the dominant problem. If the branch is closed in the entrance, no channels are eroded across the island. A shallow bypass channel is present after two years only (Figure 6.35 left), but the effectiveness of the intervention does not decrease. Water depth in the open branch becomes even higher, reaching a relative increase of 65%, which is the highest value achieved in any of the simulations (Figure 6.36). On the other hand, closing the channel in the middle is ineffective. A wide channel is eroded across the island and overall morphological changes are dangerously large (Figure 6.35 right).

![Image](image1.png)

**Figure 6.34:** Bed topography at the end of the second consecutive wet season when a channel is closed by three submerged weirs.

For higher water levels, erosion on the island is already a problem after one year if emerged weirs are used. After a longer period, the situation deteriorates further. If the weirs are submerged, little or no erosion occurs even after two years (Figure 6.37). The same conclusions hold for all the tested geometries.

![Image](image2.png)

**Figure 6.35:** Bed topography at the end of the second consecutive wet season when the channel is closed with a weir and a 1500 m embankment near the entrance of the closed channel (left) and in its middle (right).
Figure 6.36: Comparison between the effectiveness of three representative interventions after one and two years of closure.

Figure 6.37: Bed topography at the end of the second consecutive wet season when a channel is by a submerged weir and a 1500 m long embankment in the middle of the closed branch, with water levels 4 m above the island.
7. Analysis of channel reopening

7.1. Introduction

In this chapter, this combined data generated with numerous simulations is analysed. The aim is to find connections between the initial hydrodynamic conditions during the wet season after a channel is closed and the erosion of channels on the island. Two methods are used. In the first, the connection is sought based on conditions and erosion in each numerical cell on the island. The second is based on average hydrodynamic properties at the location of the eroded channel(s). The data from the simulations with the same water depth on the island is analysed simultaneously. An attempt is made to predict erosion of channels on the island from initial hydrodynamic conditions. The method to predict the location of the eroded channels is based on initial velocities and shear stresses on the island and their maximum values. To predict the degree of erosion, a model based on quasi-steady flow and sediment transport capacity is set up in Matlab. Finally, the relation between the erosion of new channels on the islands and the effectiveness of closure is shown.

7.2. Erosion analysis of numerical cells

Conditions at individual numerical cells on the island are analysed to determine the connections between initial hydrodynamic conditions and erosion. For each cell, relations with the water level gradient, water depth and flow velocity are plotted. No clear connection is found. For different values of the water level gradient, water depth and velocity, various erosion magnitudes are possible and erosion cannot be predicted from particular initial conditions in this way. For a certain degree of erosion, there are minimum values of different parameters that still cause it (Figure 7.1). This indicates the relations do exist.

Figure 7.1: Relation between the water level gradient (left) or water depth (right) and erosion, for each numerical cell on the island separating the two branches. The data is taken from the simulations with 0.5 metre water depth on the island.

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2 Defining the initial hydrodynamic situation in the simulations is problematic, as some morphological changes already occur before the water levels reach the peak flow value at the beginning of the wet season. When water depth is used in the analyses, it is not taken directly from Delft3D output, but is rather calculated by subtracting the initial bed level from the water level, mostly eliminating the effect of erosion on input data.
7.3. **Erosion analysis at the location of channels on the island**

In the second method, initial hydrodynamic conditions at the location of the eroded channels are linked to degree of erosion. To identify the position of the channels and extract their properties from Delft3D output files, a post-processing script is prepared in Matlab. It identifies the position of the channels by following the path of maximum erosion from the initial points next to the two edges of the weir, where the channels start or end (Figure 7.2). Based on this, the initial water level gradient between the two sides of the channel, the initial average water depth and the average velocity can be extracted from Delft3D results.

![Figure 7.2: Identification of the eroded channels with a Matlab script. The two blue lines designate the points that are taken into account to extract the average values used in the analysis.](image)

Using this method, connections between variables and erosion are found. The strongest relation is found with initial average velocity and average shear stress at the position of the eroded channel ($r=-0.88$). This is logical, as the shear stress directly causes erosion. However, it also indicates that sediment input does not play a significant role (or that it is similar in all cases). A correlation between water level gradient and erosion is found as well, but the scatter is slightly larger, especially for high gradients ($r=0.73$). The correlation is weakest for water depth ($r=-0.6$). It indicates that the degree of erosion is higher when water depths are larger, which agrees with the findings from case-by-case analysis of interventions (Figure 7.3). If simulations with 2-metre water depths on the island are analysed in the same way, the correlation between water depth and erosion disappears. The influence of water depth can also be seen in Figure 7.4. The difference between cases with moderate and severe erosion is mainly in water depth, not water level gradient.
Figure 7.3: Relations between the initial hydrodynamic conditions on the island and the average erosion depth of new channels at the end of the wet season. The data is taken from the simulations with 0.5-metre water depth on the island.

Figure 7.4: Relation between severity of erosion at the end of the wet season and the initial water level gradient and average water depth (small < 2 m, moderate 2 - 6 m, severe > 6 m). The data is taken from the simulations with 0.5-metre water depth on the island.

The data is analysed further in order to identify the hydrodynamic conditions that determine which type of eroded channel will likely be most important. Since channels across the island do not always develop, the method of extracting the hydrodynamic conditions from the previous step cannot be used. Instead, the average conditions are extracted along three straight lines, between the most likely points where the channel would lie (Figure 7.5). It is found that the channels across the island become dominant once the water level gradient around the structure falls to approximately one to two times the gradient across the island (Figure 7.6). The comparison with values of water level gradient obtained from actual channel position, this method underpredicts the water level gradient across the island and overpredicts it around the structure. Therefore, it is most likely that erosion of channels across the island becomes the dominant mechanism of reopening when the gradient across the island becomes larger than the
gradient around the structure. This enables some degree of prediction as to which type of erosion will occur with different interventions.

![Figure 7.5: Schematic representation of the three lines along which the average properties are taken in order to compare water level gradients, water depth, average erosion and the type of channel that is dominant on the island.]

From the outliers in Figure 7.6 it can be observed that when average water depth at the likely position of the bypass channel is larger than the water depth at the position of the channel across the island, bypass channels dominate even when gradients are similar for both types. This shows that low water depth has an effect on erosion of new channels.

7.4. Prediction of erosion

Numerical morphodynamic models can be time consuming. A way to predict the morphological response to closing a channel is sought based on initial hydrodynamic conditions during the wet season. This would enable a quick assessment of various interventions in projects involving closing a channel.

An attempt is made to relate the location of channels that are eroded on the island to initial shear stresses and velocities using the same method as for the identification of channels in the previous section (following the path of maximum values). It is found that even in cases where the channels across the island dominate, this method predicts only the erosion of a bypass channel. This method cannot be used to predict the exact location of channels on the island in general.
The relationships between erosion and water level gradient, depth and velocity shown in the previous section can be used to predict the extent of erosion to a certain degree, but only in conditions similar to those in the simulations (sand diameter of 0.2 mm, water depths of about 0.5 m, and 4 months of high flow period). Without a direct physical explanation, predictions cannot be extended beyond this range.

Therefore, an attempt is made to establish a physics-based predictor of the degree of channel erosion from the initial hydrodynamic situation after closure. A simple model based on water level gradient and water depth is set up in Matlab. It uses the water levels (taken from a hydrodynamic simulation) at both edges of the likely channel position as the boundary conditions. It calculates the erosion depth or the duration until a certain erosion depth is reached.

Between the two points at the island edges, 1D steady non-uniform flow is assumed. All variables are defined per metre width. Sediment transport capacity is calculated from the bed shear stress with the same formula that is used in the numerical simulations. The sediment transport is averaged over the length of the new channel. No sediment input is assumed. Average erosion $\bar{E} [m]$ is calculated by multiplying the average sediment transport capacity $\bar{s} [m^3/s \text{ m}]$ with duration of the wet season $T_{ws} [s]$ and dividing by the distance around the structure or across the island $L_{ch} [m]$. $\lambda_p$ is the porosity of the bed [-] (Figure 7.7).

$$
\bar{E} = \frac{\bar{s} \cdot T_{ws}}{\lambda_p \cdot L_{ch}} \tag{7.1}
$$

Figure 7.7: Schematic representation of the simplified predictor of erosion of channels on the island.

Without morphological updating, the model underpredicts the degree of erosion in comparison with Delft3D results (0.25 m vs. 2.5 m for the channel across the island when the branch is closed in the middle with a weir and a 1500 m long embankment). This is because without changes in water depth, the velocities and the sediment transport rates remain too low throughout the wet season. On the other hand, including morphological updating leads to overprediction of the degree of erosion. It does not take into account the reduction of the water level gradient due to channel reopening and input of sediment when velocities increase in the closed channel increase. Despite failure to accurately predict the degree of erosion, this analysis does show that water depth and sediment input play a part in the process of channel reopening.
The failure to predict the degree of erosion with such a model shows that the problem is clearly two-dimensional as well as that predictions require taking changes in time into account. A morphodynamic physics-based numerical model like Delft3D is best suited to this task and shortcuts are apparently not possible. Without it, it is only possible to predict the type of channel that will most likely be eroded on the island.

7.5. **Erosion and effectiveness of closure**

The hypothesis of this study is that erosion of channels on the island causes reopening of the closed branch, which in turn decreases the effectiveness of closure. The causal relation is already shown with individual simulations. In this section, the correlation between the erosion and effectiveness of closure is shown based on combined results of multiple simulations. Only simulations with the reference geometry are used in the analysis, as the discharges and channel properties are different in other cases. Even if all simulations are considered together, significant correlation is still found. This is in part a consequence of comparing relative discharge reduction instead of absolute, as well as the same duration of wet season in all of the simulations. The results should not be used as a prediction of channel effectiveness, but they do show that a connection indeed exists.

7.5.1 **Discharges in the closed channel**

Average erosion depth of new channels on the island relates to discharges in the closed branch during both the wet season and the dry season (Figure 7.8). The depth of the eroded channels determines their conveyance. Even during the wet season, when there is flow across the whole island, these channels convey the largest part of the total discharge. The scatter is likely a consequence of flow over the island, of averaging the erosion in the channels, different types of eroded channels, varying water depth and not taking into account the variation in width of the eroded channels. During the dry season, the correlation is even larger. The eroded channels are the only source of water in the closed branch. If they do not develop or are too shallow, the channel is completely closed during the dry season. This can be seen in the right part of Figure 7.8, where if average erosion is lower than 3 m, discharges are reduced by 100%. If the drop in water level during the dry season would be larger, this limit would shift to an even higher erosion depth.

![Figure 7.8: Relation between the discharge reduction in the closed branch and the average erosion depth of the deepest of the two possible channels on the island during the wet (left) and dry (right) season.](image-url)
7.5.2 Water depth in the open branch

Improvement of navigability in the open branch during the dry season is one of the possible goals of river training in braided rivers and channel closures. The increase of the water depth in the open branch is considered as a measure of the navigability improvement. It has not been mentioned much in the report so far, because it is found to be correlated to the other parameters of closure effectiveness.

