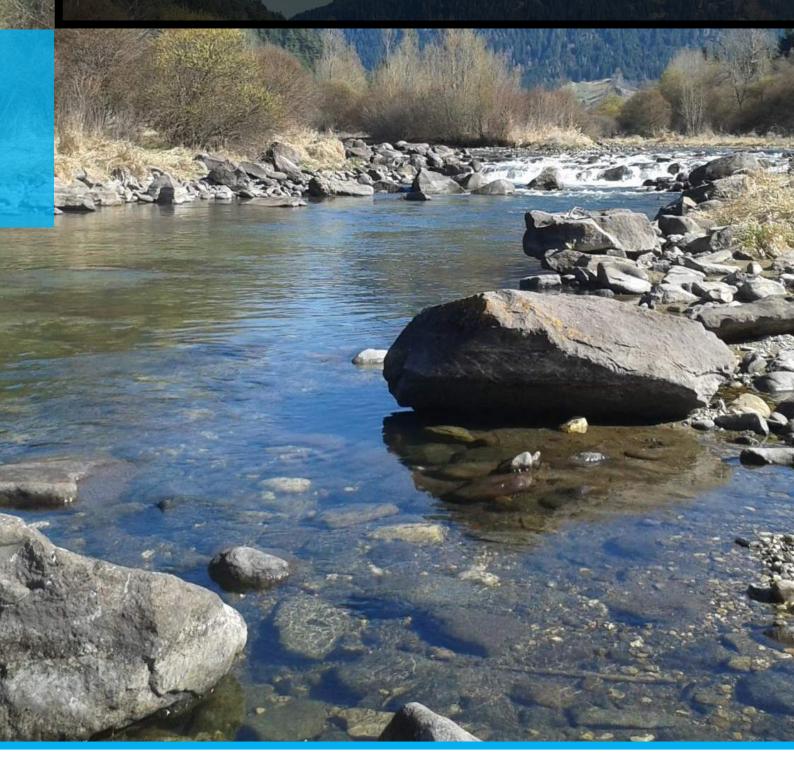
Implications of Fine Sediment Dynamics in Relation to Flushing Operations for Physical Habitats at the Meso-scale

Vera G. Knook









Implications of Fine Sediment Dynamics in Relation to Flushing Operations for Physical Habitats at the Meso-scale

by

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Preface

This thesis is the final step for completion of the master's degree in Hydraulic Engineering at Delft University of Technology. Looking back, there is one quote that illustrates this study period perfectly:

"Live as if you were to die tomorrow. Learn as if you were to live forever."

- Mahatma Gandhi,

Before anything else, I want to express my gratitude to my Portuguese and Belgium friends, Antoine, Bram, Bob and Yoran, who defined my luck and ensured that I could continue to learn till this day.

When I told Kees Sloff in February of this year, that I was interested in the topic of dams and particularly their consequences to nature, he suggested to work together with professor Guido Zolezzi. Soon Guido expressed his interest which marked the beginning of a valuable collaboration. My civil engineering background and my passion for nature met each other in the topic. Finding the link between physics and ecology proved to be a worthwhile challenge. I want to thank Kees for creating this opportunity, and for his guidance along the way. I thank Guido for welcoming me to the University of Trento, treating me as one of his own students and engaging with the project during my visits.

I would like to thank the other members of my committee; professor Wim Uijttewaal, professor Michael McClain and Astrid Blom. Wim Uijttewaal for his constructive advice and valuable support in choosing my direction within the research, Michael McClain for the fruitful, interesting discussions that shed light on the ecological aspects and Astrid Blom for her valuable involvement at the exact right moments.

For all my questions about the model setup in Delft3D, I could turn to Binh Le, a PhD student at the TU Delft. I enjoyed our various enthusiastic and constructive discussions. Also I owe a thank you to the colleagues at Deltares where I enjoyed a pleasant working atmosphere and to the colleague-students of room 4.84 who soon became friends.

The visits to Italy would have been not even half as valuable without David Faró, a PhD student at the University of Trento. I want to thank him for his continuous input, critical discussions and his encouragement to find the story in this research. Also, I would like to thank him and Moritz for making me feel so at home and immersing me in the Italian culture. I further enjoyed the support from Mauro, Martino and Luca and their patient explanations on biological modelling aspects, of which I hardly knew the existence before I started this project.

The last months were not the easiest, and it is thanks to the warm care and endless support of my mother that I stand here with a smile today. It was a time in which I experienced abundant love from friends from around the world. Tessa, Petra, Hanna, Maartje, Marijke, I want to thank you explicitly for supporting me in my downs, and celebrating my ups. I thank my father and my brother, Guido, for their moral support and faith.

This thesis also marks the end of my time as a student. Two years ago, I was not sure whether to start a master's degree, but then committed to it with the aim to combine learning with living to the fullest, following my passion for whitewater kayaking. I look back to a great amount of opportunities that I got as a student and through which I experienced various different learning environments, close to rivers, all over the world. These experiences I take with me not only as an engineer, but as a person. My life as a student officially ends here, but the time to learn continues.

Vera G.Knook Delft, November 2017

Summary

Worldwide, dam reservoirs loose over one percent of their storage capacity every year due to sedimentation. Proper management is therefore urgent. While drawdown flushing is considered an effective method to remove sediments from the reservoir, the increased sediment flux has an impact on the downstream environment. On the short term, several species suffer high mortality rates due to increased turbidity. Also on the long term the impacts might be significant. The deposition of fine sediments can change the habitat suitability and thereby jeopardize the conditions for recovery.

The aim of this research is to evaluate the effect of different flushing operation scenarios on the physical habitats at the ecologically relevant meso-scale. An idealised, depth-averaged hydro-morphodynamic model is set up in Delft3D-Flow, a modelling software package developed by Deltares. The model represents a reach of the Avisio, a river situated in the Eastern Italian Alps. Across this river, the Pezzè dam was built in 1952, trapping all incoming sediments. Every three years the dam is flushed, which gained more public attention over the last years. A specific reach was chosen as a reference case as it consists of a channel bar topography where fine sediments accumulate up to ten times more during a flushing event than in other, more channelised reaches. It is therefore considered the most affected by the flushing event. The reach has a length of roughly a kilometre and is situated 10 kilometres downstream of the dam.

The hydro-morphodynamic model assumes a non-erodible bed, as the coarsened river bed is not expected to move significantly during a flushing event. This bed has the shape of an alternate bar topography. The simulation of the flushing event is simplified as an influx of bed load transport with a fraction size of one millimetre, and a magnitude close to the equilibrium transport capacity. Deposition occurs upstream and to a higher extent downstream of the bars, where flow velocities are low and secondary flow aids the movement of sediments into these areas. Subsequently, a clean water peak is imposed to investigate its effectiveness in removing the fine sediments from the reach. The hydrograph of this peak is varied in shape, duration and magnitude to simulate different operation scenarios and natural rainfall runoff events.

By applying the Mesohabitat Evaluation Model (MEM), a habitat suitability model developed for the meso-scale, it was possible to divide the reach into classes based on flow velocity, flow depth and shear stress. Such classification highly depends on the governing discharge. The classes are mainly distinctive by the division between high and low energy classes and in this way show a high correlation to the deposition of fines. The model suggests that fine sediments remain in the system only when low energy classes are present. Although the MEM classification aims at the meso-scale, it follows a micro-scale approach and therefore undermines the advantages of assessment at the ecologically more relevant meso-scale. It is recommended to develop the MEM-procedure by accounting for neighbouring computational cells.

The MEM-procedure gives an useful indication of the spatial variety in deposition and erosion patterns. It however does not provide insight into the implications of sedimentation to the ecology, without the coupling with a biological model. Such a biological model describes the suitability of the physical habitat for a specific organism and thereby incorporates a functional goal.

As such a biological model could, due to time restrictions, not be applied in this research it was chosen to perform a micro-scale based suitability study. This illustrates the potential of morphodynamic modelling as a tool for habitat suitability modelling. Simplified preference curves were derived for spawning trout, of which the physical habitat requirements are sensitive to the deposition of fine sediments. It was found that the deposition of fine sediments hardly effects this habitat. When required nonetheless, any considered peak flow recovers a substantial amount of suitable habitat. This implies that, if a clean water peak of a sufficient magnitude follows the flushing operation, the impact on the spawning habitat, and probably any habitat, is minimal.

Whether such a clean water peak occurs, can be partly controlled by the dam operation, but also depends on the hydrology of the catchment. A ten-year hydrological time series of the Avisio river, measured upstream of the dam, shows that the catchment of this reservoir does not provide sufficient water to guarantee a clean

water peak during any season. However, with the significant contribution of two tributaries that flow into the Avisio river between the dam and the reference reach, it is highly probable that a peak flow of sufficient magnitude occurs during high flow season. To ensure the benefits of a clean water peak, it is recommended to plan the flushing event at the start of the high water season, which lasts from May to July. For other rivers, it might be possible to adopt such a clean water peak as part of the flushing operation strategy, providing a higher level of control. Even though this study suggests that the implications of the flushing event to the physical habitats are minimal, and of no comparison to the potential direct impacts, this method of evaluation shows potential to assess other morphological relevant events and even long term morphological changes.

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List of Symbols

α	[-]	Calibration factor for the Engelund und Hansen transport formula
A_{Sh}	[-]	Coefficient for the slope effect
b	[-]	Linearity of the Engelund und Hansen Transport formula
β	[-]	Width to depth ratio
B_{Sh}	[-]	Coefficient for the slope effect
C	$[m^{\frac{1}{2}}/s]$	Chezy's friction coefficient
C_{Sh}	[-]	Coefficient for the slope effect
D_{50}	[m]	Mean and representative diameter of the sediment fraction
Δ	[-]	Relative density
F	[-]	Dimensionless Froude number
g	$[m/s^2]$	gravitational acceleration
h_0	[m]	Equilibrium flow depth
\boldsymbol{k}	[s]	Characteristic time for exponential approximation of a peak flow
L_{Bw}	[m]	Characteristic length for the backwater curve
L_{s}	[m]	Characteristic damping length
λ_s	[m]	Longitudinal adaptation length to perturbations in cross sectional bed profile
λ_w	[<i>m</i>]	Longitudinal adaptation length to perturbations in streamwise flow velocity
n	$[s/m^{\frac{1}{3}}$	Manning's friction coefficient
Q	$[m^3/s]$	Discharge
R	[m]	Hydraulic radius
S	$[m^3/s]$	Total transport
S_b	$[m^3/s]$	Bed load transport
S_s	$[m^3/s]$	Suspended load transport
t	[s]/[days]	time
θ	[-]	Shield's parameter
θ_{cr}	[-]	Critical Shield's parameter
U	[m/s]	Depth averaged flow velocity
u_*	[m/s]	Local flow velocity
V	$[m^3/s]$	Peak discharge
W	[m]	Width
w_s	[m/s]	Fall velocity

Introduction

This thesis focuses on the downstream implications of dam flushing operations. This chapter introduces the problem starting with its background in a wider context. The effects of dams on the natural flow of the river are discussed. Consequently, it is explained how increased ecological awareness currently leads to the urge of better sediment management which provides the motivation for this research. The problem is then defined followed by the research question. The chapter finalises with the research approach and an outline of the thesis.

1.1. Dams Worldwide

Already in the time of the ancient Egyptians, more than 3000 BC, humans built dams to aid their development [53]. These dams were built for irrigation, which nowadays is still a main function of a dam. Ever since, various benefits have stimulated new dam projects. These include navigation, fisheries, flood control and leisure activities. A second main function emerged with the invention of electricity. From all energy sources, hydropower is by far the most efficient, with hydropower plants converting up to 95% of their potential energy into electricity [8, 16, 46].

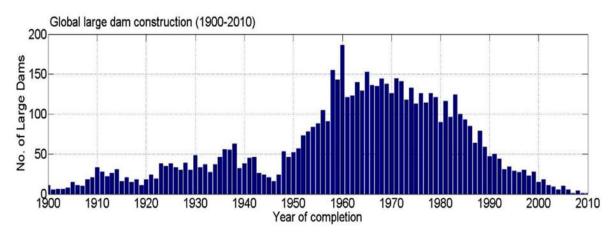


Figure 1.1: Number of large dam constructions per year between 1900 and 2010 [27]

From figure 1.1, it can be seen that the second half of the 20th century knew a worldwide boom of large dam construction [27]. By the end of 2015, 70% of the renewable energy comes from hydropower, which means a global share of 16.6% in the total electricity production [36]. Where other renewable energy sources are often generated with weather dependent peaks and therefore call for storage capacity, hydropower can be generated when demand is high and the reservoir is its own storage.

Besides the many clear benefits of dam construction, these anthropogenic interventions may have large, negative impacts. Complete villages and cities have been relocated, cultural heritage got submerged and ecological impacts are widespread [19].

If we focus on Europe, only 28% of the large rivers (over 1000 km) are still free flowing [52]. Also many of the smaller rivers are altered. It has become increasingly apparent that these interventions have diminished the ecological integrity of rivers [32].

The construction of a dam has consequences as well upstream as downstream of the construction. Upstream, a normally vibrant flow becomes a stagnant lake, completely changing the present ecological system. The dam itself forms a physical barrier for migrating species, jeopardizing their life and reproduction. The consequences in the downstream reach begin with the change in hydrological regime. Where the natural river flow is determined by the amount of precipitation and the hydrological processes that occur before water enters the river, it is now governed by dam operation. Seasonality is dampened to ensure year through power generation, releases are shifted to hold back water for irrigation and on a daily basis power demands require hydropeaking resulting in excessive flow fluctuations.

1.2. Ecological Awareness

Until the 1970's, dams were built to support agriculture, optimize flood protection and maximize hydropower generation. A growing awareness for the ecology reached the river managers and scientists were prompted to find a way to increase the ecological integrity of rivers. Minimum environmental flow definitions were followed by instream flow definitions to ensure enough water for the survival of certain (fish) species.

Scientists however found that maintaining this minimum flow neglects the importance of river dynamics that exist due to variable flow. Different flow magnitudes fulfil different functions. That a river will lose its biodiversity if these functions are lost due to anthropogenic interventions, became wide spread knowledge [29, 41, 42]. In 1997 N. Leroy Poff et al. collected this environmental directed thinking in a paradigm on the Natural Flow Regime for river conservation and restoration. It stresses the importance of dynamic flows to preserve biodiversity.

Continuing on this movement, Yarnell et al. (2015) suggests a shift from environmental flows to functional flows. Where environmental flows focus on the minimum flow that is necessary for certain species to survive, the functional flows aim at retaining the processes that are involved with different components of the hydrograph. Key functional components include wet-season initiation flows, peak magnitude flows, recession flows, dry-season low flows, and interannual variability. Figure 1.2 illustrates this process-based way of thinking [54].

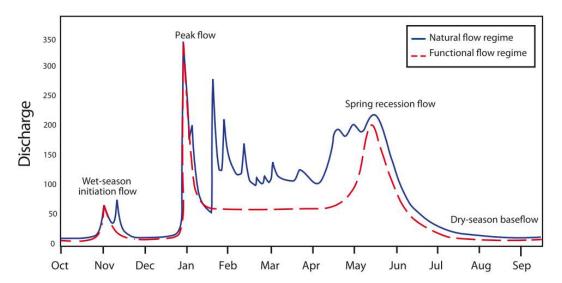


Figure 1.2: The functional flow approach translates a natural hydrograph to one that contains the functional elements, but does not exactly mimic the full natural flow [54]

1.3. Dam Flushing

1.2.1. Natural Sediment Regime

The flow patterns govern the morphological processes in the river. A wide range of flows are necessary to maintain channel and floodplains, river bars and rifflepool sequences [33]. Changing the flow pattern can change the morphology and with that the hydraulics and the ecological habitats. Wohl et al. (2015) explains that focusing on natural/functional flows could still overlook the importance of sediment transport, as fluxes are nonlinear and episodic [51]. As an example, enforcing a high flow aimed to maintain the channel without a sediment influx could cause severe erosion instead.

The lack of data on sediment transport in comparison to the data available for discharge illustrates the wide focus on flows rather than proper sediment management. This data gap makes research difficult and the understanding of sediment sources and transport still has a long way to go [51]. Incorporating hydromorhpodynamic modelling can aid this research.