Theoretically, two mechanisms increase the water depth in the open branch. The first one is bed level adaptation caused by river narrowing. This happens both during the initial low flow period and during peak flow. A measure of the potential for bed degradation during the wet period is the discharge in the open branch that causes higher sediment transport rates. The second mechanism is the increase of discharge during the dry season that raises water levels directly.

A correlation is found between the dry-season discharge reduction and depth increase in the open branch (Figure 7.9) for the simulations made with the reference geometry (r=0.84). This indicates that the distribution of discharges during the dry season plays an important role in improving the navigability conditions as it directly influences the volume of water in the open branch. The relation between depth increase and reduction of discharges during the wet season (Figure 7.9) is weaker (r=0.64). However, this does not mean that bed degradation plays no part in the increase of water depth in the open branch. It just indicates that variations in discharge during the wet season between simulations are not as important. Significant bed degradation already occurs during the previous year’s dry season. This development is the same for all simulations, and is not captured by the analysis above.

If the channel is closed at the end of the wet season, so that no bed adaptation at all occurs, the increase in water depth in the open branch is caused only by increased discharges. The increase is found to be only 54 cm or 17%. With the most effective interventions, increases up to 50% are found. If the channel is not closed during the wet season, there is deposition in the open branch, which causes a decrease in water depth. Moreover, bed degradation already occurs during the previous year’s dry season. This development is the same for all simulations, and is not captured by the analysis above. Bed adaptation due to channel narrowing plays an important role in improving the navigability conditions, but its effect is similar for different interventions. The actual differences in the increase of water depth between interventions are caused by the discharge distribution between the two branches during the dry season.

![Figure 7.9: Relation between the discharge reduction in the closed branch and the relative increase of the maximum water depth in the shallowest cross section of the open branch during the wet (left) and dry (right) season.](image)
8. Discussion

In this section the results of case-by-case and combined analysis, presented in the previous two chapters, are discussed. The aim is to address the research questions not already directly resolved in the previous parts of this report. The latter are repeated again in the final chapter only, as they do not require additional discussion.

8.1. Channel reopening

A typical response to channel closure is present in almost all simulations. When one of the channels is closed, water flows around the interventions and from one of the channels towards the other, across the island separating them. This flow erodes channels on the island leading to channel reopening. Erosion starts from the upstream side due to excess sediment transport capacity and propagates downstream. The eroded channels can be separated into two categories. The first are bypass channels or outflanking channels around the closure intervention that end on its other side in the closed channel. The other types are channels that form across the island, connecting the two branches. The depth of the channels increases over time as they capture more water, but the erosion rates slow down when the sediment supply increases. During the falling period, additional incision of these channels is usually observed. Both types of channels may or may not remain open during the dry season, depending on their depth. The extent of channel formation to a large degree determines the effectiveness of channel closure.

Bypass channels are the main mechanism of channel reopening and they form almost in all cases at least to some degree. There is some uncertainty regarding the degree of erosion but their location is predictable. In previous modelling studies related to channel closure deep bypass channels developed, as only weirs with no embankments were used (Hooning, 2011; Schuurman et al., 2016).

Channels crossing the island are more problematic. They start forming when the water level gradients around the structure and across the island become similar. Their direction is usually from the closed branch towards the open one, upstream of the intervention. The only exception is when the embankment reaches the entrance of the closed channel and there is no island upstream to cross. These channels change the island morphology much more and their exact location is difficult to predict. Moreover, there may be villages or agricultural land on the island, being able to withstand the flood, but not erosion. Therefore, this type of channels should be avoided. A channel across the island head caused reopening in the FAP 22 pilot project in the Jamuna river (Mosselman, 2006). The process is similar to the natural formation of channels across the island that is mentioned in Section 3.4.

8.2. Variables influencing channel formation

The width, depth and type of the channels eroded on the island largely determine the discharge and velocities in the closed branch. To prevent reopening, the understanding of the causes of erosion is important. In the next sections, variables affecting channel reopening are discussed and where relevant, measures limit their effect are defined.
8.2.1 Effect of physical properties and processes

Effect of different physical properties is tested with a sensitivity analysis. Choice of a sediment transport predictor influences the response to closure mainly by changing the sediment transport rates on the island. Higher sediment transport rates translate to more erosion and less effective closure. The Engelund-Hansen formula (when it is combined with depth dependent roughness) predicts lower transport rates on the island and results in less erosion than the general formula that is used in other simulations. When sediment is smaller, closure is more effective. This is found to be due to larger input of sediment into the bypass channel, preventing further erosion, and due to larger bed adaptation in the open branch during the dry season. Using different roughness parameters, w keeping water levels constant, does not significantly affect the results. Parameterization of turbulence does not play a large role, except when very low values for eddy viscosity are used. Generally, lower eddy viscosity results in a narrower and deeper bypass channel that conveys less water. Similar consequences can be observed when the bed slope effect is lower. Helical flow plays a smaller role.

A wider and deeper bypass channel results in higher discharges in the closed branch. A wider and shallower channel results in higher discharges than the other way around. This indicates that correct prediction of bypass erosion is important for accurate predictions of discharges and velocities. However, small changes in input parameters sometimes result in large differences in discharges and velocities in the closed channel. This is likely caused by non-linearities and thresholds related to the process of channel erosion and cannot be easily explained or predicted. Exact prediction of discharges and velocities is thus not possible, and the values should be taken just as relative indications of effectiveness of channel closure.

The general morphological response to closure during high flow remains almost the same for the different simulations of the sensitivity analysis (Figure 8.1). The same holds for the trends of erosion and sedimentation, flow patterns and the final planform. It can be concluded that the various physical properties of a particular braided river will influence the exact values and rate of morphological changes, whereas the general morphological response to closure will remain the same. The results of a study using a particular set of parameters can be generalized to large braided rivers as long as we are interested only in general consequences and relevant processes, not in detailed values.

Figure 8.1: Bed topography at the end of the wet season for the simulations of the sensitivity analysis that result in the largest differences in the quantitative parameters for the effectiveness of closure. Eddy viscosity = 0.01 m²/s (upper left), sediment grain diameter = 0.1 mm (upper right) and A_shields = 1 (bottom).
8.2.2 Water level gradient

Water level gradients determine the direction and magnitude of flow on the island. In the closed channel, the water level upstream of the measure is higher than in the case without interventions. It is close to the water level at the bifurcation. Downstream, it is lower, close to that at the confluence. The water level drop is mainly concentrated at the location of the intervention(s). This causes locally steeper water level gradients, which force flow around the structure that results in erosion of bypass channels. The maximum water level difference is essentially the difference between water levels at the bifurcation and confluence, and is determined by the bed slope and the length of the island.

The water levels in the open branch are raised by the backwater effect due to narrowing, but their drop is still evenly distributed along the branch. This means that water level gradients are present across the island and between the two branches in the transverse direction. They cause flow from the closed towards the open branch upstream of closure, and the other way round downstream of it. If the shear stress on the island is high enough, this results in erosion.

The water level gradient across the island depends on the position of closure and on island geometry. The gradients are highest if closure is made in the entrance or end of the channel (Figure 8.2 and Figure 8.3). Moreover, the island is usually narrower at these locations. The water level gradient across the island is smallest when the channel is closed in the middle, where the water level difference is smallest and island is wider. A correlation is found between the water level gradient and depth of both types of eroded channels.

The simplest way of reducing the water level gradient around the weir is by building a longitudinal embankment on the island next to the weir, parallel to the closed channel. This extends the flow path with the same water level difference. The upper limit is when the water level gradient across the island becomes larger than around the structure, resulting instead in erosion of channels in that direction. In the simulations with low water depths, vegetation appears to function similarly to longitudinal embankments, but further tests are required before definite recommendations regarding its use for channel closure can be given.

If the weirs are submerged, part of the flow passes the structure in a controlled manner. This reduces the local water level drop. A portion of it occurs over the whole channel. Both gradients around the structure and across the island are reduced. Using submerged weirs is found to be effective when water levels are high. The water level gradient is decreased which can reduce or even prevent erosion of the island. At the same time, the discharge in the closed channel is not much larger as with other effective interventions, as the gradient reduction also diminishes the transverse flow across the island separating the two branches.
Figure 8.2: Water levels and depth averaged flow velocities at the beginning of peak flow when the channel is closed in its entrance by a combination of a weir and a 1500 m long embankment. The water level gradient directs the flow around the structure and from the open towards the closed branch downstream of the intervention.

Figure 8.3: Water levels and depth averaged flow velocities at the beginning of peak flow when the channel is closed in its end by a combination of a weir and a 1500 m long embankment. The water level gradient directs the flow around the structure and from the closed towards the open branch upstream of the intervention.

The water level drop can also be achieved in multiple locations by building more than one structure. If properly positioned, this can reduce or even eliminate water level gradients and transverse flow across the island (Figure 6.9). The highest water level difference is normally located at the most upstream weir, but this can be controlled by varying the weir crest levels. Simulations show that as long as one weir is used to close the channel completely, the rest can be replaced by roughness elements for the same effect.

### 8.2.3 Water levels and water depth

Different water levels affect the response to closure. If the island is not submerged without any interventions, closing one channel can cause flooding, whereas erosion will be limited. Higher water levels result in higher water depth on the island, causing faster erosion due to higher velocities.

Variations of water depth on the island play a role when water depths are relatively low (0.5-1 m). In those cases, it is observed that extending the embankment until the entrance of the closed branch can prevent the formation of channels across the island and result in better effectiveness of closure in comparison with closing a channel in its middle, where water level gradients are lowest. Upstream of the structure, the water level in the closed channel is high relative to the island, whereas downstream, it is low. When the channel is closed near its end, this relative
increase in water levels is amplified upstream of the structure and reduced downstream. The opposite holds when closure is located in the upstream part of the channel. Water levels on the island are determined by the water levels in the two branches and the flow between them (Figure 8.2 and Figure 8.3). This means that water depths on the island upstream of the structure are relatively higher than downstream (Figure 8.4 and Figure 8.5). In addition, this difference can be amplified by the position of closure as described above.

This difference in water depth is enough to affect velocities and influence erosion. Erosion of channels across the island is more severe when closure is located downstream in the closed channel. Downstream of the intervention, channels across the island do not develop. Relatively lower water depth downstream of the structure slows down the flow on the island and retards the erosion process. This makes closure in the entrance more effective. A weak correlation between water depth and average erosion of channels on the island is found for all cases with low water levels. When wet-season water levels are higher, the relative difference in water depth stops playing a role and the correlation disappears.

Figure 8.4: Water depth at the beginning of peak flow when the channel is closed in the middle by a combination of a weir and a 1500 m long embankment. Note the increase in water depth just upstream of the embankment edge and the higher water depth overall.