1.2.2. Sediment Management

The problems arising from sediments are getting more apparent. Not only the ecology suffers but also dam operators seek for solutions. Because of the stagnant charachter of the reservoir, up to 100% of the incoming sediment is trapped. This reduces the storage capacity of the dam, limiting the functionality for which it was constructed. Worldwide, nearly 1% of the storage capacity is reduced yearly because of sedimentation. For many dams built in the boom of the second half of the 20th century, this problem is getting urgent. For more than six decades, the dam industry has invested great efforts to reduce sedimentation. Nevertheless, it remains probably the most serious technical problem faced by the industry [19]. The challenge is clear.

"Whereas the last century was concerned with reservoir development, the 21st century will need to focus on sediment management; the objective will be to convert today's inventory of non-sustainable infrastructures for future generations."

- Third World Water Forum, Kyoto 2003

The most effective solution is the reduction of erosion at the sediment source. Once in the river, sediment can hardly be removed before ending up in the reservoir. Here, the only solutions can be found in removal by dredging, mitigation by bypassing or flushing of sediments [24]. All have their drawbacks, of which the high costs play an important role in decision making.

1.3. Dam Flushing

One way to get rid of (part of) the sediment from a reservoir, is by drawing down the water level partially or completely so that the flow velocities increase and the sediments are flushed downstream naturally. This is considered a very effective operation and is therefore often applied, mainly for smaller reservoirs. It results, however, in an increased sediment flux which imposes stresses on the ecology. These stresses can be roughly divided into direct impact and long term impact.



Figure 1.3: A photo of the downstream reach taken during the flushing event of 2016 $\,$

Direct Impact During the flushing event, the turbidity of the downstream flow is highly increased. The photo in figure 1.3 gives an impression of this situation and it is easy to imagine that this flow imposes stresses on certain species. One example is the damage caused to gills and filter-feeding apparatus [20]. Flushing events can therefore lead to high mortality rates under different species.

Long Term Impact The increased sediment load does not only result in higher turbidities, but also causes deposition of fine sediments. This deposition changes the river bed and therefore the natural environment of riverine species. The natural environment of an organism can be defined as its habitat. When the conditions serve the needs of this organism, the habitat is considered suitable.

After a flushing event, the organisms need suitable habitats to recover and recolonize the river. If the deposition of fine sediments has affected these suitable habitats, the flushing event can have a longer lasting impact on the ecology than the direct mortality due to increased turbidity. This thesis aims at this long term impact that is caused by the deposition of fine sediments.

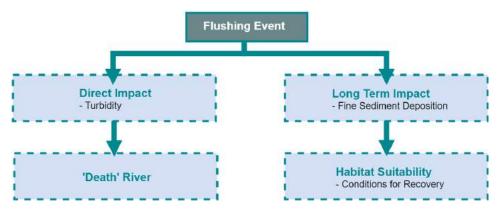


Figure 1.4: The ecological impact of a flushing event can be distinguished between direct and long term impact

1.4. Assessment of the Long Term Impact

In order to understand this long term impact on the physical habitats, one has to determine which changes occur in the habitats due to the deposition of fine sediments. A prerequisite for determining the change in a habitat, is having a meaningful description of the state of the habitat. This begins with its definition: A habitat can be defined as "the area or natural environment in which an organism or population normally lives" [44]. One way to describe this natural environment, is by the use of physical attributes, of which flow velocity, depth and substrate are often considered [3, 31]. When characterizing the environment based on such attributes, one is describing the physical habitat. Observing the change of these physical attributes is in principle a hydro-morphological study.

1.4.1. Various Spatial Scales

A river can be divided into physical habitats at various spatial scales. An increasing amount of research is directed at defining the suitability at the meso-scale, which divides the river into hydromorphological units [3, 22, 31, 40]. Examples of these units are riffles, pools, runs and glides. Which of these units experience most deposition during a flushing event, would again be a hydro morphological study which can be used to describe a change in habitat suitability.

1.5. Research Motivation

One river where flushing events are experienced as a problem, is the Avisio river in Italy. The removal of sediments is no more only a matter of cost efficiency of the dam, but it the impacts of the event are a political sensitive topic [48]. Especially fishermen are vocal about the impact on the fish population. This river has been subject to research. A section has been evaluated on habitat suitability under normal flow conditions at the meso-scale. In addition, this river has been subject to morphodynamic studies in order give insight in the dynamics of the fine sediment transport originating from the flushing event. The link between these studies

1.6. Problem Definition 5

has, however, not been made so far. It is this linkage that could give insight in the impact of the flushing on the habitat suitability.

1.6. Problem Definition

Flushing operation of a dam impose long term impacts on the downstream ecology due to deposition of fine sediments. The deposition changes the physical habitats and therefore changes the suitability.

Dam Operation Many dams were built in a period with less ecological concerns than nowadays. Operation procedures are mostly governed by the power demands, while redesigning the operation of dams could significantly benefit the ecology [37]. Here lies a big opportunity.

Habitat Suitability In order to know which operation strategy would be beneficial, the morphological change needs to be assessed in terms of habitat suitability. Habitat suitability studies however, are performed under the assumption of a fixed bed. With substrate being one of the three important parameters for habitat suitability, including morphological change in habitat suitability evaluations seems an essential step.

Spatial Scale The close link between morphodynamics and the description of physical habitats would allow for predicting impacts caused by morphological change, even under unmeasurable conditions. On the spatial scale however, the two fields of studies miss overlap. Most hydro-morphological studies either look at sediment budgets over longer reaches, or consider one-dimensional sediment transport [2, 4, 20, 28, 50]. They thereby easily neglect the spatial variability that would determine the impact at a smaller spatial scale.

With the habitat suitability studies moving towards the meso-scale, an opportunity arises to link habitat suitability studies to the larger scale morphodynamic studies.

1.7. Research Question

The overall goal is be able to evaluate the effect of different flushing operation scenarios on the physical habitats. The main research question therefore is:

What are the spatial and temporal dynamics of fine sediment in gravel bed rivers in relation to flushing operations and what are their implications for the physical habitats at the meso-scale?

This research question can be answered through enhancing the understanding of related morphological processes that define the spatial and temporal dynamics of fine sediment deposition and removal. Consequently this knowledge can upscaled to the ecologically more relevant mesoscale. The following sub questions are thereby considered:

- Which spatial patterns occur in the deposition and removal of fine sediments in a gravel bed river in the presence of bars and what are the governing processes?
- Which meso-scale physical habitats are most affected by the deposition and removal of fine sediments?
- How can operation be changed in order to optimize the most affected physical habitats?

1.7.1. Research Approach

In order to answer the research questions, a literature study is performed which focuses on the state of the art in linking the different fields of study, namely morphodynamics and habitat suitability studies. Consequently, an idealized morphological model is set-up with the aim to better understand the fine sediment dynamics. This model represents the Avisio river, an alpine river where bars are present that influence the deposition and removal of sediments. Once in three years, one of the river's reservoirs is flushed, inducing an increased sediment flux on the downstream reach.

To make the step towards the assessment of the habitat suitability at the mesoscale, the reach is divided into ecologically relevant classes, based on physical attributes. To understand the potential implications to the ecology, an evaluation is made aimed at specific functional habitat goals.

This classification and the further evaluation approach are used to evaluate different operation scenarios. The scenarios are designed by varying the sediment load and the magnitude of post-flushing discharges,

1.8. Thesis Outline 6

representing clean water peaks that aim to clean the downstream river reach from deposited fines. The results and discussed in reference to flow time series of the case study catchment.

1.8. Thesis Outline

The general outline of the thesis follows the sub questions as presented earlier in this section. Chapter 2 aims to answer the first sub-question and thereby approaches the problem from a physical point of view. The study reach is analysed and the resulting model set-up is described. The chapter concludes with a discussion on the capabilities of the model, and the limitations resulting from this approach.

The second sub-question is answered in chapter 3. It elaborates on existing evaluation methods and consequently presents approaches that are adapted to evaluate the modelled reach from an ecological point of view. These approaches are then used in chapter 4, where the different operation scenarios are presented and evaluated. Both these chapters conclude with a discussion of the applied methodology and the results.

The knowledge acquired these three chapters is concluded in chapter 5. This chapter gives an answer to the research question. Consequently, chapter 6 presents recommendations for further research as well as for improving the operation of dams.

Figure 1.5 gives a schematic representation of the thesis outline.

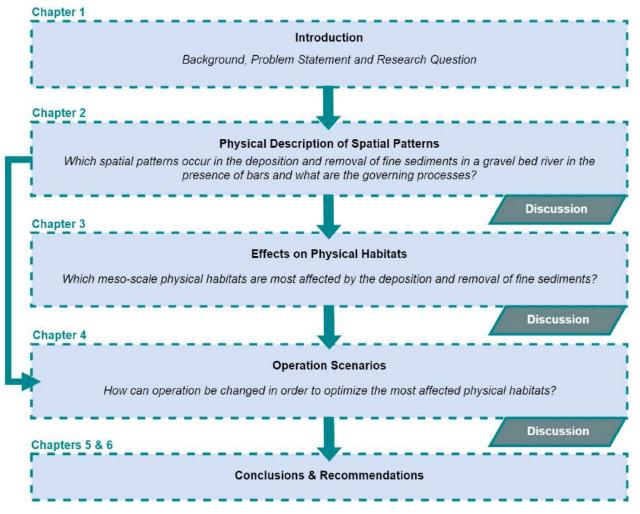


Figure 1.5: Schematic representation of the thesis outline

Physical Description of Spatial Patterns

With the aim to assess the impacts of fine sediment deposition at the meso-scale, it is necessary to know in which meso-scale units the sediments deposit. In a complicated river bed, the spatial variety in deposition might be high, affecting one habitat more than the other. This chapter aims to understand which spatial patterns occur at this meso-scale, focusing on a river system that represents the Avisio river. It thereby answers the first sub question:

Which spatial patterns occur in the deposition and removal of fine sediments in a gravel bed river in the presence of bars and what are the governing processes?

The reference river system is presented in section 2.1 and the governing processes are pinpointed. It first zooms out to a larger scale and consequently zooms in to a smaller scale to understand which patterns play a role at this meso-scale.

The increased fine sediment influx originates from the flushing operation, which sets the boundary conditions for the system. It is analysed in section 2.2. This river system with its boundary conditions are translated into an idealized model that aids to further understand the spatial patterns that occur. The set-up of this model, its sensitivities and its capabilities are presented in section 2.3. This model will be the starting point for studying the effects on the physical habitats in the chapter 3.

2.1. From Macro- and Micro-scale, to Meso-scale

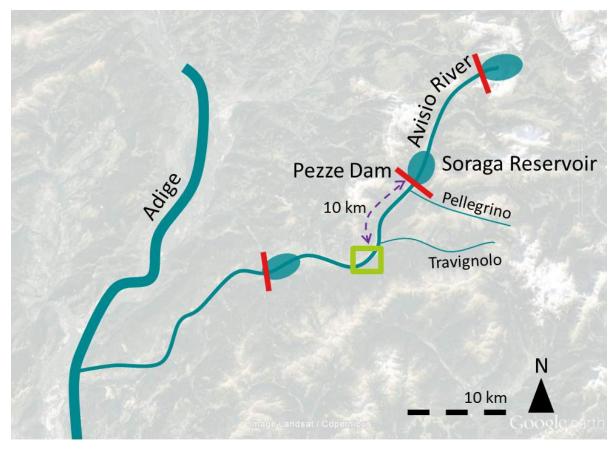
Spatial patterns in sediment transport, erosion and deposition can be observed at several spatial scales. These patterns at various scales influence each other, and the considered meso-scale is affected by the larger and smaller scale. Conceptually, the larger scale patterns define the geometry of the meso-scale and therefore act as a boundary condition, while smaller-scale patterns can cause 'disturbances' in this geometry. Appendix A elaborates on the spatial patterns that can be observed on these various scales. This concept of scales is used to analyse the reference case.

2.1.1. The Avisio River: A Reference Case

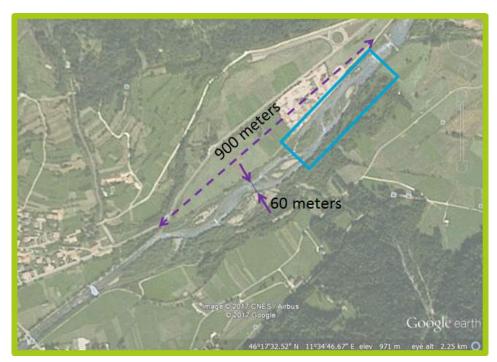
One river that experiences impacts from fine sediments is the Avisio River in the Italian Alps. The Pezzé dam was constructed in 1952 and has obstructed the natural flow ever since. Fine sediments are trapped in the reservoir which results in a cut down in sediments that reaches the downstream river reach. This changes the sediment balance and causes erosion of the river bed and banks because of lower sediment loads than the equilibrium load. A result is coarsening of the river bed [33].

Once in three years, this reservoir is flushed to restore the storage capacity, inducing an increased sediment flux the downstream reach.

The Avisio river consist of several canalized reaches, but the area, indicated in green in figure 2.1a, has a relatively natural bar channel topography. From former modelling exercises, it was shown that this reach accumulates up to ten times more sedimentation than the channelised reaches [35]. How variable this sedimentation is within the reach, is yet unknown. This specific reach is taken as the starting point within this



(a) The Avisio river system with its multiple dams. The reference reach is indicated in the green box



(b) Zoom of the above figure on the reference reach. Some relevant distances are given that are used in the set-up of the model. In blue is the reach that was studied during a MesoHABSIM field survey.

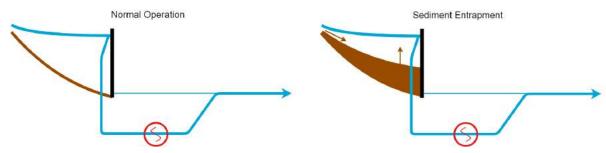
Figure 2.1: System analysis of the reference area at the Avisio River

thesis. The considered characteristics are as follows:

- The river has a coarsened river bed caused by the dam which exists since 1952,
- it has a channel-bar topography that originates from the braided character of the river. This topography consists of riffles, rapids and glides. Pools are not found.
- The average slope is 2 % as measured between coordinates 46°18′05.67" N 11°35′28.16" E (elevation = 1001 meters) and 46°17′14.01" N 11°34′15.71" E (elevation = 956 meters) which is a distance of 2228 meters covering the reach and roughly half a kilometre up and downstream.

2.2. The Influence of Dam Operation on the Flow

The operation of the dam determines the flow and transport conditions in the reach downstream of the dam. This section addresses this influence. Having a good understanding of this operation is important as it imposes restrictions on the scenario's that are presented in chapter 4. During normal operation of the Pezzé dam, the downstream flow is dependent on the energy production of the power plant. Water is lead through a diversion pipe and drives the turbines. After roughly 10 kilometers this water flows into the Avisio River and determines the flow. In addition, a minimum environmental flow is lead through the dam to maintain the biological integrity of the river stretch between the dam and the pipe outlet. A schematisation is shown in figure 2.2a. As the water flows either through the diversion pipes or from a high-level outlet of the dam, the water is clean as all sediments have settled in the reservoir, see figure 2.2b.



- (a) Normal operation during power generation. Water is lead through diversion pipes in order to drive the turbines
- (b) Due to the stagnant character of the reservoir, all incoming sediments are trapped which raises the bed level

Figure 2.2: Dam operation during power generation

2.2.1. Flushing Operation

Drawdown flushing is considered a very effective method to reduce the sediments that are trapped in the reservoir. Bottom gates of the dam are opened which lowers the water level of the reservoir completely so that a continuous flow develops from upstream to downstream. This increases the flow velocities which increases the transport capacity. This on its turn results in the mobilisation of the sediments that are flushed down through the gates and into the downstream river reach. During this operation, no more water is directed through the turbines so the dam is out of use for hydropower. Typically, such a flushing event lasts for 10 to 15 days. It is schematised in figure 2.3a.