Figure 8.5: Water depth at the beginning of peak flow when the channel is closed in its entrance by a combination of a weir and a 1500 m long embankment. Note the decrease in water depth just downstream of the embankment edge and the lower water depth overall.
It is difficult to directly reduce water depths on the island. The easiest way to make use of this is to extend the embankment until the entrance of the closed branch. Artificially rising part of the island just upstream of closure could improve conditions as well, but this was not tested. The duration of river adaptation to closure during low flow affects the water depths as well. In four months, the backwater effect just upstream of the island is reduced by 20 cm. Higher water depth on the island would rise the costs of embankments, and could make different measures more economical.

8.2.4 Flow velocity and flow patterns

Erosion on the island is caused by larger sediment transport rates than sediment supply. High transport rates are caused by large shear stresses, which are in turn a consequence of increased velocities. A strong correlation between average erosion depth of channels on the island, velocity and shear stress is found. Velocities can be reduced by reducing water level gradients and water depth, which is described in the previous two sections. A third possible way is to increase roughness on the island, for example with vegetation. When this is tried in the model, vegetation almost completely slows down the flow and forces it around the vegetated area. However, if it were planted more sparsely, it could allow flow through it. The near-bed shear stresses could be kept low enough to prevent erosion. Further research into the use of vegetation is required to determine if this is possible. Finally, water level gradient and water depth alone are not enough to explain and exactly predict the location and extent of island erosion. Knowledge of the two-dimensional flow patterns on the island and their changes in time is necessary.

8.2.5 Sediment transport, deposition and bed adaptation

Erosion is directly caused by the difference between sediment transport capacity and supply. A higher discharge in the closed branch due to reopening increases the sediment supply to the eroded channels, which slows their growth. Inflow of sediment depends on sediment size (smaller sediment is shown to be beneficial) and discharges in the closed branch. Finally, if the water depth on the island is larger, sediment transport rates and supply are higher overall, which prevents a significant increase in island erosion that would be expected due to higher velocities.

Deposition in the closed branch is another consequence of closure. It is caused by a drop in depth-averaged velocities in the entrance of the closed branch. Sedimentation extends into the channel during the wet season. The speed of this process depends on the discharges in the closed branch. Higher discharges cause faster movement, likely up to a limit where deposition stops altogether. This deposition is the likely reason that effectiveness of less extensive interventions such as roughness elements improves over time. It could even be a target of particular interventions, leading to gradual closure, though this is beyond the scope of this study.

Bed adaptation of the open branch increases closure effectiveness, by reducing the backwater effect and consequently water depth on the island. A short period of closure before the wet season starts is shown to be beneficial. Extending this period still improves conditions but with a decreasing rate.

8.2.6 Erodibility

Erodibility of the island material also influences channel formation. In the model, simple non-cohesive uniform sand is used for the island surface. If the island would be covered with a cohesive surface or vegetation, conditions would likely be improved. This can partly be reproduced by introducing a critical shear stress into the sediment transport formula. However,
this cannot take into account the reduction of cohesion when the top layer is washed away (Jagers, 2003). Erodibility could be reduced by planting vegetation or by placing bed protection on the critical parts of the island, such as next to the embankment, where gradients are highest. This could also work as a means of protecting the embankment against scour.

### 8.2.7 Geometry

The island geometry affects the effectiveness of closure. The length of the island and the bed slope determine the maximum water level difference around the intervention and across the island. A longer island also enhances the positive effect of lower water depth downstream of the closure on reduction of erosion. Island width reduces the gradient across the island and width variation in the streamwise direction can determine the best position of interventions. Larger width also increases the volume of sediment that has to be eroded before channels across the island develop.

Differences in width between the open and closed branch do not seem to affect the effectiveness of closure when it comes to discharge and velocity reduction, and the processes involved. The same holds for the bifurcation asymmetry and the differences in length of the two branches. If the closed branch is shorter and thus has a gradient advantage the difference might be seen on the longer term, but it is not observed in the present study. On a short time scale, the response mainly depends on local gradients and water depths, and larger scale reach properties do not seem to influence the development.

If the channels are not of the same size, the increase in water depth is smaller. In section 6.11.1 the relative increase of discharge and water depth in the main channel is negligible even when the channel is completely closed. Closing a channel in a braided river can be beneficial for navigability improvement when the relative size of the channels is similar.

### 8.3. Generalization of results

The results of simulations without interventions in the simplified case correspond well with the processes described in large braided rivers. For example, deposition in the upstream parts of the two branches is observed as well as erosion of the island head, as described by (Ashmore, 2013). The flow accelerates over the bar head and later diverges (McLelland et al., 1990). Confluence scour occurs where the flow converges again (Jagers, 2003). The island migration downstream is prevented by the fixed land boundaries of the outflow section.

The morphological response to channel closures is not well documented, so direct comparisons cannot be made. The majority of the tests is performed on a simplified geometry with water levels 0.5 m above the island and a representative set of physical parameters. To generalize these conclusions a sensitivity analysis is performed first. Later, the range of simulations is extended with varying water levels (up to 4 m above the island) and with four additional geometries. The similar results can be generalized. Those that are not provide understanding of the physical processes causing the differences. They are discussed in the previous sections of this chapter. The knowledge obtained can be used to approximately extrapolate conclusions made from the simplified reference case only. The issues with generalization related to the simplification of the test cases and the limitations of the numerical model are discussed in the next section.
8.4. Limitations of the model

This is a model study, using simplified representations of braided river reaches. Moreover, certain processes cannot be taken into account with the Delft3D numerical model. Therefore, the methodology has limitations that are listed in this section. In the end, the validity of results is discussed.

The limitations due to the simplification of the reach are:

- Initial island topography is homogenous, and does not represent possible preferred flow paths and low points that would be the likely locations of erosion due to flow concentration.
- No cohesion or vegetation on the island surface is modelled. This likely increases erodibility of the island surface and may influence the mechanism of channel erosion.
- Larger scale braided morphodynamics such as channel shifting, propagation of bars in the system and sediment pulses at the upstream boundary are not included. These processes are identified as important for changes of bifurcation properties and could force flow towards one of the channels (Schuurman & Kleinhans, 2015; Ligthart, 2017), making it easier or harder to close.
- The modelled braided planform consists only of two channels. In reality, more are possible. In that case, the interaction with the rest of the river is neglected. The increase in water levels in the open branch is expected to be lower in that case. The effects of closure upstream and downstream can be assessed only theoretically (see section 3.5.).
- The closed channel lies next to a non-erodible floodplain represented by a land boundary in the model. If the channel would lie in the middle of the braided river or next to an erodible submerged floodplain, there would be problems with erosion and flow bypassing the structure on both sides of the channel. This could make closure more problematic.

Limitations due to the use of a numerical model are:

- General unreliability of morphological predictions with numerical models, and issues with numerical diffusion.
- Local processes such as scour around groyne tips and embankments, deposition around bandals and in areas with roughness elements are not represented. They may have an (at least local) effect on the consequences of closure.
- Simplistic calculation of bank erosion (see Appendix B.3.4.) and a limited floodplain width. It is likely that the full extent of bank erosion that could occur is not represented.
- The effect of weirs on sediment transport may not be correctly represented (Vuik, 2010). The weirs as currently implemented in Delft3D do not block sediment transport. The effect of this is assessed with an additional simulation and is found to be minor (Appendix E).
- Inaccurate representation of roughness elements and vegetation, especially regarding erosion and sedimentation, but also their effect on hydrodynamics. The effect of vegetation binding the soil and reducing erodibility cannot be modelled.
8.4.1 Validation

Previous attempts at channel closure are not well documented and no exact measurement data is available from any of them. This poses a problem for the validation of results obtained with the numerical model, as they cannot be compared with measurements. Sensitivity analysis is performed, as well as a few additional simulations with different model settings (for the descriptions see Appendix E). They all result in a similar overall morphological response, which gives some assurance that the numerical model results are representative of real situations. Moreover, a simplified case based on the documented pilot closure in the Jamuna River is simulated (Appendix A), which shows a similar morphological response to closure as what happened in reality (section 6.11.1 and in particular Figure 6.30). Finally, the morphological module of Delft3D has been validated by its previous uses.

This is the most that could be done to assure the validity of results without access to measurements. To validate the results further, physical experiments or pilot case studies are necessary. For the purposes of validation, the most important question will be if bypass channels and channels across the island are reproduced and if the mechanism of erosion is the same. In parallel with this study (with some delay), flume experiments on channel closure are performed in the Hydraulic Laboratory of TU Delft by Peter Spielmann. A comparison should be available soon after the publication of this thesis.
9. Conclusions and recommendations

9.1. Conclusions

In the present study, a sensitivity analysis is made, different interventions are tested in various circumstances, and the results are analysed in several ways with a goal of answering the following question as accurately and extensively as possible:

How to use river training measures in order to close channels of large sand bed braided rivers in a way that remains effective during and after high flow?

As could be expected, no single simple answer is found. It is possible to (almost completely) close a channel with the use of appropriate but extensive interventions. However, even in the simplified model, the best way to achieve that depends on closure objectives, expected water levels during wet season and to a degree the river reach geometry. In this chapter, the sub-questions are answered first, followed by recommendations for channel closure in different situations, which are essentially the answer to the main research question. The findings of the study can be used in implementing channel closures as part of river training projects and as a basis for further studies of this type of interventions in braided rivers.

What are the causes by which channel closure measures in braided rivers fail in the short term?

Partial or complete failure of channel closures occurs due to channel reopening. Channels are eroded on the braided island. They convey water to the closed branch, increasing the discharges and velocities in it. Two types of channels can develop. The first type are bypass channels that form directly around the intervention. The second are channels that cross the island and connect the two branches. They usually develop from the closed branch towards the open branch. The latter are more problematic over time and more difficult to predict. They should be avoided if possible. No other causes of failure are found, but possible structural failures still need to be explored. Subsurface flow is found not to be an important direct cause of channel formation that leads to reopening. It is possible that it could contribute to erosion of channels from the downstream side by enhancing fluvial erosion. This cannot be simulated with the numerical model and goes beyond the scope of this study.

Which variables play a role in channel reopening and which are the mechanisms of channel formation?

High shear stress due to flow and low sediment supply directly result in erosion of channels on the island. The most important parameter determining this erosion is the water level gradient around the closure structure and across the island separating the two branches. Higher water levels increase the erosion rates, whereas the variation of water depth on the island due to closure can reduce them, when water levels are relatively low (when water depth on the island is below 2...
m). Flow patterns on the island determine the exact position of the channels. Sediment supply to the channels reduces their growth. The geometry of the island separating the channels affects the water level gradients and the variation of water depth on the island. It also determines the volume of sediment that needs to be eroded before a channel forms. Finally, the erodibility of the island is theorized to play a role in determining the rate of channel erosion. The effects of the above-mentioned variables are discussed more extensively in Chapter 8.

Two mechanisms of channel formation are identified through theoretical analysis. Channels can develop either from downstream through backcutting, a combination of fluvial erosion and geotechnical instabilities. The more common mechanism in braided rivers is erosion from upstream due to excess sediment transport capacity. In almost all simulations, the latter mechanism was found to be the cause of reopening. Both with erosion of bypass channels and erosion of channels across the island, the process starts due to excess sediment transport capacity as the water flows onto the island. The erosion starts from the edge of the island and propagates downstream, until a connection is established. Afterwards the channels deepen until sediment supply equals the transport capacity.

When water levels in the closed channel are barely higher than the island, erosion from the downstream side occurs even in the model. This happens when the water flows from the island into the closed channel and accelerates near the edge of the island due to a rapid decrease in water depth. Initial erosion causes further flow concentration. As geotechnical instabilities cannot be reproduced in the model, it is possible that in such cases downstream erosion plays a larger role than observed.

**What are longer-term trends in the response to channel closure and how long can closure remain effective?**

The long-term effectiveness of closure depends on the type of intervention. In most cases, the conditions do not change much. Most changes related to channel reopening occur in the first few weeks. Later, the erosion of bypass channels slows down and sediment deposits in the closed branch. The latter particularly improves the effectiveness of partial closures, as they cause the most sedimentation. On the other hand, when the main mechanism of failure is erosion of a channel across the island, the conditions become worse over time. The depth and width of the new channel increase and effectiveness of closure drops as the channel on the island takes over the conveyance function from the closed one. The planform of the reach is severely reworked. Measures that have such consequences should not be used for an extended period.

A simplified river reach is used to study channel closures. Larger-scale changes that are present in braided rivers, such as channel shifting and propagation of smaller bars into the reach, are not included in the analysis. These could cause problems for the longer-term effectiveness of closure. For example, a shift of the upstream channel could completely bypass the closure. A propagating bar could block the flow into the open branch, diverting it towards the closed one, worsening the conditions. Because of that, the discussed interventions would most likely have to be combined with other river training measures upstream and downstream as part of a larger river training project in order to be effective on a longer time scale.

**How is the morphodynamic response to channel closure (island erosion) related to the initial hydrodynamic conditions after closure and how well can the response be predicted from it?**

Relations between erosion of new channels on the island and the initial water level gradient, water depth and flow velocities are found by analysing the aggregated results of numerous
simulations. For situations with similar properties as the modelled cases, these could be used to predict the degree of erosion. Beyond this, attempts to predict erosion with a simple model based on initial hydrodynamic conditions and one combined also with physical relations are not successful. The problem is two-dimensional and time dependent and it appears that numerical simulations are unavoidable.

The type of channel that will develop is based on the difference between the water level gradients around the intervention in the closed channel and across the island separating the two branches. It can be reasonably well predicted. Usually when the two water level gradients become approximately equal, the channel across the island becomes the most important cause of reopening. When water levels are relatively low, the water depth on the island may prevent the formation of channels across the island even when the water level gradients are similar. The location of bypass channels around the structure is predictable, whereas the prediction of the exact path of channels across the island is likely unreliable even with a numerical model.

**To what degree can the results obtained with a numerical model be generalized to large braided rivers?**

The simulations without interventions correspond reasonably with documented behaviour of braided rivers, taking into account the fact that a simplified river reach is used in the analysis. The wider applicability of the results is tested with a sensitivity analysis and by performing the simulations in various geometries and different water levels. Particularly water levels affect the morphological response to closure, but a physical explanation for this difference can be found. The same holds for differences in geometry. The sensitivity analysis shows that varying physical properties of the simulation does not change the general morphological response to closure. The quantitative differences that do occur can be explained reasonably well. It can be concluded that the results of the study can be applicable for different sections of large braided rivers, by taking the known consequences of these differences into account.

However, it must be kept in mind that this is a model study based on simplified test cases. Simplification, model limitations and the lack of possibilities for validation may mean that consequences of closure in real rivers would differ. This especially holds for consequences of inhomogeneous island topography and the influence of larger scale morphological changes in a braided river. These effects should be analysed in further studies. Validation of the model results with physical experiments or pilot studies is required as well.

**9.2. Recommendations for channel closure**

It is found that the best way to close a channel in a braided river depends on the pursued goals and the conditions in the particular river section. In this section, recommendations are given based on these two criteria. A schematic representation of the recommendations is shown in Figure 9.1.

When water levels relative to the island are low (below 1 m water depth on the island in this study), the best option for full closure is a weir in the upstream part of the channel combined with a long embankment parallel to the island banks that reduces the gradient around the structure. The embankment should reach the entrance of the closed branch to prevent the formation of a channel across the island upstream of the intervention. The alternative is a combination of multiple structures at appropriate intervals in the closed branch. Only one structure needs to block the channel completely, while the rest can be replaced with roughness elements for a similar effect.
When water levels are relatively high (2 or more above island level), the best option is to use multiple submerged weirs in the closed branch or alternatively one submerged weir and a long embankment in the middle of the closed channel, where the water level gradient across the island is the lowest. Complete closures with emerged weirs are not recommended, as significant erosion occurs in those cases. The choice between different options would likely depend on economic considerations. Where the closed channel is wide and deep and the flow on the island is shallow, embankments are probably a better option. On the other hand, if the channel is narrow and the water depth on the island is substantial, combining weirs with permeable structures can be a cheaper alternative.

Whenever complete closure is not required, it is advised to reduce the discharges in the channel only partially and rely on gradual closure due to deposition in the channel. This can be done with a combination of low weirs and roughness elements. Single weirs with short embankments are not recommended due to bypass erosion. Gradual closure due to deposition needs to be studied further before recommendations can be elaborated further.

Near-bank velocities can be most effectively reduced by pushing the flow away from the bank using bandals or groynes that partially block the channel. Constriction of the channel could cause gradual channel abandonment over the course of a few years as well. If this is not an option, the best results are achieved with a combination of a weir and a long embankment on the island.

If the main goal is that the channel remains closed during the dry season, the most important consideration is that channels on the island do not develop. This can be best guaranteed by using multiple low or permeable structures, with at least one of them fully closing the branch during the dry season. A combination of a submerged weir and a long embankment works as well. Improvement of navigability is correlated with dry-season discharge reduction, so the same approach works best for it as well. When the closed channel is much smaller than the open branch, navigability improvement is minimal.

Figure 9.1: A schematic representation of recommendations for channel closure derived from the results of this model study.
9.3. **Recommendations for further research**

Further research is required to confirm the findings, validate assumptions and fill the discovered knowledge gaps. Validation of the model results should be done before further steps are taken. Comparison with a flume experiment will be available soon. Further validation could be done with a well-documented pilot study that would include measurements of discharges, velocities, sediment transport rates and changes in bed topography. The sensitivity analysis could be repeated with cases where channels across the island form, cases where no significant erosion occurs, as well as with higher water levels.

Once the results are more thoroughly validated, other limitations should be addressed. Taking into account larger scale braided processes and interactions can be done by expanding the simplified case both in size of the river reach and complexity of the included processes, or by doing a case study on a real river and specifically analysing the effect of the processes missing in this study. Simulations should be extended for a longer period as well, to obtain more information on long-term response to closure.

Limitations of the numerical model cannot be addressed until these aspects are improved in Delft3D or new modules are added. However, particular measures such as vegetation, roughness elements and bandals can be studied in scale experiments. The focus should be on their effect on sediment transport (a current MSc thesis by Lieke Lokin), erosion, deposition and roughness.

Various measures should be studied in more detail, to identify possible local causes of failure. This includes analysis of flow forces that could damage weaker structures, and the effect of scour holes and subsurface flow erosion on the stability of structures.

Finally, additional interventions should tested, such as placing bed protection or raising the local island level with dredged material next to embankments and weirs. Guidelines regarding the required extent and position should be provided. In particular, further research into possibilities of gradual closure over time with strategically placed smaller interventions that harness the power of the river would be beneficial. This should focus on the effect of different structures on deposition in the closed channel. It is recommended that such analysis be combined with analysis of the influence of local topography and geometry, as well as various braided processes that are neglected in the present study.
10. Bibliography


Appendices
A FAP22 - Channel closure pilot project

The only well-documented case of channel closure is a pilot project in the Brahmaputra-Jamuna River, which was part of Flood Action Plan 22. In this section, the project will be quickly summarized, mainly to serve as a point of reference and comparison for the numerical models used in this research (FAP21/22, 2001).

Objective of the project was to find effective and efficient alternative measures to manage bank erosion and stabilize the braided river. An aggressive outflanking channel was located as the western side of the river (Figure A.1). The main channel is shown only in the upper right corner of the left picture. The Fulchari channel was separated from it by a large island consisting of higher and lower areas. The closed Katlamari channel was separated from the Fulchari channel by a low island about 3 km long and 1200 m wide. The width of Fulchari channel was about 500 m, whereas the width of the closed channel was from 100 to 300 m. Two cross sections are presented in Figure A.2 and Figure A.3.

Figure A.1: Location of the pilot test site within the reach (left) and within the larger course of the Jamuna River (right) (FAP21/22, 2001).
Figure A.2: Cross-section and measured velocities in the Fulchari channel upstream of the bifurcation with the Katlamari channel, during the high-flow period (FAP21/22, 2001).

Figure A.3: Cross-section and measured velocities in the Katlamari channel just downstream of the interventions during the high-flow period (FAP21/22, 2001).
A combination of bandals and an earth dam was used to close the secondary channel. Bandals were positioned in the entrance of the channel. They were used to divert the upper portion of the flow away from the Katlamari channel and let lower sediment rich part in. This would cause deposition in the channel. Few hundred metres downstream an earth dam was constructed. Crest level of the dam corresponded with the level of the opening below the bandals, which closed the upper half of the predicted high flow cross section. Thus, as soon as the dam was overtopped, bandals started functioning. This combination was predicted to cause largest amounts of sedimentation in between the structures, which would lead to channel abandonment.

After the measures were constructed, the flow velocities in the Katlamari channel were reduced to a half of average velocities in the main channel. Sediment concentration was increased, which resulted in deposition. Large scour occurred under the bandal, with a depth of 3-5 metres in only 4 days, but then it stabilized. Sedimentation of about 2 metres on average was documented downstream of the screens. During the high flow periods, water levels rose by about 6 m (Figure A.4), almost completely submerging the island between the channels (Figure A.5). Water depths on the island reached up to 2 metres.

![Figure A.4: Measured water levels at the Katlamari test site during three subsequent years (FAP21/22, 2001).](image)
After the earth dam was overtopped by the flow, a 30 wide part of it that connected to the bank of the island was eroded away in a few days. However, this structure was not meant to completely block the flow anyways, so it still performed its purpose as most of it remained in place. This erosion could likely have been prevented by protection on the dam. Bandals mostly survived the flood season, except for a smaller end component, that was weaker and was destroyed as the Fulchari channel started shifting towards the closed branch.