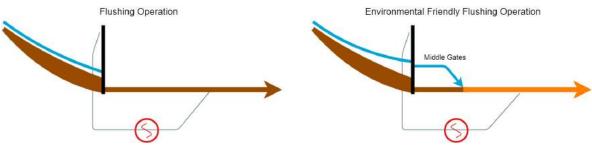
How efficient this method is depends on several factors. Some are defined by the site: the shape of the reservoir (long, narrow reservoirs are ideal as the flushing channel width is independent of the reservoir width), hydrological conditions and sediment inputs from upstream. Other factors can be controlled by:

- the operation of the reservoir between flushing operations,
- the design of the flushing system, and
- the operation of the flushing system, including discharge and duration

Environmental Friendly Flushing

This 'hard' flushing is at the same time known to be very harmful for the downstream environment. Therefore an environmental friendly flushing method was developed which aims to keep the concentration of suspended sediments below a certain value. An example is a continuous limit of 1.5 g/L, with maximum peaks of 3 g/L. It seems that the Pezzé dam flushing is operated in the same way. The concentration is kept low by releasing relatively clean water from gates at middle height. Figure 2.3b shows the difference with the hard flushing method.

This environmental flushing is aimed at lowering the concentration, so reducing the direct impact. Whether it also helps to decrease the potential impacts on the habitat suitability, will be investigated in chapter 4.



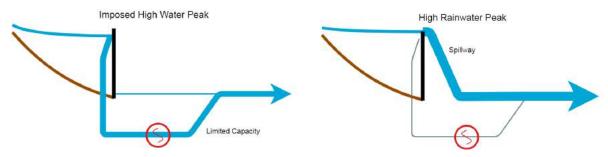
(a) During a flushing event, the reservoir is drawn down to allow the sediments to flush downstream. This is also called 'hard' flushing.

(b) By opening the middle gates, cleaner water can be mixed, which allows the control of the turbidity.

Figure 2.3: Flushing Operation

2.2.2. Clean Water Peak

One way to remove the fine sediments (partially) from the downstream reach, is by increasing the flow so that the transport capacity is increased. A distinction can be made between an imposed clean water peak and a more natural clean water peak. In the first case, as illustrated in figure 2.4a, the discharge through the diversion pipes that lead to the turbines is increased so that more water runs through the pipe outlets. This peak is limited to a maximum design capacity. Also, the first kilometres of the downstream reach do not benefit from this peak.



(a) The flow through the turbines can be increased to impose a peak flow.

(b) A rainfall runoff peak can flow downstream if the level in the reservoir is so high that the spillway is used.

Figure 2.4: A clean water peak can originate from dam operation, or from a peak in rainfall.

The more natural clean water peak, which will be referred to as a rainwater peak, requires a high inflow into the reservoir. Once the reservoir is full, the surplus will flow over the spillway, as illustrated in figure 2.4b. If the normal operation is shut down, the full reservoir inflow can be equal to the outflow. This operation mode has the advantage that the reach directly downstream also benefits from the clean water peak. However, it might jeopardize a potential flood protection function of the dam, as the buffer capacity is fully used up.

2.3. Morphodynamic Model

With the aim of investigating the spatial patterns of fine sediment dynamics occurring at the meso-scale, a morphodynamic model was set up. The Delft3D modelling software is used and is able to simulate the hydrodynamic flow around large scale bed forms, like bars, as long as the grid size is chosen accordingly. The software can compute transport phenomena based on different transport formulae, and can therefore be used to predict the deposition and removal of the fines. Delft3D solves the Navier Stokes equations for an incompressible fluid under the shallow water and the Boussinesque assumptions. The depth-averaged continuity equation is derived by integrating the continuity equation for incompressible fluids over the total depth. Although the model is used in two-dimensional modus, the direction of the bed load transport can be adjusted to account for spiral flows. This is key to modelling sediment transport around complicated bed forms and is therefore used as standard. In section 2.3.7, the importance is further discussed.

This section explains the set-up of the model, the underlying modelling concepts and choices made that aim to represent the reference reach. Subsequently, section 2.4 discusses what can be learned from the modelling results.

2.3.1. Modelling Objectives

The model is setup with the famous quote of Albert Einstein in mind:

"Everything should be made as simple as possible, but not simpler"

- Albert Einstein

To know exactly how simple the model can be, it is necessary to clarify the goal of the model. The model aims to show the variety in fine sediment deposition and removal due to spatial variability in flow patterns that are caused by two dimensional bed forms that exist at the meso-scale.

An idealized reach is designed that represents the Avisio river as described in section 2.1 where possible. The imposed discharge and sediment input represent a flushing event as operated at the Pezzé dam and described in section 2.2. Subsequently, a clean water peak is modelled to investigate its effectiveness.

2.3.2. Modelling Concept

The conditions of the Avisio river under flushing operation are translated to a modelling approach that is schematised in figure 2.5. These elements are introduced below, and the elements in the model set-up are explained in sections 2.3.4 and 2.3.5.

Case Study In stead of modelling the reference reach itself (which was not possible due to a lack of data), an idealized reach was created from a straight, prismatic channel. A channel bar topography is created and in order to represent the Avisio River. The disadvantage is that no data are available for calibration, but the big advantage is that it is easier to isolate the various physical processes that occur.

Bed Concept The river bed of the Avisio River is a coarsened river bed, that is not expected to move significantly during the flushing event. It is therefore not this coarse material that mostly influences the spatial variability in sediment deposition and removal, but the variety in flow caused by the bar topography. The problem is therefore simplified to a fixed bed system over which the increased fine sediment flux runs. This concept is also applied to an alluvial river system with a non-erodible bed. The fixed bed topography is created prior to the simulation of the flushing event.

Transport Formula The base of a realistic simulation is choosing a coherent sediment transport formula. A river like the Avisio typically has graded sediment and the formula of Meyer Peter Muller would be a logical choice. The advantage of this formula is that the concept of incipient motion is included, which makes it possible to account for hiding and exposure. It was developed especially for gravel bed rivers with sediment sizes larger than 0.4 millimetres. It is only valid when bed load transport is more important than suspended load:

$$\frac{w_s}{u_*} < 1 \tag{2.1}$$

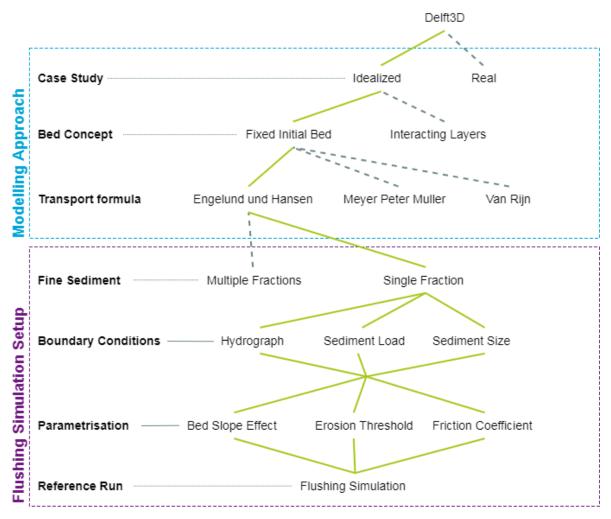


Figure 2.5: Schematisation of the modelling choices.

in which w_s is the fall velocity of a particle and u_* the flow velocity [15]. This thesis, however, focuses on the fine sediment that is transported through the river after a flushing event. This requires the calculation of bed material load, including suspended load. At the same time, the movement of the coarse bed is not considered significant, making the interaction between the coarse and the fine fraction not of such importance.

Engelund und Hansen would therefore be appropriate. It calculates, just like Meyer Peter Muller, the total transport but is not limited to bed load only:

$$\frac{w_s}{u_*} > 1 \tag{2.2}$$

the Engelund und Hansen formula calculates total transport by:

$$S = S_b + S_s = \frac{0.05\alpha U^5}{\sqrt{g}C^3\Delta^2 D_{50}}$$
 (2.3)

in which α has to be calibrated, U is the flow velocity, g is the gravitational acceleration, C the Chezy friction coefficient, Δ is the relative density of the sediment and D_{50} the representative fraction size. This formula is easy to interpret and assumes that the total transport is related to the velocity to the power 5 (U^5). Engelund und Hansen does not include the concept of incipient motion. When it is not in range of the critical Shields parameter, this is not an issue. It is therefore important to check whether the Shields parameter is large enough in order to justify the use of this formula.

A third formula that could apply to the problem is the formula of Van Rijn (1984). This formula calculates for bed load as well as for suspended load, also including wash load. Furthermore it includes the concept of incipient motion. This formula can therefore be used when the interaction between various fractions becomes important. It however splits bed load transport from suspended load transport, making it more difficult to interpret the results. In principal therefore, the more straight forward formula of Engelund und Hansen is used.

2.3.3. Creation of the Initial Bed

The first step is to create an initial bed for the modelling exercise. This section describes the setup used to create this initial bed. It therefore does not consider the simulation of the flushing event itself, which will be described in section 2.3.4.

As the spatial variety that originates from an alternate bar topography is investigated, it is essential to create a bed that contains the significant bed forms. Looking at the meso-scale, the bed forms that are of the order of magnitude of the river width are important i.e. bars, rather than dunes and ripples. Emerged bars strongly influence the flow pattern and deposition of fines is observed around them. Therefore a bar-channel topography will be the base of the model. Even though the bar-channel topography at the Avisio originates from its braided character, a first approximation was done by creating alternate bars.

In the Avisio, just like in any relevant river, bars are created during peak flow events and on time scales in the order of 10 years.

Grid Measurements This model consists of a rectangular, prismatic channel of 30 by 1200 meters. The width of the reference reach at the Avisio is roughly 60 meters in total, as was indicated in figure 2.1. The main channel however, has a width of 20 to 30 meters. When creating alternate bars from a straight channel, the resulting flow under lower discharge will have a slightly smaller width than the initial channel. An initial channel of 30 meters results in a flow with a width of around 20 meters that moves around bars, therefore representing the flow of the Avisio, even though the bar patterns are different.

The length of the channel must be long enough to ensure that multiple bars can form and that boundary conditions do not influence the results. A length of 1500 m meets those requirements, when an appropriate lower boundary condition is applied. This is discussed further down in this section.

The minimum number of grid cells required to solve important geometrical or hydrodynamic phenomena is five by rule of fist [15]. It thereby aims to describe the curve of the significant bed forms. Figure 2.6 shows how a lower amount of cells describes a different curve, even though the values at cell centres are the same.

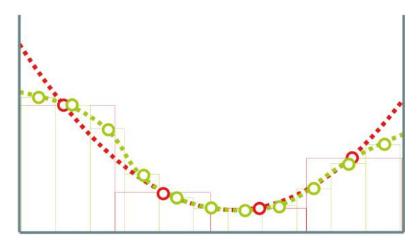


Figure 2.6: Schematic illustration of the difference in description of the bed when a lower amount of computational cells is considered.

With an altering bar pattern, the bars in principal exist at one side of the channel at a time. At the end of a bar, another bar will start at the opposite side of the channel. To describe this shape, it was chosen to include ten cells in the lateral direction. That this can describe such a shape is illustrated in figure 2.6. This makes the width of a grid cell 3 meters. In the longitudinal direction, the changes in bed is smaller over the same distance as the bars are longer than they are wide. The grid length can therefore also be longer. A value of 6

meters is chosen which gives an aspect ratio of 1:3, resulting in 250 grid cells in the longitudinal direction.

Slope and relating sediment size Bars will be created by imposing a flow on an initially flat, sloping, river bed. When applying the values of the Aviso river, with an average slope of 2 % and a Chezy value of 25 (order of magnitude of the value as calibrated by Rabitti (2014)), the model is in the super-critical regime as Froude numbers run up to 1.3. This makes calculations with Delft3D not trustworthy. The slope is therefore decreased to 0.7 %, following Turinna's approach [45]. This results in a Froude number of 0.67 based on equilibrium flow, which is still high but well in the sub-critical regime. This change has its influence on the resulting patterns, which is discussed in section 2.4.

The equilibrium slope of a river bed depends on the size of the bed material. Or reversely, the sediment size that is present depends on the slope of the river. Adjusting the slope therefore calls for adjusting the sediment size as well. The Engelund und Hansen transport formula (equation 2.3) can be written as:

$$S = Wa \cdot U^b \tag{2.4}$$

where W is the width and $a \sim 1/D_{50}$. When assuming the flow and sediment transport are in equilibrium and constant, the slope can be calculated by:

$$i = \frac{W}{C^2 Q_{inflow}} \left(\frac{S_{inflow}}{Wa} \right)^{3/b} \tag{2.5}$$

where b=5. From this, the slope relates to D_{50} as $i\sim D_{50}^{5/3}$. This means that going from the Avisio slope of 2 % to 0.7 % implies decreasing the D_{50} to 0.0087 m. A sediment size of 1 centimeter is therefore chosen to create the initial bed, which is in this order of magnitude. The use of Engelund und Hansen in this calculation is justified, as the Shield's parameter of 0.376 \gg 0.047 which indicates the threshold for motion.

Bar Pattern The formation of bars has been simulated in numerical models as well as in flume experiments regularly. Different modes are described in the literature and characterized by the number of bars over a cross section. Mode m=1 stands for alternate bars and is the form that can be most controlled. This is therefore the mode that is aimed at. Bars can either be migrating or non-migrating. Non-migrating bars can form when the depth-to-width ratio is exactly at the value of resonance. As this is a very specific, sensitive value, bars would normally migrate in a straight channel. Due to obstructions however, bar formation can be forced at specific locations. In practice, this occurs in river bends or behind an obstacle like a bridge pillar. In flume modelling as well as in numerical modelling this concept has been applied to force non-migrating bars [13, 14]. Also Turinna used this by placing a thin dam in the upper reach of his model [45]. The close relation to the depth-to-width ratio however, makes that if moving far away from the value of resonance while forcing the bars to be non-migrating, the modelled bars become less natural. To get a more natural solution while implementing a disturbance, the discharge is related to the longitudinal damping coefficient as described by Crosato which is based on the linear theory of alternate bars by Struiksma et al [13, 43]:

$$\frac{1}{L_D} = \frac{1}{2\lambda_w} \left(\frac{\lambda_w}{\lambda_s} - \frac{b - 3}{2} \right) \tag{2.6}$$

where

$$\lambda_w = \frac{C^2 h_0}{2g} \tag{2.7}$$

$$\lambda_s = \frac{1}{\pi^2} h_0 \beta^2 f(\theta) \tag{2.8}$$

in which β is the width to depth ratio, C is Chezy's coefficient, λ_w and λ_s are the longitudinal adaptation lengths characterizing the distance needed to adapt to perturbations in the streamwise flow velocity and the cross sectional bed profile respectively.

The effect of gravity on the direction of sediment transport over transverse bed slopes is accounted for by $f(\theta)$:

$$f(\theta) = A_{sh} \theta^{B_{Sh}} \left(\frac{D_{50}}{h_0} \right)^{C_{Sh}} \tag{2.9}$$

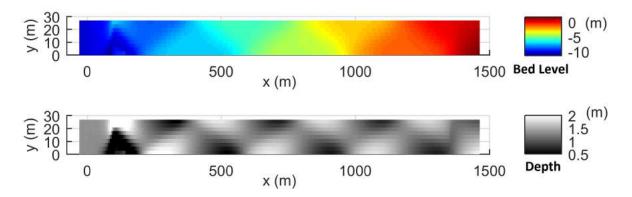


Figure 2.7: The upper image shows the resulting bed level, in negative which is how it is processed in Delft3D. The below image shows the bar pattern through the water depth under a governing flow of $100 \ m^3/s$ when the bars are fully submerged

where

$$\theta = \left(\frac{U}{C}\right)^2 \frac{1}{D_{50}} \tag{2.10}$$

and A_{sh} , B_{sh} and C_{sh} are parameters that can be set in Delft3D. The most sensitive is A_{sh} which decreases the bed slope effects the higher the value. B_{sh} and C_{sh} are taken as 0.5 and 0 respectively. A_{sh} can be estimated by

$$A_{Sh} \approx 9 \left(\frac{D_{50}}{h_0}\right)^{0.3}$$
 (2.11)

For the setup of this run, with $D_{50} = 0.01m$ and $h_0 > 1$, the value of A_{Sh} should be more than 2. The validity of this formula is, however, limited to the range of 0.5 to 1.5. In stead a value is estimated that is valid in the further runs which simulate the flushing event. A value of 1 is chosen that would be valid for sediments of (and smaller than) 1 mm.

Discharge In order to determine the flow that will create the most natural bars, equation 2.6 is calculated for different flow magnitudes. A damping coefficient of zero is found at a flow of $120 \ m^3/s$, meaning that the system is at resonance. For higher flows resulting in a positive value, the system is sub-resonant and for lower flows the system is super-resonant. A flow of $120 \ m^3/s$ therefore implies a bar mode of 1, which stands for alternate bars. Imposing this flow of $120 \ m^3/s$ however, results in a dampened system while working with a bar mode of 2 results in an undampened system and creates the bar patterns as shown in figure 2.7. This bar modus relates to a discharge of $50 \ m^3/s$. Table 2.1 summarizes the values that belong to an equilibrium flow that would hold if no morphological change would occur. The Shield's parameter is 0.376 which is an order of magnitude larger than the critical value of 0.047, justifying the use of Engelund und Hansen as the transport formula.

Downstream Boundary The downstream boundary is setup as a fixed water level. This value is chosen as the equilibrium depth based on a flow over a flat bottom as calculated by:

$$h_0 = \left(\frac{Q}{W \cdot C\sqrt{g}}\right)^{2/3} \tag{2.12}$$

where Q is the discharge, W is the width of the channel, C is Chezy's roughness coefficient (taken as 25) and g is the gravitational acceleration.

If this value is different from the flow depth, this can have its influence on the upstream flow conditions. This influence can be described by a backwater curve. The length of the backwater curve can be calculated to check whether the length of the channel is long enough to be able to neglect the effects of such curves. This characteristic length can be calculated by:

Model Input				Reference Case		Resulting Characteristics			
Slope	i	0.7	%	2	%	Froude Number	F	0.67	[-]
Width	W	30	[m]	20-60	[m]	Equilibrium Velocity	u_0	1.94	[m/s]
Sediment Size	D_{50}	0.01	[m]	0.05	[m]	Shield's Parameter	θ	0.376	[-]
Chezy Coefficient	C	25	$[m^{\frac{1}{2}}/s]$	25	$[m^{\frac{1}{2}}/s]$	Bar Mode	m	2.01	[-]
Discharge	Q	50	$[m^3/s]$						
Relative Density	Δ	1.6	[-]						
Linearity	b	5	[-]						
Coefficients for	A_{Sh}	1	[-]						
Slope Effect	B_{Sh}	0.5	[-]						
	C_{Sh}	0	[-]						

Table 2.1: Input variables for the creation of the initial bed compared to the values of the reference case. The resulting characteristic values are summarised on the right

$$L_{bw} = (1 - Fr^2) \frac{h_0}{i} (2.13)$$

where Fr is Froude's number which is 0.67 (see next paragraph), h_0 is the water depth taken as the equilibrium depth of 0.859 meter and i is the slope of 0.7 %, resulting in a characteristic length for the backwater curve of 67 meters. This characteristic length represents the distance where the proportion of the disturbance is reduced to 10 % of the original disturbance. This formula was taken from Samuels (1990) [39]. The setup of the model ensures that the disturbance of the downstream boundary is small in itself, by setting the water level at the downstream boundary at the equilibrium depth in accordance to the governing flow, defined in table 2.1. Together this makes that the effects occurring due to a possible backwater curve are negligible, even when the bed changes which influences the water level.

Run time and resulting bathymetry The model was run at this flow of $50 \, m^3/s$ for 6 months with a morphological factor of 10 to speed up the morphological change. This represents five years in reality, which is well enough to create an equilibrium situation. Already after one computational day this bathymetry is steady so no long term changes are expected and the long run time was unnecessary. This longer run time is only important when a dynamic, seasonal hydrograph is induced.

The system is considered to be in equilibrium, establishing a good initial condition for the further runs. The resulting bathymetry is illustrated in the lower image of figure 2.7 by plotting the water depth during an increased flow of $100\ m^3/s$, ensuring that the bars are submerged. The difference in water depth between deep and shallow points is about 1.5 m, making the amplitude of the bars 0.75 m. The bars are thus distinctive enough and emerged bars can be expected with lower flows. This rounds of the requirements stated at the start of this chapter.

2.3.4. Setup of the Flushing Event

As explained in section 2.3.2, the flushing event can be seen as an highly increased influx of fine sediments over a coarsened river bed that does not move significantly. The interest lies in the spatial distribution of deposition and removal of these fines due to a variety in flow patterns. Different choices have to be made to arrive at a model that best contributes to increasing the understanding in this spatial variety so that the effects on the different physical habitats can be evaluated. This section describes the setup of the flushing simulation.

Grid Measurements and Initial Bathymetry The initial bathymetry is the one created as presented in the previous section. The same grid is used which is measured 30 meters by 1500 meters. Also the same grid cell size (3 meters by 6 meters) is adopted as it is able to describe the flow around the bars in sufficient detail, which is the underlying driver in the sediment deposition and removal processes.

Boundary conditions The boundary conditions imposed at the upper boundary of the model, contain discharge conditions and sediment load conditions. For the latter, the sediment size plays a role in combination with the imposed load magnitude. These conditions are discussed below.

Hydrograph To represent a flushing operation use was made of the data as presented in the thesis of Rabitti (2014) which are shown in figure 2.8 [35]. The discharge during the flushing event is roughly $20 m^3/s$.

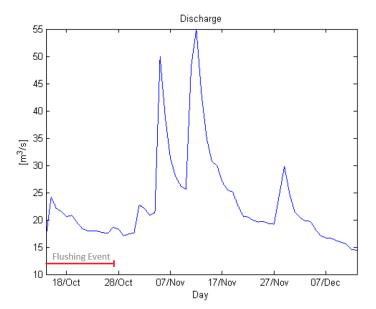


Figure 2.8: The hydrograph as described by Rabitti (2014) represents the discharges during and after the flushing event at the Avisio in 2012

The hydrograph imposed at the upstream boundary contains the following elements:

- a base flow of 5 m^3/s that represents winter conditions,
- the flushing event having an increased flow of 20 m^3/s with an increased sediment influx which lasts for 10 days, and
- a clean water peak flow of 30 m^3/s which lasts for 5 days.

Starting at base flow, the flow is increased to the flushing flow discharge by the end of day 1. After both the flushing flow and the clean water peak flow, the flow is brought back to base flow in order to be able to compare the situations. This is especially of importance when assessing the change in habitat suitability. The resulting hydrograph is illustrated in figure 2.9. The total run time of the simulation is 40 days.

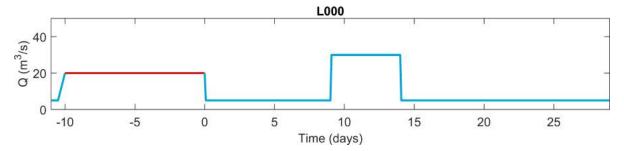


Figure 2.9: The hydrograph that is imposed at the upstream boundary for the reference run. The flushing event is indicated in red during which time an increased sediment influx is imposed.

Downstream Boundary The downstream boundary is described by one value of the water level. The aim is to choose this value as close to the equilibrium flow depth at the downstream boundary, in order to minimize the possible influence of a backwater curve. Therefore, the equilibrium depth is calculated that corresponds

to the varying discharge. Because of the shape of the initial bed, the depth varies over the cross section, but an average value is -1.22 meters from the original reference level. This value is therefore substracted from the equilibrium depth as calculated by equation 2.12 and thereby varies in time according to the hydrograph described above.

As described in section 2.3.3, the length of this backwater curve is small already, so even some small disturbance will not have a significant effect on the upstream flow.

Size of the fine sediment fraction The size of sediments that are flushed out of the reservoir ranges between one micrometer and one millimetre [35]. Sediments smaller than 63 micrometers (the distinction between silt and sand) are considered to be washload which does not interact with the river bed and are therefore out of the scope of this research [4]. Two runs were performed with a sediment size of 0.1 millimetre and 1 millimetre respectively, in order to see the effect within the range of sizes. The patches that develop with a 1 millimetre fraction follow the same patterns, but grow larger, therefore having a potential larger impact on the physical habitats. As both sizes fall under the same substrate category in the MesoHABSIM model (and therefore have a similar ecological value, see section 3.2.1), it was chosen to focus of the largest potential impact. The modelled fraction is therefore 1 millimetre. It was chosen not to calculate for multiple fractions as this will not be of added value to the evaluation of the spatial patterns.

Sediment load The flushing event will be simulated as an increased bed load material influx at the upstream boundary of the magnitude of the full transport capacity. Because of the high availability of sediments in the reservoir, the flow is assumed to be capacity limited. Any more sediment would deposit so it can be seen as the sediment transport that would exist in equilibrium conditions if the whole bed would consist of the modelled fraction. To get to this capacity, the model was run with a movable bed consisting of the fine sediment fraction, assuming an equilibrium inflow. Based on this equilibrium inflow, the bed load transport was defined as $5.0 \cdot 10^{-4} \, m^3 / s$. This is the influx during the 10 day flushing event, as indicated by the red line in figure 2.9. During this time of increased sediment influx, variabilities in flow magnitude and direction will cause the fines to accumulate at various locations. Subsequently, the influx of sediments will be set back to zero, allowing the sediments to be picked up again as transport capacities are not reached.

Numerical Set-up The boundary measurements and grid size of the computational cells are the same as during the creation of the initial bed. Although relatively coarse, the flow patterns around the bars can be well described. The sedimentation patterns follow these flow patterns and therefore this grid was considered coherent.

The time step required for the simulation can be based on the courant number, which links the grid size to the equilibrium water depth. With the base flow of 5 m^3/s , the equilibrium depth would be roughly 0.2 meters if the flow were over the full river width. Due to the bars, the depth will be slightly bigger on average. Calculating with this 0.2 meters depth however, and the shortest grid size length of 3 meters, a time step of 0.2 minutes would suffice. However, due to high sedimentation values (especially with higher values for A_{Sh}), instabilities occur in the bars. This has been solved by reducing the time step to 0.02 minutes. For the total run time of 40 days, this results in 2.88 \cdot 10⁶ time steps.

A spin up for morphological change is introduced in order to ensure a stable hydrodynamic flow prior to morphological computations. This spin up time is set at 2 hours after the moment that the flushing discharge is established (which is after 24 hours, see section 2.3.4).

The results are written with an interval of 120 minutes, resulting in 480 written time steps.

2.3.5. Parametrisation

With the above conceptualisations and boundary conditions, a flushing event can be simulated in Delft3D. Many parameters are, however, of influence on the results. In a real case scenario, only after calibration based on trustworthy measurements, the results draw a useful image of the modelled event. In this idealized case however, calibration based on results is not possible and the parametrisation has to be based on logical thinking. This motivates to understand the real processes whereas calibration is often just about matching numbers. A sensitivity analysis was performed to give insight in the parameters that influence the results the most. The findings are summarised below and further details are found in appendix B.

Bed Slope Effect One of the most sensitive parameters is found to be A_{Sh} , which partly describes the bed slope effect. The higher the parameter, the lower the bed slope effect which means that particles have a lower tendency to role down a slope. This has the effect that the slopes can be steeper making that the patches can get bigger and higher. This effect is indeed observed for $A_{Sh} = 0.7$ compared to $A_{Sh} = 1$ and $A_{Sh} = 1.3$. The location of the patterns does not differ showing that the spatial patterns are comparable. The patches change in size however, which also changes whether some cells are covered or not.

Friction coefficient The amount of friction together with the flow velocity and the sediment size determine the magnitude of the transport capacity, and are therefore important parameters. The flow velocity depends on the discharge in combination with the friction coefficient, making that the influence of the latter is twofold. Friction is dependent on the roughness of the bed, and can be described with a constant value using Chezy's coefficient, or dependent on the flow depth using Manning's coefficient. Chezy's coefficient relates to Manning's coefficient as follows:

$$C = \frac{1}{n}R^{1/6} \tag{2.14}$$

where n is Manning's coefficient and R is the hydraulic radius which is roughly the same as the depth. From literature the values for the Manning's coefficient lies between the value for normal channels, less than 30 meters wide with some weeds and stones (0.035) and the value of mountain streams, cobbles and boulders (0.05) (from [49]). The value of 0.04 is therefore chosen.

A comparison was made with of Chezy values of 17 and 25, which relate to this Manning's coefficient for a depth range of 0.1 meter to 1 meter respectively. The value of 25 is close to the value calibrated by Rabitti (2015) on the Avisio river. The results of this comparison are shown in appendix B. The differences with the Chezy value of 25 are not significant. Using Manning's coefficient relates to the depth and, with the high variety in water depths considered in this model, is therefore considered more realistic. The use of Manning's coefficient is chosen.

Erosion Threshold The erosion threshold is a very sensitive parameter. It describes a conceptual layer thickness for the reduction of erosion, for a supply limited situation. As soon as the available sediment is less than the defined thickness of the alluvial layer, the bed load transport is corrected by a factor that is the ratio between the depth of available sediments and this threshold (f_{FIXFAC}). It thereby reduces the erosion.

Figure 2.10 shows the effect a bigger threshold has on this model. The bed load transport is calculated based on the acting shear stress, but subsequently reduced due to multiplication with the f_{FIXFAC} , as long as the layer of sediment is not as thick as the erosion threshold. Once the system is in equilibrium however, the volume of sediments is the same (as can be seen by the tail of the figure, where only the green line is not yet in equilibrium) which shows that this threshold controls only the speed of the erosion processes.

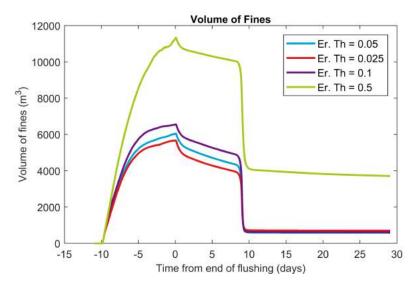


Figure 2.10: The total volume of deposited sediment is very sensitive to the erosion threshold as shown by this sensitivity analysis.

Threshold for drying and flooding Delft3D uses a threshold to stop the calculation of sediment transport from a certain flow depth. As the accumulation of fines can be high in some computational cells, but these cells should not become inactive as long as water flows over them, it is important to choose this value low enough. A threshold of 1 centimetre results in a very low amount of inactive cells and is therefore used in further runs.

Influence of Secondary Flow One process that highly influences the spatial patterns in sediment deposition and removal, is the process of secondary flow. This process accounts for the difference between the depth averaged flow direction and the near bed flow direction, which is the result from a helical flow that occurs when the flow follows a curve. This change in direction is illustrated in figure 2.11. Delft3D accounts for this process by adjusting the direction of the bed load transport. It is included as standard in the modelling within this thesis, but to show its importance, one run was performed without. At the end of the flushing event, the difference is most clear. Figure 2.12b shows the accumulated fine sediments along longitudinal cross section Y = 3 meter. Figure 2.12a shows the total volume of accumulated fines in the representative reach. The figure shows that including the process of secondary flow not only has an influence on the quantity of sediment deposition, but also influences the spatial patterns. The curvature of the flow decreases the sedimentation upstream of the bars, while it increases the sedimentation downstream.

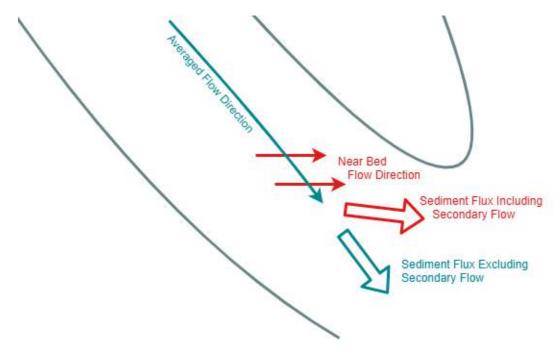
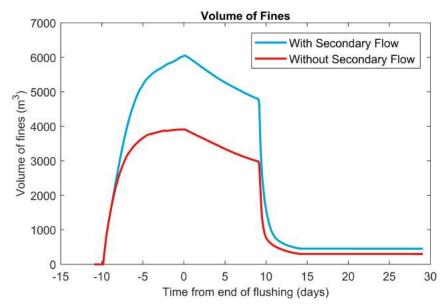
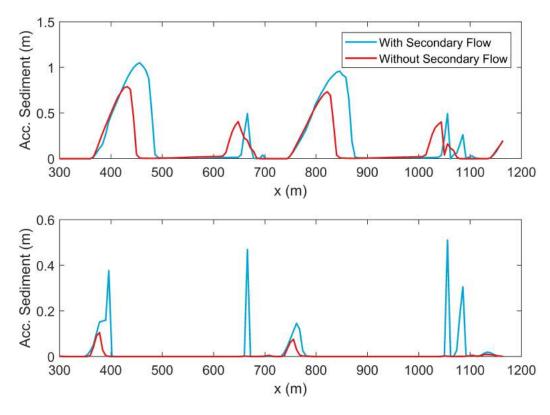


Figure 2.11: The direction of the bed load transport can be different from the depth averaged direction of the flow, as the near bed flow direction is a result of the secondary flow



(a) The total volume of fines in the representative reach between X = 180 meters and X = 1200 meters for a run with secondary flow and without.