During the flood, a new channel was eroded across the island, with its end just downstream of the dam. The topography, including the new channel, can be observed in Figure A.6. Location was likely partially determined by local bed topography, as the island was not fully submerged.
Figure A.6: Bed topography after closure showing the eroded channel across the island head that lead to branch reopening (FAP21/22, 2001).
B Model set-up

B.1. One dimensional model

The one-dimensional hydrodynamic model is written in Matlab. It is based on the assumption of steady non-uniform flow. The model consists of four sections (Figure B.1). These are the two branches around the island and the upstream and downstream section. A constant rectangular cross-section is used in each for simplification. The flow is always assumed to be confined to the two branches and the island does not have a conveyance function. During high flow, this is not accurate, but is considered acceptable as calculations during high flow are only meant to get insight on the effect of various parameters, not to make accurate predictions.

![Figure B.1: Scheme of the one-dimensional hydrodynamic model in Matlab.](image)

Normal flow is assumed in the downstream section. Backwater curves are calculated numerically, by discretizing the Belanger equation using an Euler scheme. Distribution of discharge between the two branches is calculated iteratively, until upstream water levels match. When the water level at the bifurcation is known, the upstream part can be resolved.

Once hydrodynamic conditions are known, sediment transport rates are calculated. They serve as an indicator of morphodynamic changes that would occur. Sediment transport capacity is calculated from depth-averaged velocities in the cross section. Two of the sediment transport formulas present in Delft3D are implemented, the Engelund Hansen formula and the general formula (based on Mayer-Peter Mueller formula with arbitrary coefficients). The formulas are shown in the part of the appendix devoted to Delft3D.

Initial hydrodynamic effects of closure during the dry season can be calculated (Figure B.2). A weir is implemented at an arbitrary location in the closed channel. It may either completely block the flow or just dissipate energy. This mainly allows a first indication of the change of water depths and sediment transport capacity in the open branch and maximum water level gradients that could occur due to closure.
The model is also tested for its ability to predict initial water levels and water level gradients after closure during the wet season. For complete closure, the water level difference across the weir and the island predicted with the 1D model is much larger than what the numerical 2D model shows. The 1D model cannot incorporate flow around the structure and across the island, which reduces the water level difference in the 2D model. If a submerged weir is used, the water level difference and discharge depend on weir properties. However, even if the weir is calibrated so that the discharge in the closed channel is the same as in the numerical model, the predicted water level difference is still much higher and vice versa (Table B-1). The situation after channel closure is clearly two-dimensional and the flow on top of the island cannot be neglected. A one-dimensional model cannot describe the most important parameters accurately enough to be of use in predicting the river response to closing one of the channels.

Table B-1: Attempted calibration of weir properties with results of the numerical model. The water level differences across the weir and the discharge in the closed channel do not correspond.

<table>
<thead>
<tr>
<th>Case/Model</th>
<th>1D</th>
<th>2D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle,350m&lt;sub&gt;low&lt;/sub&gt;</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Entrance,350m&lt;sub&gt;low&lt;/sub&gt;</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**B.2. Planform prediction**

Numerical model was set up by specifying initial topography and letting the river develop more natural bed topography by a sort of a morphological spin-up. In order for this development to be realistic, the planform predictor of Crosato and Mosselman (2009) is used to check if the eventual planform of the channels would be as required before the simulations are run.

The model is based on the concept of steady bars that are forced by non-uniform bank lines. The method allows the prediction of the number of bars in a river, or bar mode. Meandering
rivers have at most one bar in a cross section, which corresponds to a bar mode lower than 1.5. Transitional stage is between bar mode of 1.5 and 2.5. Braided rivers are characterized by more than 2.5 bars per cross section on average. The derivation of the formula can be found in the paper, here only the equation used is presented:

\[
m^2 = 0.17 g \frac{(b - 3) B^3 i}{\sqrt{\Delta D_{50}}} CQ\tag{B.2}
\]

\[m\] is the bar mode, \(g\) [\(\text{m/s}^2\)] is the gravitational acceleration, \(b\) [-] is the non-linearity of dependence of sediment transport on depth averaged velocities, \(B\) [\(\text{m}\)] is the channel width, \(i\) [-] is the bed slope, \(\Delta\) [-] is the relative submerged mass density, \(D_{50}\) [\(\text{m}\)] is the median sediment grain diameter, \(C\) [\(\text{m}^{1/4}/\text{s}\)] is the Chézy roughness coefficient, and \(Q\) [\(\text{m}^3/\text{s}\)] is the flow discharge.

The degree of non-linearity of four is used, which is also the parameter used in the sediment transport formula in later simulations. When setting up the model, the aim is for each channel to have bar mode around 1.5 or less. Especially smaller channels had to have a small number of bars; otherwise their already narrow cross sections could be further reduced, changing the desired geometry of the simulation.

### B.3. Delft3D

Delft3D is a physics-based numerical model, in which a wide variety of hydrodynamic and morphodynamic and water quality phenomena can be simulated. It is used to solve an unsteady system of equations, which includes equations of motion in horizontal direction, continuity equation and equations of transport. Equations can be solved in three dimensions or in two dimensions (depth averaged). A two dimensional model is used in this study. Its core is comprised of solving conservation of mass and conservation of momentum in two horizontal directions:

\[
\frac{\partial \eta}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = 0 \tag{B.3}
\]

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} - v_h \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) = -g \frac{\partial \eta}{\partial x} - \frac{\tau_x}{\rho h} \tag{B.4}
\]

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} - v_h \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) = -g \frac{\partial \eta}{\partial y} - \frac{\tau_y}{\rho h} \tag{B.5}
\]

#### B.3.1. Roughness

Multiple roughness parameterizations are possible in Delft3D. The flow is always calculated using the Chézy parameter, so if another way of specifying roughness is used, it is transformed to Chézy in each grid cell. The second equation is the Manning equation:

\[
C = \frac{1}{n} \frac{h^1}{i} \tag{B.6}
\]

The third option is the White-Colebrook formula:
A fourth option is implemented through the trachytopes module, based on the considerations of higher depth dependence of roughness in large braided rivers:

\[ C = 25h^{0.5} \]  \hspace{1cm} (B.8)

**B.3.2. Sediment transport**

Various different sediment transport predictors can be used in Delft3D. In this study, the Engelund-Hansen formula and the general formula were used:

\[ s = \frac{0.05}{\sqrt{gC^3D^2D_{50}}} u^5 \]  \hspace{1cm} (B.9)

\[ s = \alpha D_{50} \sqrt{\Delta gD_{50} \theta^b \left( \mu \theta - \xi \theta_{cr} \right)^c} \]  \hspace{1cm} (B.10)

\[ \theta = \left( \frac{u}{C} \right)^2 \frac{1}{\Delta D_{50}} \]  \hspace{1cm} (B.11)

Engelund Hansen formula can be rewritten as the general formula in the following way:

\[ s = \left( \frac{0.05 C^2}{g} \right) D_{50} \sqrt{\Delta gD_{50} \theta^{2.5}} \]  \hspace{1cm} (B.12)

Which means that:

\[ \alpha = \left( \frac{0.05 C^2}{g} \right) \]  \hspace{1cm} (B.13)

Dependence of \( \alpha \) on roughness cannot be included in Delft3D, so the general formula depends less heavily on roughness than the Engelund-Hansen formula.

**B.3.3. Bed slope and spiral flow effect**

The direction of sediment transport is further affected by gravity pull along bed slopes and the effect of spiral flow. The latter is a 3D phenomenon that has to be parameterized in two-dimensional simulations. Secondary flow is present in both directions in the water column (Figure B.3).
Appendix B: Model set-up

Figure B.3: The flow velocity distribution in the water column due to secondary flow in river bends (Deltares, 2010).

It changes the direction of bed shear stress and thus bed load and total sediment transport. Due to different directions in the vertical, the effect of secondary flow on suspended sediment is not accurately modelled in river bends (Arailopoulos, 2014). For 2D simulations, it is thus better to use a total load transport formula. Generation and transport of spiral flow is calculated with an advection-diffusion equation. The result is spiral flow intensity in each grid cell in each time step, which can then be used to calculate the deviation of sediment transport direction from main flow direction:

\[
\tan(\phi_x) = \frac{v - a_i \frac{u}{l_s}}{u - a_i \frac{v}{l_s}}
\]  
(B.14)

\[
a_i = \frac{2}{\kappa^2} E_{spir} \left(1 - \frac{1}{2} \frac{\sqrt{g}}{\kappa C}\right)
\]  
(B.15)

Equations of Talmon are used to calculate the bed slope effect:

\[
\tan(\phi_z) = \frac{\sin(\Phi_z) + \frac{1}{f(\theta)} \frac{dz_b}{dy}}{\cos(\Phi_z) + \frac{1}{f(\theta)} \frac{dz_b}{dx}}
\]  
(B.16)

\[
f(\theta) = A_{shield} \theta^{B_{shield}} \left(\frac{D_{shield}}{h}\right)^{C_{shield}}
\]  
(B.17)

B.3.4. Bank erosion

The parameterization of bank erosion in Delft3D is simple. Erosion of wet cells that are situated next to dry cells (bank) is distributed between the two by a user specified factor between zero and one. For example if the factor is 0.5, erosion calculated in one time step in a grid cell next to a bank is split in half. Half of it occurs in the actual cell, and the other half is subtracted from the level of the dry cell next to it. The process has some physical background.
Erosion next to the bank causes the bank slope to steepen and possibly removes the bank toe, which results in bank instability.

**B.3.5. Morphological time scale factor**

Hydrodynamic and morphodynamic processes do not occur on the same time scale. Therefore, calculating both together would be unnecessarily time consuming. Using a morphological time scale factor, the speed of morphologic changes is scaled up so much that the change in each time step has an effect on the flow. Essentially, morphologic change in each time step is multiplied by the time scale factor. This way, actual computation time is reduced by the time scale factor whereas, if used correctly, the morphological development should be the same. Care has to be taken that hydrodynamic properties of the hydrograph are not changed.

**B.3.6. Turbulence**

In a 2D depth averaged model, only turbulence in the horizontal direction is calculated. It is modelled as a sub-grid process with the concept of eddy viscosity. Eddy viscosity affects flow patterns by increasing the dispersion of momentum, reducing local peaks in velocity. Local effects of turbulence may be lost like this, which needs to be taken into account when interpreting the results.

**B.3.7. Hydraulic structures**

Large gradients in water levels and velocity as well as possibly non-hydrostatic flow are present around hydraulic structures. In Delft3D, the structures are modelled as sub-grid phenomena. Their effect is parameterized as energy loss and/or prevention of flow in one direction. The computed energy loss is added to the momentum equation as a local sink term. Hydraulic structures are located in velocity points, with a specified direction. In this study, 2D weirs and porous plates are used.