(b) The accumulated sediments along longitudinal cross section y = 3 meters as a result of the reference run with and without secondary flow. The above image shows the situation at the end of the flushing event while the lower image shows the situation at the end of the run after the clean water peak.

Figure 2.12: Influence of the secondary flow

2.3.6. Reference Run

The model setup as described above, is used as the reference run within this thesis. The deposition of fine sediments occurs before and behind the bars, as can be expected due to flow diversion and differences in flow velocities. Figure 2.13 shows a top view of the simulated reach and indicates the locations where most sedimentation occurs. The above image is at the end of the flushing for which a longitudinal cross section is shown in the middle image, for y = 3 meters. The lower image indicates the location of the bars in black.

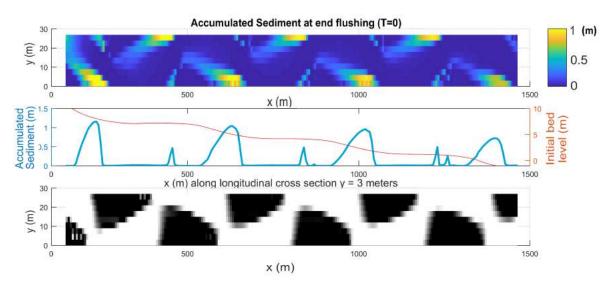


Figure 2.13: The above image shows a top view of the accumulated sediments, visualising the patterns of deposition upstream and downstream of the bars. The middle image shows this accumulation for a longitudinal cross section, in combination with the initial bed level as a reference, again showing the same patterns. The lower image is included to indicate the location of the bars (in black) from a top view. The flow is from left to right.

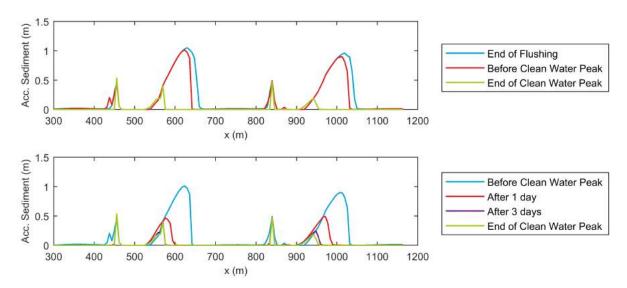


Figure 2.14: Both images show the accumulated sediments along longitudinal cross section y = 3 meters for several time steps. The below image focuses on the removal of fines and shows how most reduction occurs within three days.

To give an idea of how this accumulated sediment develops, we look at a longitudinal cross section that is the line between the first and the second computational cell, so at y=3 meters. Figure contains three images, of which the below image is included to identify the bar patterns. The above image in figure 2.14 shows the accumulated sediment at the same time steps as described above; the end of the flushing, just before the

clean water peak and just after the clean water peak. The below image zooms into the effect of the clean water peak, by showing the accumulated sediment just before the clean water peak, after one day, after three days and at the end of the clean water peak. It shows that, after the clean water peak most of the deposits are removed again.

Computation Time The run time of the model, with its $2.88 \cdot 10^6$ time steps, is $4.199 \cdot 10^4$ (11.7 hours) of which $2.35 \cdot 10^4$ seconds (56.0 %) are taken up by the updating of the river bed. The transport equation takes up 9 % and the hydrodynamic computations (momentum equation, continuity equation and turbulence) the remaining 35 % (7.0 %, 9.9 % and 0.1 % respectively).

2.3.7. Modelled Processes

The calculation for sediment transport in the model by the transport equation of Engelund und Hansen, represents the transport capacity based on the depth averaged flow velocity. This calculation is performed per cell. If the incoming sediment flux is equal to the transport capacity as calculated in the cell, neither erosion nor sedimentation will take place. If the incoming sediment flux is higher, the difference will deposit, increasing the bed level. This situation is referred to as **capacity limited**. If the incoming flux is lower than the transport capacity, sediments will be picked up until the influx is equal to the transport capacity, resulting in an eroding bed. If no sediments are available on the bed to supply in this transport deficit, the resulting sediment transport is lower than the capacity. This situation is referred to as **supply limited**. The modelling concept of a non-erodable bed is based on this idea.

If the upstream boundary conditions are constant in terms of discharge and sediment influx, the system will adapt itself to these conditions. If the outflux of sediments is equal to the influx this shows that within the system, the amount of deposition is equal to the amount of erosion. In some systems, bed forms move in time due to erosion at the one side, and deposition at the other, e.g. resulting in migrating bars. Only if the local conditions are also constant, meaning that the per cell influx is equal to the outflux, no movement of the bed takes place. Note that this does not mean that no transport takes place. This situation is referred to as a **dynamic equilibrium**. Also in this model, the bars are not moving. The reason however, is that the flow is restricted by the fixed bar topography. This represents the real situation as the transport capacity defining flow is restricted by the non moving coarsened river bed.

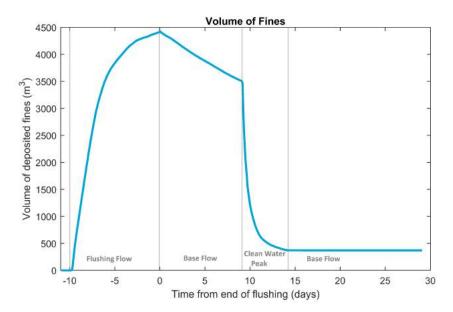


Figure 2.15: The total volume of deposited fines between X = 180 meters and X = 1200 meters, which is the representative reach. An increase means netto deposition while a decrease means netto erosion. If the value is constant, the system is in equilibrium.

When a perturbation of the equilibrium system occurs, the system adapts and seeks for a new equilibrium. The flushing event can be seen as such a perturbation. After such change in boundary conditions in

terms of sediment influx as well as discharge, the modelled system adapts itself to a new dynamic equilibrium. Following the principle of influx - outflux = storage, an increase in accumulated fines means system averaged deposition. Figure 2.15 shows the deposited fines within a representative reach. During the flushing event, the volume increases, but the steepness of this increase declines. This means that the system is moving towards a dynamic equilibrium. After the flushing, when the flow is reduced to base flow, the volume steadily decreases showing that also with this low discharge, the flow has some capacity to remove the fines out of the system. The big decrease however occurs during the clean water peak. After this peak, the value remains constant, meaning that the base flow does not have the capacity to move any more sediments and the system is again in equilibrium.

Secondary Flow The use of secondary flow cannot be neglected in the use of this model, as it highly influences the locations where sediments accumulate. The accumulation is higher downstream of the bars than upstream. This shows that the sedimentation patterns are not only dependent on the transport capacity.

2.4. Discussion: Spatial Patterns

The simulation of the flushing event, based on the reference run as presented above, describes the sedimentation due to the varying flow patterns that result from a bar channel topography. In this section the limitation of the model are discussed and the processes are described with the uncertainties that remain in the understanding of the spatial patterns.

2.4.1. Limitations of the Modelling Approach

In the set-up of the model, simplifications were made that isolate the fine sediment dynamics occurring due to flow patterns around the channel bar topography, but simultaneously impose limitations to the model. The most important limitations are described below.

Grid Cell Size The grid cell size is chosen based on the minimum number of cells needed to calculate the flow patterns around the bars. This results in a rather coarse grid which has the risk of missing detail. Any processes that occur on the scale of two or three times the grid cell size, cannot be computed adaquately. Even though the flow patterns are the drivers for the sediment deposition and removal processes, lower scale processes play a role. From this setup, it is not fully clear to what extent e.g. bed slope effects play a role on the smaller scale, and it is advisable to decrease the grid cell size as a check.

The drying and flooding of the cells is another process that is sensitive to the grid cell size. The only way the results seem to suffer from this, is when considering the sedimentation on top of the bars. This will be discussed in chapter 3.

Other processes that are disregarded, are the micro-scale processes as described in appendix A. Due to an immobile rock or a group of larger cobbles, locally the deposition of sediments can be higher. Figure 2.16 illustrates this by an example of an immobile rock at the Avisio. The sediments behind the rock are much finer than around, indicating that a spatial variety is consequent to these micro-scale processes. If more of these rocks are present, this could cause a higher amount of accumulated sediments than expected from this model setup. In order to include such processes, not only the grid cell must be smaller, also the bathymetry must me much more detailed. In addition, a depth averaged flow will still disregard the flow around immobile rocks, and a full 3D model is required. This would mean an immense increase in computational time, in addition to effort to create the proper mesh, which is not in balance with the aim of the model. Another idea would be to locally increase the roughness to approximate this level of detail.

In essence, this model succeeds to simulate the meso-scale patterns, induced by bed forms that are a result of macro-scale patterns, but ignores any micro-scale patterns.

As the model is set up not to contain any of these micro-scale patterns, it was expected that the model does not suffer from the coarse character of the grid.

Increasing the number of cells would significantly increase the computational run time as it not only has to calculate for more cells, but also the time step needs to be reduced to avoid disturbances that result



Figure 2.16: An immobile rock can locally cause sediment deposition, even if the surrounding velocities are higher.

from an increased Courant number. The level of detail is therefore always a compromise with the amount of computational run time.

Interaction with the coarse layer The choice of a fixed bed principle isolates the effect of flow patterns but ignores any interaction with other sediment fractions. Once fine sediments deposit in the model, in reality they could fill up the interstitial spaces between the coarsened river bed. Within this layer, the flow velocities are lower than the averaged hydrodynamic flow as modelled in Delft3D. It depends on many more processes like preferential flow pathways and viscosity, which Delft3D does not account for. Therefore the erosion based on the transport capacity as calculated based on the depth averaged flow velocity is an over estimation for those sediments that are hidden between the coarse sediments. In case the coarse sediments also move, hiding and exposure can be included as a process in the model, which increases the critical shear stress for the finer fraction. Another approximation is by including an entrainment and deposition term in the mass balance which aims at the entrainment of the suspended sediments.

Mild Slope The slope was reduced in order to stay in the sub-critical regime. This changes the hydrodynamics of the model, and therefore the sediment transport. With a steeper slope, the flow velocities are expected to be higher and the level of turbulence increases. Depending on the flow directions, this could also increase the transport capacity. It is therefore expected that the modelled deposition is an over estimation of the reference situation.

Sediment Size The chosen fine fraction represents the largest fraction that is flushed down the reservoir [35]. The smaller the fraction, the higher the transport capacity would be as $S \sim \frac{1}{D_{50}}$. As the influx at the upstream boundary is also based on this transport capacity, and would therefore be bigger accordingly, it was not expected that the size of sediments changes the patterns in sedimentation and erosion. Turrina (2014)

investigated the influence of hiding and exposure. By calculating for different fractions at a time, he found different patterns for different fraction sizes. In such a calculation, it would be more difficult to introduce a threshold for the thickness of the layer of fine sediments (see chapter 3). It does nonetheless suggest that the patterns are more sensitive to the sediment size than was assumed in this thesis research and it is therefore recommended to investigate this sensitivity and the influence of a combination of fractions.

Neglecting the Threshold of Motion By using the formula of Engelund und Hansen, the concept of incipient motion is neglected. The critical shear stress occurs at a velocity as calculated by:

$$U = \sqrt{\theta_{cr} C^2 \Delta D_{50}} \tag{2.15}$$

and is $0.22 \, \mathrm{m/s}$ for $\theta_{cr} = 0.047$ with a sediment size of 1 millimetre. This is a very simplified approach as the critical shear stress follows a curve described by the Shield's diagram and is dependent on the dimensionless shear stress and the Reynolds number, which both depend on the velocity. On average, the flow velocities are of such magnitude that the critical shear stress is well surpassed. However locally, around the bars, this flow velocity is sometimes lower, especially during base flow. This would result in some areas where the sediments would stay in place. Because of the use of Engelund und Hansen, even those areas would have some sediment movement, though very low as the $S \sim U^5$. This simplification is not considered a problem, as in a real case, the flow would be fluctuating and therefore these low flow areas would vary in space more than in the model, making that areas without movement do not exist for such a long time either.

Neglecting Fluctuations Such fluctuations could change the sedimentation and eriosion processes and is therefore further investigated in chapter 4.

Super- or Sub- Critical As described in section 2.3.3, the bed slope was reduced so that the flow is subcritical which ensures trustworthy morphological computations. A sub-critical flow reacts differently to an obstacle than a super-critical flow, which is illustrated in figure 2.17. When a sub-critical flow encounters an obstacle, the flow depth decreases as a result of a constant energy level. For continuity of momentum, the flow accelerates which results in an increased transport capacity. This could lead to erosion. The opposite happens downstream of the obstacle, where the flow velocity and therefore its transport capacity, decrease which can cause deposition.

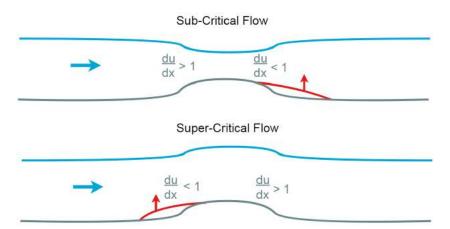


Figure 2.17: When a sub-critical flow encounters an obstacle, deposition occurs behind the obstacle as a result of a decreasing flow velocity. With a super-critical flow, this occurs upstream of the obstacle.

When a super-critical flow encounters an obstruction, the water level is forced up and a decrease in velocity occurs due to pressure differences, resulting in a lowering of the transport capacity in front of the obstacle. The location of deposition is therefore opposite from sub-critical flow.

This change from super- to sub-critical flow can therefore have very significant influences on the spatial patterns in sediment deposition. It alluvial river systems, it can make the difference between downstream and

upstream migrating bars. In the model, it is the difference between deposition of fine sediments upstream or downstream of the bars (as bars don't migrate).

Even though theoretically this difference would mean that the model is not so representable for the Avisio river as thought, yet the Avisio river together with most mountain rivers that have characteristic channel-bar topographies, do not flow in a super-critical regime. The difference with the first calculation that pointed towards the super-critical flow, considered the full width of the channel with equilibrium depths accordingly. Due to the bar pattern however, the depth is significantly higher as the average width of the flow is significantly less under lower discharges, as illustrated in figure 2.18. This situation (which was also represented in the model) is much more according to reality. Therefore, the high Froude numbers would probably not exist in a model that is based on a real bathymetry, even if the slope is much steeper.

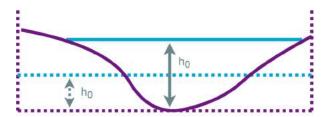


Figure 2.18: The equilibrium depth under the same discharge is higher in a bar topography than in a rectangular channel.

2.4.2. Validity

The presented model gives an indication of the spatial patterns that occur due to existence of bars, under the assumption that the coarse bed does not move significantly. The slope is adapted and the parametrisation was mostly aimed to find the largest possible impact. The patterns are as expected and it can therefore be used as the base for further investigation towards the integration with habitat suitability models, which is done in the next chapters. The influence of changing boundary conditions can be tested on these patterns rather than quantitatively. Whether this model is fully valid under the reference circumstances, requires validation with data. In the recommendations, suggestions are given to prepare a measuring campaign during the next flushing event. The model concept can also be applied to other rivers that have a variable bed topography and are in the sub-critical regime and similarly needs a validation through field data.

Effects on Physical Habitats

The deposition of fine sediments as described in the previous chapter changes the physical habitats in the river reach downstream of the dam. This chapter discusses how to assess the impact of these changes. It thereby aims to answer the second sub question:

Which meso-scale physical habitats are most affected by the deposition and removal of fine sediments?

Habitat suitability modelling is introduced in section 3.1 as it can be used to assess whether the conditions are still suitable for specific organisms. The different types of habitat suitability models are presented with a focus on the varying spatial scales. Subsequently, two existing approaches are presented that aim to assess the suitability at the mesoscale in section 3.2, namely Mesohabitat Simulation (MesoHABSIM) and the Mesohabitat Evaluation Model (MEM). In this research, the first approach is applied to classify the real life study reach. It thereby demonstrates the advantages of suitability assessment performed at the meso-scale. The second approach is applied to the morphodynamic model which was presented in chapter 2, in order to classify this idealised reach. This gives insight in which classes are most affected. To assess the actual ecological impact of the flushing event, an analysis is performed on the effects on two specific habitats that are sensitive to the deposition of fine sediment in section 3.3. A discussion of all results follows in section 3.4.

3.1. Habitat Suitability Modeling

To get a better understanding of the habitats and what determines their quality, different habitat models were developed throughout the years. The principle aim is to give a measure of suitability based on different attributes of the habitats. The application differs from model to model and puts various requirements and restrictions to the model development. A short summary of habitat modelling types that exist in literature is given below with a focus on the difference in spatial scale.

Habitat model types The most applied habitat models are Habitat Suitability Index (HSI) models that are based on preference curves for a range of chosen variables. Univariate models exist that consider the variables independently from each other. Multivariate models account for a combination of variables by (mostly) multiplication, possibly with different weight factors [10]. A division can be made between literature and expert knowledge based modelling, and empirical or statistical modelling which is based on field data. Where the first can have large uncertainties due to a lack of understanding and wrong assumptions, the second is highly time consuming and difficult to generalise, as presence or abundance can differ from reach to reach [11]. Emperical or statistical modelling require the gathering of an adequate set of field observations for every specie.

Other types of modelling are fuzzy rule-based models that follow if-statement rules, linear models and non-parametric regression models [10].

Different spatial scales All existing models have a specific spatial scale at which they are aimed. The following quote draws a clear picture of the trend that was observed in the second half of the 20th century.

"A trend which is apparent in the literature, when it is reviewed chronologically, is that of scale. Older studies (pre-1950) have more of a watershed or system approach. As studies progressed through the decades the system emphasis was lost to specialized studies for very specific areas"

- J. Castro and F. Reckendorf (1995)

This trend existed to provide more quantitative data, and this specialized approach allowed for relating local parameters to suitability, giving a much better understanding of the habitat complexity. This microscale approach is generally applied in the Habitat Suitability Index studies, but also other types of modelling are performed at micro-scale.

In order to improve the integrity of the river, a larger scale approach is necessary. River management issues play at a reach or catchment scale. Pitlick and Wilcock stress the importance to not only look at microscale habitat changes, but also to look at reach or river scale processes [50].

In an attempt to predict basin wide impact of fine sediment accumulation, Wilkinson et al. used network sediment budgets to predict the locations of accumulation of fines, including spatial variability of sediment supply and transport capacity. Although the results sound promising (a 71% accuracy in presence or absence of accumulation in the rivers considered), the method simplifies the river into homogeneous reaches with a length of the order of magnitude of 10 kilometers [50]. This macro-scale approach can give a good, first indication of potential accumulation, but the effects on habitats at micro and meso-scale is not considered. A relevant level of detail is missing to evaluate these effects.

3.1.1. Hydraulic-Habitat models

As seen above, water managers have a quest for meso-scale modelling rather than micro-scale modelling. A different interest that puts requirements on the model development, is their needed insight in the habitat suitability under changing circumstances. Therefore instream physical habitat models are combined with hydraulic models to form 'hydraulic-habitat' models [10].

Flow dependent habitat models aid to develop environmental flow regimes, as they can give insight in e.g. the number of days that certain stress conditions appear or assess habitat suitability in specific (ecologically relevant) seasons. These models know a wide field of application.

3.1.2. Development of Morphydynamic-Habitat Models

The relevance of hydraulic-habitat models is apparent, but as stressed by Wohl (2015), designing environmental flow regimes based only on the hydrology is not sufficient. A natural sediment regime is essential in proper river management as changing sediment fluxes could have a long term effect on habitat suitability. This requires the coupling of a hydromorphodynamic model, that predicts the morphological change, with the habitat modelling. This follows the same approach as hydraulic-habitat modelling but then further developed with a changing bed instead of assuming a fixed bed. 6

This idea was incorporated in a modelling framework developed by Kail et al. (2015). It aims to assess the effects of different pressures (among which fine sediment accumulation) on river abiotic habitat conditions and biota. Aside of ecohydrological modelling (like SWAT), 1D hydrodynamic models (like HEC-RAS) and channel planform modelling (like MIANDRAS), also 2D hydromorphological modelling is part of the framework. For the Treene case study which was presented in his article however, no morphodynamics were modelled. The only mobile substrate was sand, so movement would have no effect on the habitat modelling results [22]. The idea nonetheless was put in place and next studies applying this framework might therefore incorporate morphodynamic modelling.

That this incorporated process can be applied in engineering work, is well described by Duel et al.:

"The approach with simulations of river rehabilitation is interesting due to its ability to predict the effect of the changes without the need to do any large scale field trials. This can be used to improve the design process and the planning of the construction work. It also gives a visual

explanation of the habitat improvement structures that can be used to present the work to various interest groups in the river and it will work as a mean to enhance the discussion around the planned improvement works."

- Duel et al. (2003)

To the best of the writer's knowledge, only one example exists of habitat modelling that uses 2D hydromorphological modelling results and is applied to an engineering project that is related to the meso-scale. It was applied for rehabilitation and artificial habitat design by K. Alfredsen et al. [1]. Two examples are discussed that predict the effects of human interventions to improve the ecological habitat. As this is done on river reach scale, the application of the 2D model is found to be an efficient tool in the design and development of artificial habitats. Preference curves for different physical parameters are translated into a visual map of habitat suitability per grid cell. Also the accumulation of fine sediments in pool habitats and the filling of artificial substrate is considered. This indicates the predictive use of applying morphodynamic modelling. This study however has a micro-scale character.

3.2. Assessment at the Meso-scale

A high potential is found in meso-scale habitat models that use hydromorphological units to assess reach-scale physical characteristics. It can translate the micro-scale habitat modelling capacities towards macro-scale applications in which river management issues are tackled [5]. These models map channel features such as riffles, glides and pools and consider probability density functions of micro-scale habitat conditions within these features [22]. One example is the MesoHABSIM model which is introduced in the next section. It will later be compared to the use of a numerical modelling based evaluation model to pinpoint the gap between the two approaches.

The Advantages of Upscaling to the Meso-scale

The trend of upscaling from micro- to meso-scale has several reasons. The first originates from a management point of view, as it brings the suitability modelling a step closer to the project management scale. The goal to e.g. maintain a riffle pool sequence is more concrete than to maintain a certain percentage of defined depth and velocity areas.

A second reason has a more ecological sense to it. While specific, micro-scale conditions might be ideal for an organism, it often seeks these ideal conditions in close presence of other habitat conditions. Take a fish that depends on drift-feeding. The required conditions can be described as relatively high velocity flows in which macroinvertebrates drift down. These conditions are however exposed to predators (e.g. birds) and the fish will therefore seek these conditions in the near presence of a decent cover. Only the combination of these conditions describes the suitable habitat.

A third reason is from practical origin. Field surveys at the meso-scale are much less time consuming than the former micro-scale approaches. This allows to assess a much larger reach within a shorter time-frame without loosing significant information.

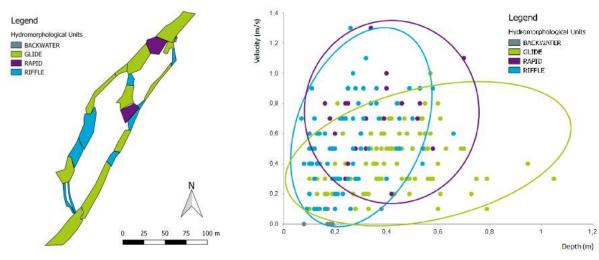
3.2.1. MesoHABSIM

The physical habitat simulation model PHABSIM, applied in the United States in the establishment of minimum stream flow requirements, is the starting point of the development of MesoHABSIM. This state of the art model was created in 2000 by Dr. Piotr Parasiewicz, with the aim to upscale to the mesoscale to better address river management issues [31].

The method is as follows: during field work, the reach of interest is divided into hydromorphological units on sight. Within these units, seven to ten measurements are taken of flow velocity, flow depth and size of the substrate. With this information, the biological model that is part of the MesoHABSIM approach can determine the suitability of each hydromorphological unit for specific target species, based on the distribution of the measurements within the unit. It also accounts for presence or absence of different types of cover (e.g. undercut banks of woody debris).

A more elaborate explanation of the model procedure and how it uses physical attributes to define suitability is given in appendix C.

MesoHABSIM mapping of the Avisio River The study reach on the Avisio was mapped according to the MesoHABSIM procedure. This resulted in the map in figure 3.1a. Note that the designation of the areas is according to the MesoHABSIM method, which is different from the designation used later in this thesis. Detailed explanation can be found in appendix C. Within each unit, seven to 10 measurements of flow depth, flow velocity and substrate were taken of which the former two are plotted in figure 3.1b. This shows that within the specified units a large spread in velocities and depths were observed.



- (a) Division into hydromorphological units of the study reach
- (b) Distribution of Flow Depth and Velocity Measurements per HMU. The circles roughly indicate the spread for the glide, rapid and riffle.

Figure 3.1: Results of the MesoHABSIM field survey as performed in April 2017 at the study reach of the Avisio river.

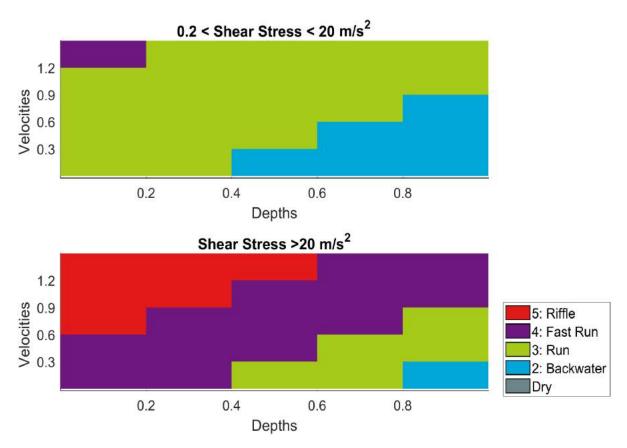
3.2.2. Mesohabitat Evaluation Model (MEM)

Looking at the meso-scale requires the division of the reach into hydromorphological units (HMU's). In the above described MesoHABSIM model, this division is done visually in the field based on expert judgement. Current research aims to extract these units from hydrodynamic modelling. So far, the MEM (Mesohabitat Evaluation Model) procedure is the best practiced method that was developed for this purpose [18]. As the model that was introduced in section 2.3 represents an idealised, visual classification is not possible and this method was applied in an attempt to extract meaningful hydromorphological units.

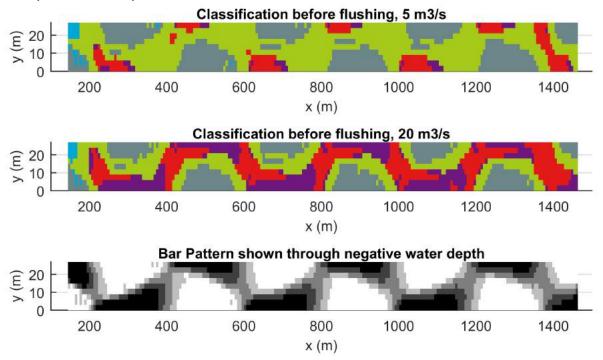
This section introduces the method. It then explains how this method is applied to the morphodynamic model that was presented in chapter 2, in order to evaluate the outcome. Two evaluation approaches are therefore chosen, which are presented in section 3.2.3. Hereafter the results are presented with relevance to the research question.

Classification method The MEM method combines data of flow velocity, flow depth and shear stress to categorise the computational cells. The division between these parameters is calibrated using field measurements, where the reach is classified into hydromorphological units. In this study, this calibration is done visually from the modelling results, in a way that ecologically meaningful hydromorphological units are distinguished during the base flow $(5 \ m^3/s)$ as well as at the start of the flushing flow $(20 \ m^3/s)$. The resulting classification is shown in figure 3.2a. This classification is applied to the model from which the hydromorphological units are visualised in figure 3.2b. The details of this classification procedure in general, and how it is adopted in this research, including the performed calibration are described in appendix D.

The way that classes, as shown in the diagram of figure 3.2a, relate to the real-life hydromorphological units and are further clarified below. A first remark that eases the interpretation, is that under high shear stresses, low velocities will not be present, and vice versa. This means that, looking at the bottom image in this figure, the fast run class will contain more deep and high velocity areas rather than shallow, low velocity



(a) The assigned classes based on the flow velocity and water depth in a cell. When cells have a depth smaller than 0.08 m, they are considered dry.



(b) The cells classified with a discharge of 5 m^3/s (base flow) above and 20 m^3/s (flushing flow) in the middle. The lower image illustrates the bar pattern. The white area represents the bars and the black area is the deepest.

Figure 3.2: Classification performed using the adapted MEM procedure

areas. This implies that it is important to bear in mind the distinction in shear stresses. Figure 3.3 describes the classes with representative images taken at the Avisio during base flow. Note that the calibration is performed to include make a distinction between areas both under base flow and under flushing flow. The riffles are classified so that they represent the expected riffle area under the flushing flow and therefore follow the expected patterns. However, this conditions the velocities and depths in such a way that during base flow, the so called riffles occur at different locations. This is further discussed in section 3.4.

Backwater



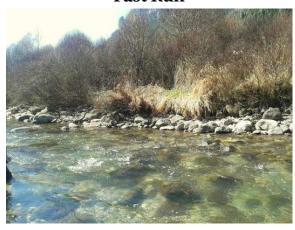
(a) This area is barely existent in the modelled reach, but represents a relatively deep area with low velocities.

Run



(b) During lower discharges, most area is classified as a run and represents mostly slow, shallow areas. Note that deep, high velocity areas are normally not existent if the shear stress is less than $20\ m/s^2$.

Fast Run



(c) This area is mostly present during higher discharges as it represents deep, high velocity areas.

Riffle



(d) The so called riffle represents relatively shallow, high velocity areas that are mostly found during higher discharges where the bed slope is steeper.

Figure 3.3: Description of the different classes, accompanied by representative images

3.2.3. Evaluation approach

The division in these classes makes it possible to analyse the spatial variety in fine sediment dynamics in relation to physical habitats at the meso-scale. Three key physical parameters that are used to assess the suitability are depth, velocity and substrate. All of these parameters can change due to the flushing event. Depth and velocity can be lumped as the geometry and the analysis is therefore twofold:

- As the classification is mainly based on the geometry, looking at the change in classification enables to understand the impact of changing flow velocity and depth. This way of classifying, which changes over time, is referred to as dynamic classification. This approached is further explained followed in section 3.2.4.
- Change in substrate is simplified as a distinction between cells that are covered with a certain layer of fines and cells that remain coarse. A threshold for layer thickness is introduced. For this analysis the classification will be defined before the flushing and is therefore referred to as static classification. An elaboration on this approach is given in section 3.2.5 after which the results are presented.

In this way, insight is given in which habitats are most sensitive to the deposition and erosion of fines, and how this can be explained from a physical point of view.

3.2.4. Evaluation: Class Shift

The classification changes depending on the flow velocity and flow depth. An increased discharge represents the influence of hydrology and changes the overall flow velocity and flow depth. The geometry of the river bed represents the hydraulics, which determines the local flow velocity and flow depth. An altering geometry therefore also alters the flow velocities and flow depths. Both the hydrology and the hydraulics change during the flushing event and during post flushing operation and therefore change the classification. This change is analysed for the reference run as introduced in section 2.3.6.

Figure 3.4 illustrates this change over time by percentage of represented area per class. The results start at t=-11 days where a base flow of 5 m^3/s is imposed on the model. Note that the first time step is extended to the left until t=-15 days to better illustrate this initial condition. The flushing event lasts from t=-11 days to t=0, imposing a flow of $20 \ m^3/s$ with an increased sediment load. Hereafter, the flow reduces back to base flow in order to compare the situation to the initial state. At t=9 days, a peak flow of $30 \ m^3/s$ is imposed for 5 days. The flow is reduced to base flow again until the end of the run at t=30 days. For further details on the setup of the model, the reader is referred back to chapter 2. The results are averaged over a representative reach (cells between t=180 meter and t=1200 meter) to ensure that the thin dam and downstream boundary conditions are of no influence.