For a 2D weir, energy loss is added to the momentum equation:

\[ M_x = -\frac{gh\Delta E_{\text{weir}}}{\Delta x} \]  \hspace{1cm} (B.18)

In supercritical conditions, flow is determined only by energy head upstream:

\[ Q_{\text{super}} = \Delta y \frac{2}{3} E_{\text{up}} \left( \frac{2}{3} g E_{\text{up}} \right) \]  \hspace{1cm} (B.19)

\[ E_{\text{up}} = \eta_{\text{up}} - z_{\text{crest}} + \frac{(U_{\text{up}})^2}{2g} = \eta_{\text{weir}} - z_{\text{crest}} + \frac{(U_{\text{weir}})^2}{2g} \]  \hspace{1cm} (B.20)

\[ \Delta E_{\text{weir}} = E_{\text{up}} - E_{\text{down}} \]  \hspace{1cm} (B.21)

The equation assumes conservation of energy from upstream until the weir crest. Flow on top of the weir is critical, which allows the calculation of the velocity. Flow is supercritical if:
For subcritical conditions, weir energy loss is based on a combination of experimental data and the Carnot formula, depending on the velocity on top of the weir crest \((\Delta \text{res}, 2010)\).

\[
\eta_{down} - z_{crest} \leq \frac{2}{3} E_{up} \tag{B.22}
\]

Carnot formula reads:

\[
U_{\text{weir}} = \frac{Q_{\text{weir}}}{\Delta y(\eta_{up} - z_{crest})} \tag{B.23}
\]

\[
\Delta E_{\text{Car}} = \frac{(U_{\text{weir}} - U_{\text{down}})^2}{2g} \tag{B.24}
\]

Porcupines are modelled using porous plates in Delft3D. Porous plates are sub-grid, partially transparent structures. They allow the exchange of mass and momentum, but cause a quadratic energy loss. Sediment transport is not obstructed. The only input parameters are the position and a friction coefficient that determines the energy loss. The latter is added to the momentum equation with the following formula:

\[
M_{\xi} = - \frac{c_{\text{loss}} - u}{\Delta x} u \sqrt{u^2 + v^2} \tag{B.25}
\]

### B.3.8. Vegetation

Delft3D offers four roughness predictors to model effect of vegetation as area trachytopes, representing rigid cylinders. Only the fourth implementation, the formula by Baptist (2005) is used. The increase of roughness in other three formulas is translated to an unrealistic increase in sediment transport in the vegetated area. In the fourth formula, flow resistance is split from bed roughness, so that vegetation only affects the flow but not sediment transport. For submerged vegetation (which is used in the model), bed roughness simply remains the same:

\[
C = C_b \tag{B.27}
\]

Flow resistance is added to the momentum equation with a quadratic resistance term:

\[
\text{flow resistance} = - \frac{\lambda_{\text{lin}}}{2} u^2 \tag{B.28}
\]

\[
\lambda = C_d n_{\text{veg}} \tag{B.29}
\]

### B.4. Set-up of the reference case

Acceptable grid size is determined with preliminary calculations. At least six cells are required in a channel for accurate representation of dominant morphological processes. Schuurman et al. (2013) found that if the grid is too rough, eroded channels across the island separating the branches are straight and perpendicular to main flow direction. The length of the simulated
reach is 6 km upstream and 6 km downstream. This means that backwater effects from the bifurcation and the downstream boundary cannot be avoided. However, longer reaches would increase computation time significantly. As braided rivers are characterized by a system of bifurcations and confluences and large hydrological variations, some backwater effect can be considered natural and acceptable in a model.

Recommendations related to grid properties are followed when creating the grid. Orthogonality of each cell is smaller than 0.02. Aspect ratio is between 1 and 2 unless flow is predominantly along one of the grid lines. Smoothness is required to be 1.2 in the area of interest and up to 1.4 elsewhere. Each case is defined on its own grid. Its dimensions are around 70X700 cells. The large number of cells in the transverse direction is a consequence of a fine grid on the island.

Simulation time depends on domain size, cell size, time step and the morphological scale factor. Smaller cells require smaller time steps, based on the Courant condition. Morphological factor can significantly speed up the simulation. When a constant discharge is used, the scale factor can be large, as flow and morphology are effectively completely decoupled. When a hydrograph is used, care must be taken that hydrodynamic properties of the flood do not change due to shortening of the simulation time. The reference simulation is tested for different grid size, time steps and morphological factors until a stable situation is found, where the results do not change if the parameters are reduced further. Different numerical advection schemes are tested as well. It was found that for the time step used, the default cyclic scheme works well. Differences in water levels between them are negligible.

Set up of a realistic reference case is more problematic than expected. The island tends to be unstable, and can be (partially) washed away during high flow (Figure B.4). Several settings had to be tried until a stable situation was found. Search for a stable condition can be understood as finding realistic conditions that enable islands in real braided rivers to be semi-stable as well.

Figure B.4: Bed topography after wet season simulation in initial problematic attempts to set up a relatively stable island. Unrealistic geometry and model parameters are the cause of problems.
C Sensitivity Analysis

C.1. Previous studies

Jagers (2003) studied the occurrence of channel cut-offs in large sand-bed braided rivers. A significant part of the research was devoted to a sensitivity analysis using Delft3D. Simplified river geometry with a single bend and a pointbar was used. He analysed the influence of discharge, downstream water level, roughness, critical shear stress, exponent in the sediment transport formula and different geometries. Differences were analysed qualitatively and with the help of various quantitative parameters.

A larger discharge resulted in faster development of the cut-off channel. Varying downstream water level essentially meant varying the backwater effect upstream. During the simulation, the river adjusted its bed level and the backwater effect was reduced. Lower downstream water level increased velocities on the point bar and caused faster erosion. A linear relationship between erosion and downstream water level was found.

In the sensitivity analysis of roughness parameters, the boundary conditions were not altered. This again caused a backwater effect. Increase in roughness slowed down the flow, raised water levels, distributed the flow towards shallow areas and increased shear stresses on the riverbed. A combination of these effects led to faster development of the cut-off channel. The type of roughness parameterization was not found to be important.

The influence of sediment transport relation was checked by varying the power on velocity and critical shear stress in the general formula. Critical stress represented possible effects of vegetation and cohesion of the bar. Different formulations were calibrated to result in the same sediment transport rates for a particular representative Shields stress. Both parameters had a similar effect. Given a constant average sediment transport, an increase resulted in concentration of sediment transport in deeper channels. The result was a slower development of the cut-off.

Schuurman et al. (2013) used Delft3D to model a self-formed braided river. They performed a sensitivity analysis on a large river reach with a focus on the development of bars and channels. They found that the choice of the bed roughness formula is important. Chézy formula resulted in shallower channels, lower bars and less flow concentration in deeper channels when compared to formulas that are depth dependant. Mayer-Peter Muller and Van Rijn sediment transport formulas predicted lower sediment transport rates and resulted in less morphological changes and slightly wider channels. The most important variable was found to be the bed slope effect. Higher values led to wider, more smooth bars and wide, shallow channels. High value of the bed slope effect also suppressed the formation of channels across the bars.

Williams et al. (2016) performed a sensitivity analysis of a Delft3D depth averaged model for a gravel bed braided river. Model results were validated with measurements of erosion and deposition in river in New Zealand. They found that inclusion of helical flow parameterization is important for a correct prediction of erosion patterns. It increased outer bend and confluence scour to more realistic values. Higher roughness increased morphological changes in general.

An increase in eddy viscosity by order of magnitude decreased morphological changes by 10%. Larger viscosity caused lower transverse velocity gradients, more uniform bed shear stress and
lower gradients of sediment transport. Inclusion of bed slope effects into the model reduced morphological change and decreased scour depths.

Finally, (Ligthart, 2017) performed a sensitivity analysis on a long reach of the Ayeyarwady river to study drivers of physical processes in sand-bed braided rivers. He found that using a time varying hydrograph is important. With a constant discharge, some channels started narrowing and closing. However, the duration of particular hydrograph stages was not found to have a large impact. Changes in effect of the bed slope and helical flow had the same consequences as in previous studies. A lower power on velocity in the sediment transport relation caused a decrease in bar height and a faster bar movement through the system.

### C.2. Sensitivity analysis results

#### C.2.1. Sediment transport formulas

Table C-1: Results of the sensitivity analysis of sediment transport formulas during first year dry season.

<table>
<thead>
<tr>
<th>General formula (a=25, b=2)</th>
<th>Δη_{up} [cm]</th>
<th>Δh_{end} [m]</th>
<th>%h_{end}</th>
</tr>
</thead>
<tbody>
<tr>
<td>General formula (a=30, b=1.5)</td>
<td>40</td>
<td>1.1</td>
<td>25 %</td>
</tr>
<tr>
<td>Engelund-Hansen formula</td>
<td>50</td>
<td>0.65</td>
<td>14.5 %</td>
</tr>
</tbody>
</table>

Table C-2: Results of the sensitivity analysis of sediment transport formulas during the wet season.

<table>
<thead>
<tr>
<th>General formula (a=25, b=2)</th>
<th>Q_{c, end} [m$^3$/s]</th>
<th>%Q_{c, end}</th>
<th>v_{c} [m/s]</th>
<th>%v_{c}</th>
<th>D_{scour} [m]</th>
<th>Δη_{up, end} [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>General formula (a=30, b=1.5)</td>
<td>2013</td>
<td>-31 %</td>
<td>0.86</td>
<td>-21 %</td>
<td>13.7</td>
<td>-6</td>
</tr>
<tr>
<td>Engelund-Hansen (n=0.02)</td>
<td>1395</td>
<td>-52 %</td>
<td>0.70</td>
<td>-37 %</td>
<td>14.8</td>
<td>2</td>
</tr>
<tr>
<td>Engelund-Hansen (C=60 m$^{1/2}$/s)</td>
<td>1704</td>
<td>-35 %</td>
<td>0.60</td>
<td>-39 %</td>
<td>14.9</td>
<td>-3</td>
</tr>
</tbody>
</table>

#### C.2.2. Eddy diffusivity and eddy viscosity

Table C-3: Results of the sensitivity analysis of eddy diffusivity and eddy viscosity during the wet season.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Q_{c, end} [m$^3$/s]</th>
<th>%Q_{c, end}</th>
<th>v_{c} [m/s]</th>
<th>%v_{c}</th>
<th>D_{scour} [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>D_{H}=2 m$^3$/s</td>
<td>1895</td>
<td>-35 %</td>
<td>0.85</td>
<td>-25 %</td>
<td>11.8</td>
</tr>
<tr>
<td>D_{H}=5 m$^3$/s</td>
<td>1910</td>
<td>-35 %</td>
<td>0.82</td>
<td>-28 %</td>
<td>11.8</td>
</tr>
<tr>
<td>D_{H}=10 m$^3$/s</td>
<td>1874</td>
<td>-36 %</td>
<td>0.85</td>
<td>-25 %</td>
<td>11.4</td>
</tr>
<tr>
<td>D_{H}=15 m$^3$/s</td>
<td>1742</td>
<td>-41 %</td>
<td>0.75</td>
<td>-34 %</td>
<td>11.2</td>
</tr>
<tr>
<td>D_{H}=20 m$^3$/s</td>
<td>1631</td>
<td>-45 %</td>
<td>0.78</td>
<td>-32 %</td>
<td>11.1</td>
</tr>
<tr>
<td>ν_{H}=2 m$^2$/s</td>
<td>1817</td>
<td>-38 %</td>
<td>0.76</td>
<td>-33 %</td>
<td>11.6</td>
</tr>
<tr>
<td>ν_{H}=0.5 m$^2$/s</td>
<td>1822</td>
<td>-39 %</td>
<td>0.77</td>
<td>-34 %</td>
<td>11.8</td>
</tr>
<tr>
<td>ν_{H}=0.1 m$^2$/s</td>
<td>1673</td>
<td>-44 %</td>
<td>0.80</td>
<td>-32 %</td>
<td>12</td>
</tr>
<tr>
<td>ν_{H}=0.01 m$^2$/s</td>
<td>1338</td>
<td>-55 %</td>
<td>0.69</td>
<td>-41 %</td>
<td>9.7</td>
</tr>
</tbody>
</table>
C.2.3. Bed slope and spiral flow effect

Table C-4: Results of the sensitivity analysis of the bed slope effect during the wet season (E_{Spir}=1).