The largest shift in classes is without doubt induced by changing flows. This is discussed further down in this section. The interest lies however in the change of habitat caused by geometry change. A clearer analysis can be made when looking at figure 3.5, which compares the situation before and after the flushing event. As the classification method is calibrated in order to represent the distinction between so called riffles and fast runs in both the low flow (5 m^3/s) and the flushing flow (20 m^3/s), the change in classification due to the fine sediment deposition during these flows is more meaningful than e.g. during peak flow. Figure 3.5 compares the situation before (beginning) of the flushing with the situation directly after (end of) the flushing for this base flow and flushing flow. After the high water peak, the discharge is brought back to base flow which allows to analyse this situation in addition to the before and after flushing situations.

Comparing the before and after flushing situation in base flow, the biggest change is observed in the decrease of runs. This area is substituted by dry cells as well as fast runs and riffles. After the clean water peak (at the end of the run) the situation is equal to the situation before the flushing.

The comparison between the before and after flushing situation as classified during flushing flow (20 m^3/s), shows a similar increase in dry area. Also the runs and the fast runs however increase, substituting more than half of the riffle area. This decrease in riffle area suggests an increase in depth and/or a decrease in velocity. As the total flow stays the same, and the wet area decreases, the explanation would be that the channels become slightly narrower, increasing their depth and therefore shifting in class. This narrowing of the channels is illustrated in figure 3.6.

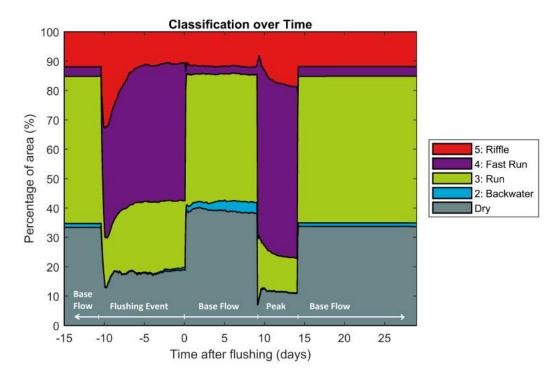
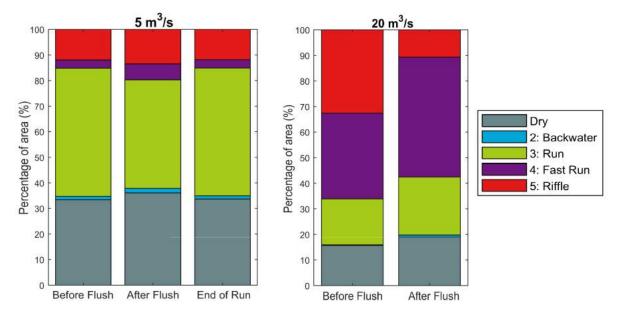


Figure 3.4: The classification of the reach changes over time due to differences in flow, as well as due to sedimentation which changes the geometry.



 $Figure \ 3.5: The \ shift in \ classification \ compared \ for \ different \ moments \ under \ the \ same \ discharge.$

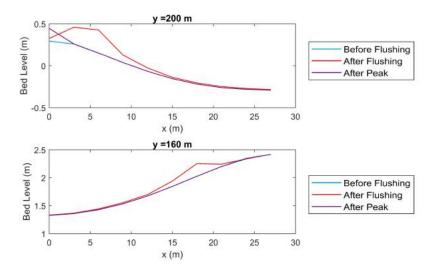


Figure 3.6: Two different cross sections that indicate the change in bed profile due to the flushing event and the clean water peak.

Sensitivity to Discharge Although there is a slight change in classification due to morphological changes caused by sedimentation, the governing discharge during classification is of much more influence. The higher the flow, the higher the amount of runs and riffles. Much of the dry area disappears which is easily explained by the fact that the overall water level is higher, submerging a larger area of the bars. To test how discharge affects the classification, a larger range of discharges is imposed on the model which results in figure 3.7. This clearly illustrates that the classification is highly sensitive to the discharge, with a large increase in high energy classes for higher discharges. This figure also clearly indicates how the bars get more submerged, as the dry area decreases. The decrease in riffles, starting from a flow of $20 \, m^3/s$ can be explained by the increasing overall depth, as riffles represent high flow velocities, but low depths.

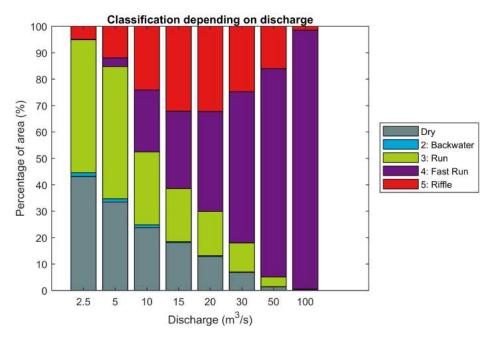


Figure 3.7: The classification is dependent on the discharge. With an increasing flow, the reach shifts into the high energy classes. First the riffles increase, but starting from a discharge of 30 m3/s, the flow becomes deeper and an increasing area is defined as a fast run.

3.2.5. Evaluation: Sedimentation per Class

A second approach, more relevant to this research, is to analyse how much area per class is covered with a significant layer of fines. For this purpose, the classes are defined before the flushing operation. The reason to choose for this static classification comes from the interest of understanding the effect on the existing habitats. A cell is defined as covered when the layer of fine sediments is larger than a certain threshold. The motivation to apply a threshold comes from an ecological point of view as fish are believed to clean the gravel bed for spawning, even if there is a small layer of sand covering it. This believe is backed up by the fact that brown trout on average lay their eggs at a depth of 8-25 centimeters and therefore are physically capable of removing a significant layer of (even coarser) sediments [12]. Whether the area can actually be considered suitable if the layer is thinner than the threshold remains debatable, see section 3.4.

Figure 3.8 shows the percentage of total cells that are covered in the reference run, divided up in the different classes. As the choice of this threshold is very sensitive, plots are shown with an increasing threshold from top to bottom. Another sensitive choice is the moment of classification. On the left, the cells are classified before the flushing with a governing flow of 5 m^3/s while on the right the cells are classified before the flushing with a flow of 20 m^3/s , showing a much higher presence of the high energy classes. The model sensitivities as described in section 2.3.5 still play a role in this analysis, but as the highest sensitivity is in the magnitude of the covered layer rather than the spatial variety, this sensitivity is already captured to a large extent by the choice of threshold for thickness of the accumulated layer of fine sediments.

A first observation is the large decrease of covered area during the clean water peak at t=10 days. This occurs for all thresholds and for the classification performed at 5 m^3/s as well as at 20 m^3/s . After the peak, only dry area and to a less extent runs remain covered. A second observation is the increasing total percentage of covered cells with an decreasing threshold, from little more than 20% for a threshold of 20 centimetres, to almost 40% with a threshold of 5 centimetres. This is a logical result, as the latter also includes the cells with a smaller threshold. The left plots, classified before the flushing, have a much higher contribution of runs and dry cells to the total amount of covered cells, as simply more of these cells are present. The right plots, classified with a flow of 20 m^3/s , show a high contribution of the fast runs and riffles.

To better understand which habitats are affected most, figure 3.9 shows the percentages of covered cells normalized for the total amount of cells within the class. The shallow flow class is left out, because the low amount of cells in this class makes this analysis worthless. This is also the reason that the line that represents the normalised percentage of covered riffle area has a squared shape. When reading the graphs on the left side (classified at 5 m^3 /) together with the graphs on the right (classified at 20 m^3 /s), one gets a sense of the implications for the different habitats.

A large decrease in covered cells is observed within the riffle and fast run classes. This trend is independent of the threshold or the classification chosen. The decrease of covered dry cells is significantly smaller. With a threshold of 0.2 meter, even an increase in covered cells is observed.

A big difference between the classification at base flow (left) and the classification at flushing flow (right), is the big percentage of covered riffle cells and runs respectively. When looking at location of riffles in the upper image of figure 3.10, and the location of the highest sediment deposition in the lower image, it shows that the original riffles are situated downstream of the bars, which is exactly the location that gets covered with fines. This cover therefore cannot be explained by the fact that it was classified as a riffle. Evaluating the covered cells classified during the flushing flow makes therefore more sense, at least from a physical point of view.

This evaluation of the covered cells that were classified during the flushing flow, shows very well how the runs are most affected by the deposition of fine sediments. Around seventy percent of these cells get covered with a layer of fines of ten centimetres. The model suggests that after the flushing event, the fast runs and the riffles are completely cleaned from sediments. The only locations where sediments remain are the runs and the dry cells, in other words, the low energy classes.

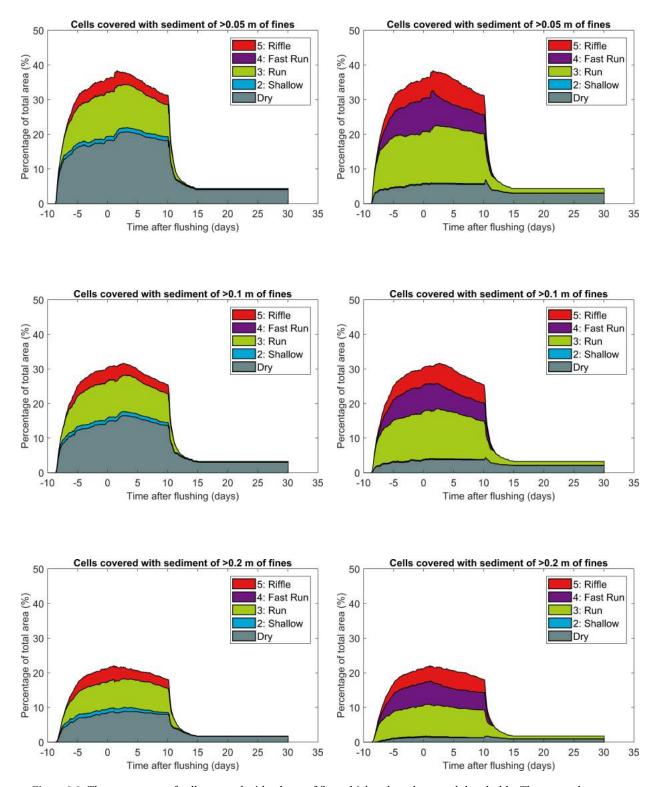


Figure 3.8: The percentage of cells covered with a layer of fines thicker than the stated thresholds. The covered areas are divided into the classes as classified during low flow on the left and during flushing flow on the right.

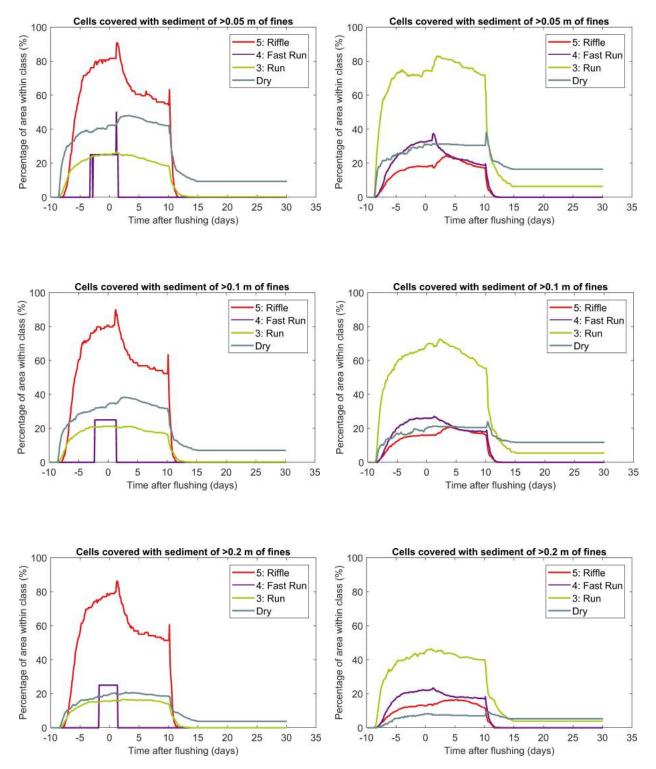


Figure 3.9: The percentage of cells that are covered with a layer of fines thicker than the stated thresholds, normalized per class. The classes are classified under low flow on the left and under flushing flow on the right.

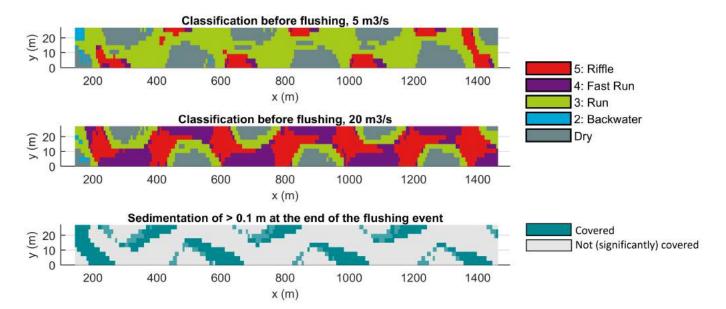


Figure 3.10: The modelled reach classified under a discharge of 5 m^3/s (base flow) above and 20 m^3/s (flushing flow) in the middle. The lower image illustrates the location where the total accumulated sediments reach a value bigger than 0.1 meter determined at the end of the flushing event.

3.3. Functional Habitat Goals

Meso-scale habitat suitability models make use of hydromorphological units to distinguish between different habitats that have similar physical characteristics. The last section presented two approaches that aim to evaluate which meso-scale habitats are most affected by the flushing event. Whether those defined habitats are suitable however, depends a lot on the specific use of a specific organism. Where a spawning trout prefers a high flow velocity because this keeps other organisms on a safe distance from the eggs and provides high levels of oxygen, another fish might prefer this same high velocity when looking for food, as insects drift by. This illustrates that the same hydromorphological unit can serve different habitat needs. The deposition of fines can therefore have a very different impact even though affecting the same habitat area in the same way. The fish that looks for food that drifts by probably does not mind the substrate to have changed, as long as the flow velocities are similar. The spawning fish on the other hand, does have specific substrate requirements. With this in mind, it is not sufficient to determine which hydromorphological units are affected by the deposition of fines. The suitability assessment depends on the requirements of specific species. Conceptually, functional goals need to be determined to understand whether the deposition actually has an impact. Habitat suitability models incorporate this concept by having different models for different species. The evaluation of a field survey will therefore give different suitable area maps for different species, even for different life stages. For further details on such method, the reader is referred to appendix C.

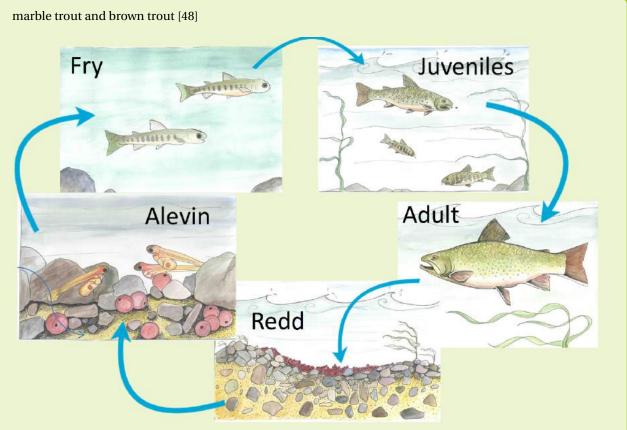
This section uses the concept of functional goals in order to investigate the impact of a flushing event on two functional habitats. As no specific habitat suitability models were available to do this evaluation, the goals were simplified to basic habitat requirements based on knowledge obtained in the preceding sections. One impact that comes to everyone's mind when thinking of fine sediments in a gravel bed river, is the deterioration of spawning habitat. Section 3.3.2 analyses the model runs with the functional goal of recovering the spawning habitat of the trout. A second goal was inspired by the old Egyptians who started cultivating land that got its fertility from deposition of fines during high discharges. With this in mind, one can imagine the fine sediments that get trapped in the reservoir could actually be beneficial to the riparian habitats. This idea is investigated with the aim to improve the channel bar habitat for vegetation in section 3.3.3. Attention is paid to the applicability of the described model setup.