<table>
<thead>
<tr>
<th>( A_{\text{shields}} )</th>
<th>( Q_{\text{cl, end}} ) [m(^3)/s]</th>
<th>%( Q_{\text{cl, end}} )</th>
<th>( v_{\text{cl}} ) [m/s]</th>
<th>%( v_{\text{cl}} )</th>
<th>( D_{\text{scour}} ) [m]</th>
<th>( \Delta \eta_{\text{up, end}} ) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>1957</td>
<td>-33 %</td>
<td>0.81</td>
<td>-31 %</td>
<td>10.7</td>
<td>-10</td>
</tr>
<tr>
<td>0.5</td>
<td>1894</td>
<td>-36 %</td>
<td>0.80</td>
<td>-30 %</td>
<td>11.9</td>
<td>-3</td>
</tr>
<tr>
<td>0.6</td>
<td>1895</td>
<td>-35 %</td>
<td>0.85</td>
<td>-25 %</td>
<td>11.8</td>
<td>-6</td>
</tr>
<tr>
<td>0.8</td>
<td>1864</td>
<td>-37 %</td>
<td>0.81</td>
<td>-33 %</td>
<td>12.0</td>
<td>-2</td>
</tr>
<tr>
<td>1</td>
<td>1284</td>
<td>-57 %</td>
<td>0.67</td>
<td>-42 %</td>
<td>10.3</td>
<td>8</td>
</tr>
</tbody>
</table>

Table C-5: Results of the sensitivity analysis of the spiral flow effect during the wet season \((A_{\text{shields}}=0.6)\).

<table>
<thead>
<tr>
<th>( E_{\text{Spir}} )</th>
<th>( Q_{\text{cl, end}} ) [m(^3)/s]</th>
<th>%( Q_{\text{cl, end}} )</th>
<th>( v_{\text{cl}} ) [m/s]</th>
<th>%( v_{\text{cl}} )</th>
<th>( D_{\text{scour}} ) [m]</th>
<th>( \Delta \eta_{\text{up, end}} ) [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>1633</td>
<td>-45 %</td>
<td>0.72</td>
<td>-37 %</td>
<td>10.2</td>
<td>-6</td>
</tr>
<tr>
<td>0.6</td>
<td>1718</td>
<td>-42 %</td>
<td>0.81</td>
<td>-29 %</td>
<td>10.2</td>
<td>-2</td>
</tr>
<tr>
<td>0.8</td>
<td>1831</td>
<td>-38 %</td>
<td>0.83</td>
<td>-27 %</td>
<td>11.3</td>
<td>-3</td>
</tr>
<tr>
<td>1</td>
<td>1838</td>
<td>-38 %</td>
<td>0.77</td>
<td>-33 %</td>
<td>11.4</td>
<td>-2</td>
</tr>
<tr>
<td>1.2</td>
<td>1774</td>
<td>-40 %</td>
<td>0.79</td>
<td>-32 %</td>
<td>9.8</td>
<td>0</td>
</tr>
<tr>
<td>1.4</td>
<td>1655</td>
<td>-44 %</td>
<td>0.75</td>
<td>-36 %</td>
<td>10.3</td>
<td>1</td>
</tr>
</tbody>
</table>

C.2.4. Roughness

Table C-6: Results of the sensitivity analyses of roughness during the wet season.

| \( n \) \(=0.02 \) | \( C=60\text{ m}^{1/2}/\text{s} \) | \( n=0.023 \) | \( n=0.017 \) | \( k_s=0.1 \text{ m} \) | \%\( Q_{\text{cl, end}} \) | \%\( v_{\text{cl}} \) | \( D_{\text{scour}} \) [m] | \( \Delta \eta_{\text{up, end}} \) [m] |
|-----------------|----------------------------|----------------|----------------|----------------|--------------------|--------------------|----------------|----------------|----------------|
| -35 %           | -35 %                      | -35 %          | -35 %          | -35 %          | 11.8               | -4                | 11.8           | -4             |
| -39 %           | -39 %                      | -39 %          | -39 %          | -39 %          | 11.9               | -1                | 11.9           | -1             |
| -43 %           | -43 %                      | -43 %          | -43 %          | -43 %          | 11.7               | -4                | 11.7           | -4             |
| -38 %           | -38 %                      | -38 %          | -38 %          | -38 %          | 11.6               | 2                 | 11.6           | 2              |
| -34 %           | -34 %                      | -34 %          | -34 %          | -34 %          | 13.7               | -9                | 13.7           | -9             |

C.2.5. Sediment size

Table C-7: Results of the sensitivity analyses of sediment size during the first year dry season.

<table>
<thead>
<tr>
<th>( 0.2 \text{ mm} )</th>
<th>( 0.25 \text{ mm} )</th>
<th>( 0.3 \text{ mm} )</th>
<th>( 0.4 \text{ mm} )</th>
<th>( 0.5 \text{ mm} )</th>
<th>( 0.8 \text{ mm} )</th>
<th>( \text{Graded} )</th>
<th>( \Delta \eta_{\text{up, end}} ) [m]</th>
<th>( \Delta h_{\text{end}} ) [m]</th>
<th>%( h_{\text{end}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>1.7</td>
<td>38</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.3</td>
<td>1.7</td>
<td>38</td>
</tr>
<tr>
<td>0.3</td>
<td>1.6</td>
<td>36</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.3</td>
<td>1.6</td>
<td>36</td>
</tr>
<tr>
<td>0.4</td>
<td>1.1</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.4</td>
<td>1.1</td>
<td>25</td>
</tr>
<tr>
<td>0.45</td>
<td>1.15</td>
<td>26</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.45</td>
<td>1.15</td>
<td>26</td>
</tr>
<tr>
<td>0.5</td>
<td>1.05</td>
<td>24</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.5</td>
<td>1.05</td>
<td>24</td>
</tr>
<tr>
<td>0.6</td>
<td>0.8</td>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.6</td>
<td>0.8</td>
<td>17</td>
</tr>
<tr>
<td>0.4</td>
<td>1.3</td>
<td>29</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.4</td>
<td>1.3</td>
<td>29</td>
</tr>
</tbody>
</table>
Table C-8: Results of the sensitivity analysis of sediment size during the wet season using a different initial bed topography for each simulation, based on dry season bed adaptation.

<table>
<thead>
<tr>
<th>Q_{cl,end} [m^3/s]</th>
<th>%Q_{cl,end}</th>
<th>v_{cl} [m/s]</th>
<th>%v_{cl}</th>
<th>D_{scour} [m]</th>
<th>∆η_{up,int} [m]</th>
<th>∆η_{up,end} [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>1729</td>
<td>-42 %</td>
<td>0.77</td>
<td>-35 %</td>
<td>12.4</td>
<td>24</td>
</tr>
<tr>
<td>0.25</td>
<td>1453</td>
<td>-51 %</td>
<td>0.76</td>
<td>-34 %</td>
<td>10.6</td>
<td>27</td>
</tr>
<tr>
<td>0.3</td>
<td>1895</td>
<td>-35 %</td>
<td>0.85</td>
<td>-25 %</td>
<td>11.8</td>
<td>30</td>
</tr>
<tr>
<td>0.4</td>
<td>1949</td>
<td>-34 %</td>
<td>0.79</td>
<td>-30 %</td>
<td>11.3</td>
<td>33</td>
</tr>
<tr>
<td>0.5</td>
<td>1863</td>
<td>-37 %</td>
<td>0.80</td>
<td>-29 %</td>
<td>10.5</td>
<td>35</td>
</tr>
<tr>
<td>0.8</td>
<td>1823</td>
<td>-38 %</td>
<td>0.85</td>
<td>-23 %</td>
<td>8.8</td>
<td>40</td>
</tr>
<tr>
<td>Graded</td>
<td>1923</td>
<td>-35 %</td>
<td>0.81</td>
<td>-28 %</td>
<td>8.8</td>
<td>32</td>
</tr>
</tbody>
</table>

Table C-9: Results of the sensitivity analysis of sediment size during the wet season using the same initial bed topography for each simulation.

<table>
<thead>
<tr>
<th>Q_{cl,end} [m^3/s]</th>
<th>%Q_{cl,end}</th>
<th>v_{cl} [m/s]</th>
<th>%v_{cl}</th>
<th>D_{scour} [m]</th>
<th>∆η_{up,int} [m]</th>
<th>∆η_{up,end} [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 mm</td>
<td>1492</td>
<td>-50 %</td>
<td>0.69</td>
<td>-42 %</td>
<td>12.4</td>
<td>30</td>
</tr>
<tr>
<td>0.2 mm</td>
<td>1419</td>
<td>-52 %</td>
<td>0.71</td>
<td>-40 %</td>
<td>11.2</td>
<td>30</td>
</tr>
<tr>
<td>0.25 mm</td>
<td>1829</td>
<td>-38 %</td>
<td>0.79</td>
<td>-32 %</td>
<td>12.4</td>
<td>30</td>
</tr>
<tr>
<td>0.3 mm</td>
<td>1895</td>
<td>-35 %</td>
<td>0.85</td>
<td>-25 %</td>
<td>11.8 m</td>
<td>30</td>
</tr>
<tr>
<td>0.4 mm</td>
<td>1829</td>
<td>-38 %</td>
<td>0.76</td>
<td>-33 %</td>
<td>10.8</td>
<td>30</td>
</tr>
<tr>
<td>0.5 mm</td>
<td>1800</td>
<td>-39 %</td>
<td>0.76</td>
<td>-32 %</td>
<td>10.5</td>
<td>30</td>
</tr>
<tr>
<td>0.8 mm</td>
<td>1771</td>
<td>-39 %</td>
<td>0.76</td>
<td>-31 %</td>
<td>9.9</td>
<td>30</td>
</tr>
</tbody>
</table>

C.2.6. Closure during the dry season

Table C-10: Results of the sensitivity analysis of different duration of closure during the dry season. The results show the conditions at the end of the wet season.

<table>
<thead>
<tr>
<th>Q_{cl,end} [m^3/s]</th>
<th>%Q_{cl,end}</th>
<th>v_{cl} [m/s]</th>
<th>%v_{cl}</th>
<th>D_{scour} [m]</th>
<th>∆η_{up,int} [m]</th>
<th>∆η_{up,end} [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 months</td>
<td>2594</td>
<td>-11 %</td>
<td>1.02</td>
<td>-5 %</td>
<td>14.6</td>
<td>52</td>
</tr>
<tr>
<td>2 months</td>
<td>2130</td>
<td>-27 %</td>
<td>0.85</td>
<td>-21 %</td>
<td>13.5</td>
<td>42</td>
</tr>
<tr>
<td>4 months</td>
<td>2013</td>
<td>-31 %</td>
<td>0.86</td>
<td>-20 %</td>
<td>13.7</td>
<td>30</td>
</tr>
<tr>
<td>8 months</td>
<td>1744</td>
<td>-40 %</td>
<td>0.75</td>
<td>-30 %</td>
<td>13.4</td>
<td>11</td>
</tr>
</tbody>
</table>

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D Simulation properties

D.1. Scenario 1

Table D-1: Geometrical and topographical properties of the small-scale asymmetric simulation based on the FAP 22 pilot study.

<table>
<thead>
<tr>
<th></th>
<th>Upstream</th>
<th>Upper branch</th>
<th>Lower branch</th>
<th>Downstream</th>
<th>Island</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width [m]</td>
<td>600</td>
<td>600</td>
<td>150</td>
<td>600</td>
<td>1000</td>
</tr>
<tr>
<td>Bed level* [m + datum]</td>
<td>-7</td>
<td>-7</td>
<td>-5</td>
<td>-7</td>
<td>0</td>
</tr>
<tr>
<td>Length [m]</td>
<td>6000</td>
<td>/</td>
<td>20</td>
<td>5</td>
<td>/</td>
</tr>
<tr>
<td>Bifurcation angle []</td>
<td>/</td>
<td>6000</td>
<td>3000</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Slope []</td>
<td>7.5 * 10^{-5}</td>
<td>7.5 * 10^{-5}</td>
<td>7.5 * 10^{-5}</td>
<td>7.5 * 10^{-5}</td>
<td></td>
</tr>
</tbody>
</table>

*without taking bed slope into account

Table D-2: Physical properties of the small-scale asymmetric simulation based on the FAP 22 pilot study.

<table>
<thead>
<tr>
<th>D_{so} [mm]</th>
<th>n</th>
<th>\nu_h [m^2/s]</th>
<th>D_h [m^2/s]</th>
<th>A_{Shields}</th>
<th>B_{Shields}</th>
<th>E_{Spir}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.02</td>
<td>1</td>
<td>1</td>
<td>0.6</td>
<td>0.5</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table D-3: Hydraulic boundary conditions of the small-scale asymmetric simulation based on the FAP 22 pilot study.

<table>
<thead>
<tr>
<th></th>
<th>Discharge [m^3/s]</th>
<th>Water level [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry season</td>
<td>2650</td>
<td>-3.16</td>
</tr>
<tr>
<td>Wet season 0.5 m above island</td>
<td>5900</td>
<td>-0.66</td>
</tr>
<tr>
<td>Wet season 1 m above island</td>
<td>6600</td>
<td>-0.16</td>
</tr>
</tbody>
</table>

D.2. Scenario 2

Table D-4: Geometrical and topographical properties of the larger scale simulation.

<table>
<thead>
<tr>
<th></th>
<th>Upstream</th>
<th>Upper branch</th>
<th>Lower branch</th>
<th>Downstream</th>
<th>Island</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width [m]</td>
<td>650</td>
<td>350</td>
<td>300</td>
<td>650</td>
<td>3000</td>
</tr>
<tr>
<td>Bed level* [m + datum]</td>
<td>-9.5</td>
<td>-8.5</td>
<td>-7</td>
<td>-9.5</td>
<td>0</td>
</tr>
<tr>
<td>Length [m]</td>
<td>12000</td>
<td>/</td>
<td>20</td>
<td>20</td>
<td>/</td>
</tr>
<tr>
<td>Bifurcation angle []</td>
<td>/</td>
<td>12000</td>
<td>6000</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Slope []</td>
<td>7.5 * 10^{-5}</td>
<td>7.5 * 10^{-5}</td>
<td>7.5 * 10^{-5}</td>
<td>7.5 * 10^{-5}</td>
<td></td>
</tr>
</tbody>
</table>

*without taking bed slope into account

Table D-5: Physical properties of the larger scale simulation.

<table>
<thead>
<tr>
<th>D_{so} [mm]</th>
<th>n</th>
<th>\nu_h [m^2/s]</th>
<th>D_h [m^2/s]</th>
<th>A_{Shields}</th>
<th>B_{Shields}</th>
<th>E_{Spir}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.02</td>
<td>1</td>
<td>1</td>
<td>0.6</td>
<td>0.5</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table D-6: Hydraulic boundary conditions of the larger scale simulation.

<table>
<thead>
<tr>
<th></th>
<th>Discharge [m^3/s]</th>
<th>Water level [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry season</td>
<td>6500</td>
<td>-4.9</td>
</tr>
<tr>
<td>Wet season 0.5 m above island</td>
<td>12000</td>
<td>-1.9</td>
</tr>
<tr>
<td>Wet season 2 m above island</td>
<td>18000</td>
<td>-0.4</td>
</tr>
</tbody>
</table>
### D.3. Scenario 3

Table D-7: Geometrical and topographical properties of the simulation with a narrower channel.

<table>
<thead>
<tr>
<th>Width [m]</th>
<th>Upstream</th>
<th>Upper branch</th>
<th>Lower branch</th>
<th>Downstream</th>
<th>Island</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500</td>
<td>450</td>
<td>250</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>Bed level* [m + datum]</td>
<td>-7</td>
<td>-6.5</td>
<td>-6</td>
<td>-7</td>
<td>0</td>
</tr>
<tr>
<td>Length [m]</td>
<td>6000</td>
<td>6000</td>
<td>6000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bifurcation angle [°]</td>
<td>/</td>
<td>20</td>
<td>20</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Slope []</td>
<td>$7 \times 10^{-5}$</td>
<td>$7 \times 10^{-5}$</td>
<td>$7 \times 10^{-5}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*without taking bed slope into account

Table D-8: Physical properties of the simulation with an narrower channel.

<table>
<thead>
<tr>
<th>$D_{50}$ [mm]</th>
<th>$n$</th>
<th>$v_h$ [m$^2$/s]</th>
<th>$D_h$ [m$^2$/s]</th>
<th>$A_{Shields}$</th>
<th>$B_{Shields}$</th>
<th>$E_{Spir}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.02</td>
<td>1</td>
<td>1</td>
<td>0.6</td>
<td>0.5</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table D-9: Hydraulic boundary conditions of the simulation with an narrower channel.

<table>
<thead>
<tr>
<th></th>
<th>Discharge [m$^3$/s]</th>
<th>Water level [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry season</td>
<td>3300</td>
<td>-2.76</td>
</tr>
<tr>
<td>Wet season 0.5 m above island</td>
<td>6400</td>
<td>-0.76</td>
</tr>
<tr>
<td>Wet season 2 m above island</td>
<td>9000</td>
<td>+0.74</td>
</tr>
</tbody>
</table>

### D.4. Scenario 4

Table D-10: Geometrical and topographical properties of the simulation with a narrower channel and an asymmetric bifurcation.

<table>
<thead>
<tr>
<th>Width [m]</th>
<th>Upstream</th>
<th>Upper branch</th>
<th>Lower branch</th>
<th>Downstream</th>
<th>Island</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>500</td>
<td>450</td>
<td>250</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>Bed level* [m + datum]</td>
<td>-7</td>
<td>-6.5</td>
<td>-6</td>
<td>-7</td>
<td>0</td>
</tr>
<tr>
<td>Length [m]</td>
<td>6000</td>
<td>6000</td>
<td>6000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bifurcation angle [°]</td>
<td>/</td>
<td>25</td>
<td>15</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>Slope []</td>
<td>$7 \times 10^{-5}$</td>
<td>$7 \times 10^{-5}$</td>
<td>$7.5 \times 10^{-5}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*without taking bed slope into account

Table D-11: Physical properties of the simulation with a narrower channel and an asymmetric bifurcation.

<table>
<thead>
<tr>
<th>$D_{50}$ [mm]</th>
<th>$n$</th>
<th>$v_h$ [m$^2$/s]</th>
<th>$D_h$ [m$^2$/s]</th>
<th>$A_{Shields}$</th>
<th>$B_{Shields}$</th>
<th>$E_{Spir}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>0.02</td>
<td>1</td>
<td>1</td>
<td>0.6</td>
<td>0.5</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table D-12: Hydraulic boundary conditions of the simulation with a narrower channel and an asymmetric bifurcation.

<table>
<thead>
<tr>
<th></th>
<th>Discharge [m$^3$/s]</th>
<th>Water level [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry season</td>
<td>3300</td>
<td>-2.76</td>
</tr>
<tr>
<td>Wet season 0.5 m above island</td>
<td>6400</td>
<td>-0.76</td>
</tr>
<tr>
<td>Wet season 2 m above island</td>
<td>9000</td>
<td>+0.74</td>
</tr>
</tbody>
</table>
E Supplementary simulations

Some additional simulations are performed as an indirect check of model validity. The idea is that even if the modelling approach is changed, the results should be the same, if the model more likely to be correct.

E.1. Weirs represented by raised bed levels

The implementation of weirs in Delft3D does not correctly represent the transport of sediment across the structure. The weir does not block bed load transport or result in increased local shear stresses (Vuik, 2010). To see if this could change the model results in the case of submerged weirs, a simulation is made where weirs are represented by a raised bed level and a small weir on top. This does not yet correctly represent the local effects of the weirs, but it does influence the sediment transport because of the bed slope effect. If the morphodynamic response for two completely different implementations is similar, the results are more likely to be correct.

Figure E.1: Bed topography after closure with a weir implemented with raised bed levels and a hydraulic structure on top (left) and just a hydraulic structure (right).

The difference between in the morphological response is almost not visible (Figure E.1). There is a difference in the quantitative results, as the energy loss at the weir is not exactly the same. Sediment transport upstream of the weir is low and almost no sedimentation reaches the weir in any of the cases. The sediment is transported around the weir through the bypass channel instead of over it. There is a possibility that this could be different if sediment transport rates upstream would be higher and if no bypass channels were present.

E.2. Three-dimensional simulation

A three dimensional simulation is made to see if a different way of calculating the flow changes the results. A total sediment transport formula is used. The calculation of helical flow is different, as it is now resolved on a three dimensional grid instead of being parameterized with equations. The morphological response to closure remains almost completely the same as in the reference simulation (Figure E.2).

Figure E.2: Bed topography after closure in a three-dimensional simulation.