3.3.1. From a Fish'-eye View

Sensitivity to Life Stages While a fish goes through different life stages, its habitat requirements change. The life cycle, as illustrated in the figure on the next page, starts with an adult female dropping the eggs in a self made 'nest' which is called a redd. The trout needs a gravel bed to build stable redds that create low velocity areas within a surrounding of higher velocities. These conditions ensure that predators cannot reach the redds while locally the conditions of low flow ensure that the eggs do not flush away. If the bed would consist of fine material, the protective shape of the redd would equalize very soon, exposing the eggs to the higher surrounding velocities leading to mortality. Secondly, the open structure of the gravel allows intragravel flow which supplies oxygenated water that is needed to incubate the eggs. If the bed gets clogged, this flow is reduced and the habitat is therefore not optimal anymore [23]

The eggs develop and after 4-6 weeks, they hatch and develop into **alevin**. The alevin stick around in the protected area of the redd. During this life stage, they depend on their yolk sack as a food source. Once they absorb their yolk sack, they develop into **fry** and swim out of the redds to look for food which is provided by the in the form of many macroinvertebrates. Once they develop to juveniles the fish become less vulnerable. As **adults** the female will start looking for spawning ground in order to reproduce und fulfill the circle of life. [21]

Sensitivity to the Region Habitat requirements do not only depend on the life stage of a fish, but very much on which fish species of which region is considered. Even when knowing the exact type of fish, their preference for physical habitats can be different from river to river, as they have adapted to the circumstances throughout many years. This dependency on region is further enlarged by the decrease in connectivity caused by the construction of dams. A thorough assessment of suitability therefore not only considers the life stage of a species, but also the region where it is found. The Avisio river in Italy knows a high presence of



The different life stages of a trout, from trouttanktales.com

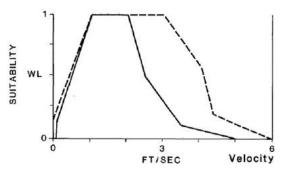
Reaction to a Flushing Event However a flushing event is an anthropogenic measure, sudden high discharges with an increased sediment load can also occur under natural conditions. It is believed that fish can 'sense' this danger and flee into tributaries until the flood has passed. If the flood is so devastating that no life remains in the main river, the fish will slowly recolonise starting from these tributaries. If the fish were not able to hide in time, the recolonization depends on the fish that occupied the tributaries beforehand and will take a long time. Roughly it can be said that five years are needed to re-establish all life stages in a balanced manner. It is worth noting that even though also macroinvertebrates might suffer highly from a flushing event, they have the advantage that they can fly in from different river basins. They develop into flying insects so are not limited to the connectivity of the river system.

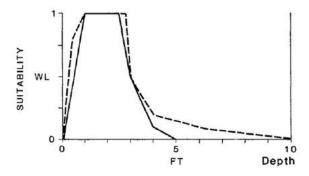
3.3.2. Recovering of Spawning Habitat

For the purpose of this research, a micro-scale approach was applied to evaluate the state of the spawning habitat for trout. These requirements are defined in terms of flow velocity and flow depth. The suitable spawning habitat is defined based on the preference curves presented by Bovee (1986) which are shown in figure 3.11. These suitability curves are simplified to form velocity and depth ranges that define suitable habitat, namely a flow velocity ranging from 0.3 m/s to 1 m/s and a flow depth range between 0.1 m and 1 m, roughly representing the range that is fully suitable according to the curves. The idealised model is divided into suitable and non suitable areas based on these criteria.

The percentage of suitable area is, just like the classification using the MEM-procedure, highly dependent on the discharge which is illustrated in figure 3.12. As the trout spawns in the low flow winter season, the classification is performed under base flow conditions of 5 m^3/s . The resulting suitable habitat is illustrated as the green area in the top image of figure 3.13 and is further referred to as the **geometrically suitable area**.

The habitat of a spawning trout becomes unsuitable if a layer of fine sediments covers the coarse gravel. With the idea as presented in section 3.2.3, the cells that are covered with a layer of fines of more than 10 centimeters are considered unsuitable. They are captured in red in the second image of figure 3.13.





- (a) Preference Curve of Flow Velocity for Spawning Trout
- (b) Preference Curve of Flow Velocity for Spawning Trout

Figure 3.11: Preference curve generated by professional judgement (dashed line) and data analysis (solid line) from Bovee (1986)

Overlapping these two images results in the third image of figure 3.13, which shows the remaining suitable area after the flushing event. The same analysis performed for the situation after the clean water peak, suggests that all geometrically suitable area is cleaned from fines.

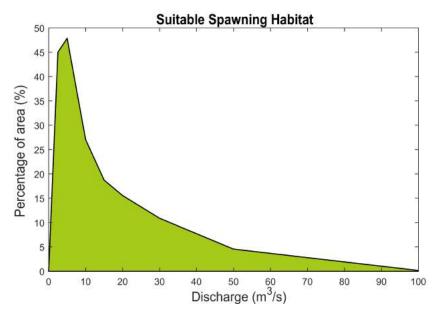


Figure 3.12: Percentage of suitable spawning habitat based on the flow velocity and flow depth criteria as defined in section 3.3.2 dependent on the discharge.

Include mobilization of gravel Due to the use of the transport formula of Engelund und Hansen, the above presented approach assumes that the fines are cleaned from the river bed without any hindering and even under very low flow, as the formula does not include the concept of incipient motion. More realistically however, one should consider that the fines can get trapped between the coarse layer of gravel and are not cleaned so easily [23]. However Delft3D is not able to calculate for flow through the interstitial spaces, approaches exist that do account for the process of hiding and exposure and aim to better address this simplification. Meyer-Peter Muller for instance includes a threshold for motion, which can adapt the mobility of a finer fraction depending on the presence of a coarser fraction. Taking it even further, one can assume that the fines only really get cleaned if the gravel gets mobilized [23].

Therefore a second analysis is performed to determine the area where gravel is mobilized, enabling full cleaning of the reach. Instead of running a full morphological model, the velocity that corresponds to initiation of motion is determined according to Shields Parameter:

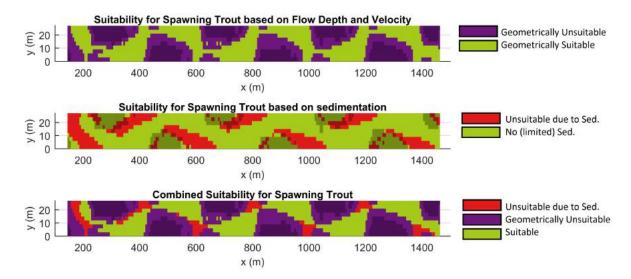


Figure 3.13: Top: Suitable area in green as defined by ranges of flow velocity and flow depth before the flushing at base flow, Middle: The area covered by a layer of fines of 0.1 meter or more in red at the end of the flushing, Bottom: Geometrically suitable area that is not affected by the flushing in green, area covered with fines in red and geometrically unsuitable area in purple.

$$u = \sqrt{\theta C^2 \Delta D_{50}} \tag{3.1}$$

With a Chezy's coefficient, C, of 25, a representative sediment diameter D_{50} of 5 centimetres and a Shield's parameter, θ , as $\theta_{cr}=0.047$, which is a representative value for the initiation of motion [15], this results in a speed of 1.5 m/s. The second image in figure 3.14 shows all the area where the coarse fraction of $D_{50}=5$ centimetres is mobilised during the peak of 30 m^3/s . The upper image again shows the habitat that is suitable based on the flow velocities and depths during base flow. Overlapping these images results in the third image which represents the fully recovered area after the peak flow. It shows that when taking into account the mobilization of gravel, more area can be considered unsuitable due to the flushing event. Note that a value of five centimetres is used here, while during the creation of the initial bed the coarse fraction was reduced to a value of one centimetre. However the slope called for this adjustment in fraction size, only the reference gravel size of five centimetres corresponds to a size that makes for a suitable spawning habitat.

3.3.3. Improving the Channel Bar Habitat

A second functional goal that is investigated in this research, aims to see if the deposition of fine sediments can also improve habitats. The idea originates from the old Egyptians that started to cultivate land when they found it was fertile due to sedimentation during overbank flows of the river Nile. Vertical accretion of fine sediments can improve the riparian habitats, and at the same time provide important spawning and rearing habitat for certain species [23]. Also in this case, deposition on the bars, which could improve the habitat for some sorts of vegetation and species, can at the same time be harmful for others. In this evaluation, it is assumed to be beneficial for the habitat to have a cover of fine sediments.

This functional goal is translated to micro-scale requirements as follows. The area that is considered dry during the flushing flow of $20 \ m^3/s$ is defined as channel bar area that could benefit from fine sediment deposition, as a measure of area that is only submerged during high discharges a few times a year. This area is indicated in green in the top image of figure 3.15 and is referred to as the geometrically suitable area. When the area is covered with a layer of fine sediments (shown in the middle image) after the clean water peak, this area is considered to be improved channel bar area. This area is illustrated by overlapping the top two images resulting in the bottom image of figure 3.15.

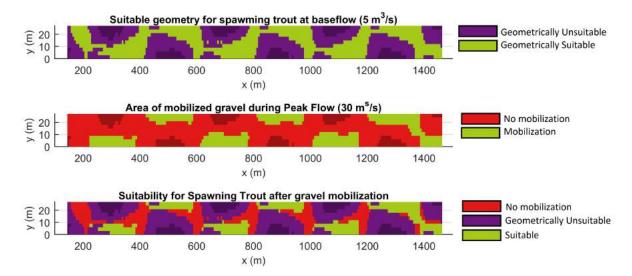


Figure 3.14: Top: Suitable area in green as defined by ranges of flow velocity and flow depth before the flushing at base flow, Middle: The area where gravel is mobilized during a peak flow of 30 m^3/s in green. Bottom: Geometrically suitable area that fully recovered through gravel mobilization in green, area not recovered through mobilization in red and geometrically unsuitable area in purple.

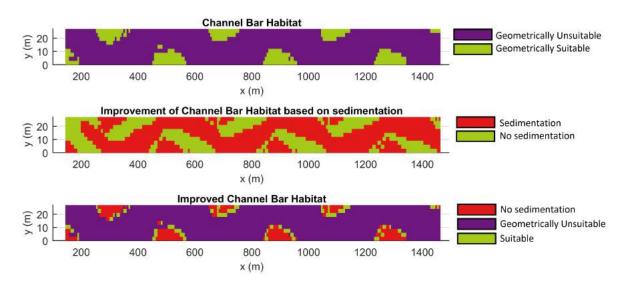


Figure 3.15: Top: Suitable area in green as defined by the dry area during a flow of $20 \, m^3/s$, Middle: The area covered by a layer of fines of 0.1 meter or more in red at the end of the flushing, Bottom: Geometrically suitable area that is covered with sediments by the flushing in green, area not covered with sediments in red and geometrically unsuitable area in purple.

3.4. Discussion: Effects on Physical Habitats

This section discusses the presented evaluation approaches. First, sensitivities of the hydro-morhpodynamic model are discussed, as these lie at the base of the results. When the results are evaluated, this influence therefore needs to be considered. Hereafter, the different presented evaluation approaches are discussed, starting with the applicability of the MEM classification method and consequently the potential of using functional habitat goals. The section finalises with a comparison of the presented approaches to the in-field MesoHABSIM method.

3.4.1. Influence of Model Sensitivities

The sensitivities of the hydro-morphodynamic model as described in section 2.3.5, have their influence on the evaluation of the results. The parametrisation of the model was aimed to show the highest potential influence which makes that the modelling results can be considered to show a probable enlarged effect of the flushing event. As seen during sensitivity testing prior to setting up the final model, which is described in appendix B, the influences of all parameters on the sedimentation patterns are similar. The adaptations of parameters can result in bigger and higher sediment patches, as well upstream as downstream of the bars. The sensitivity to the A_{Sh} parameter is by far the largest from the physical point of view, so it is the sensitivity of this parameter that is tested also on the evaluation on the meso-scale. The results are shown in the appendix, but show little difference with the earlier made conclusions. The total percentage is very different which is explained by the fact that patches are generally larger and higher with higher values for A_{Sh} , but the share of high energy classes and low energy classes that are covered are similar. The sensitivities deriving from the morphodynamic are therefore large, but do on first sight not have a large influence on the conclusions drawn in this thesis.

Change in Geometry Section 3.2.3 discusses a shift in classification due to a changing geometry that is the result of the deposition of fines. This shift is small in comparison to the shift that occurs due to a change in discharge. This is no surprising result, as the initial bed is fixed and the bars are of a higher magnitude than the deposition of fines. Also in reality, no big changes in geometry are expected, as the fines are moved too easily to create new significant bed forms. The small effect observed in the model is possibly a direct effect of the choice of A_{Sh} implying that drawing conclusions from change in geometry must be done with care. As it is so small, it is instead considered insignificant.

3.4.2. Use of the MEM procedure

The MEM procedure as described by Hauer et al (2008), was only applied partially in this study. It describes three routing steps of which the first one was applied and the second was not relevant because no shallow water areas were present. The third routing step was in principal not applied, but is discussed later in this section. 18

Moment of Classification All results are very sensitive to the moment of classification or, more concrete, to the governing discharge during classification. This does not only hold for modelling results, but is also valid for any in field classification approach. In this research, the calibration (which conditions the classification) is done to make distinctive classes under base flow and under flushing flow. It thereby represents riffle like areas well under the flushing flow, but as a result of this distinction, riffles exist at unexpected locations during base flow. Such mismatch is a result of the significant difference in discharge. The MEM classification method is only fully valid if calibrated for the discharge that is modelled, which makes the method rather sensitive.

Distinction between High and Low Energy Classes When having a clear goal in mind, smart use can be made of this sensitivity to the discharge. The case of affected spawning habitat due to a flushing event is just an example. The classification during base flow defines the suitable area, while the classification during flushing flow indicates the most affected area (through distinguishing low and high energy areas). By combining the two, it is possible to predict the affected habitats without doing any morhpodynamic modelling.

The MEM procedure is thereby mostly useful for its distinction between low and high energy classes. If an area is classified as riffle during base flow, but becomes a run when classified at flushing flow, one knows this area is vulnerable to fine sediment deposition.

Bed Stability However the third routing step of the MEM procedure is not applied in this thesis, it is very comparable to the advanced suitability assessment performed in section 3.3.2. It namely considers the stability of the river bed to assess the suitability for spawning. However, the concept is exactly opposite. Where the suitability assessment as performed in this thesis considers the mobilization of gravel as a way to recover and therefore improve the spawning habitat, by cleaning the gravel bed, the MEM approach considers the same area as unstable and therefore less suitable area. The underlying reason is that, once the eggs have been laid, the redds should not be disturbed until the fish leave the redds as juveniles. This evaluation step therefore considers the stability during base flow, whereas the presented approach in this thesis considers the stability during peak flow.

Calibration The MEM procedure requires an in field calibration step, which increases the relation to actual meso-scale hydromorphological units. This could not be done for the idealised case. The calibration performed based on the modelling results however results in similar patterns as described by Hauer et al (2008), e.g. an increase in fast runs with higher discharges, and is therefore considered meaningful enough for the aim of this research.

3.4.3. Influence of Fine Sediment Deposition on Suitability

For the approach presented in this chapter, a threshold for the fine sediment layer thickness was introduced as a measure of affected habitat. To the writers knowledge this best represents the most affected areas, as it indicates the area where most sediments deposit. It however introduces a large sensitivity to this threshold. Possible, a less binary approach could give more valuable input. This could e.g. be performed with the same idea of a suitability curve. It depends a lot on the functional habitat goals and the sensitivities of the habitat suitability model how this evaluation is best set up.

3.4.4. Evaluation of Functional Goals

The examples that were addressed in section 3.3, give an impression of the use of functional goals. Ideally, specific habitat suitability models are used to investigate the impact on specific habitats, which thereby implicitly describes the functional habitat goals. Knowing the sensitivities of such models would aid in increasing the understanding of the impacts of a flushing event. As no such model was available, in this thesis two functional habitat goals were translated into micro-scale requirements to set an example. This simplified approach thereby more gives an insight in the potential of using hydro-morphodynamic modelling as a tool for habitat suitability studies, than it provides grounded statements on the impact of flushing operations. The relevance of the simplified approaches are discussed below.

Clean Water Peak Recovers Spawning Habitat However some areas are not fully recovered by gravel mobilization, a large amount of geometrically suitable area is, which shows that a clean water peak can be considered effective in recovering spawning habitat for the trout. In addition, the mobilization of gravel might not even be necessary, as for the upper layer, it is enough to have a shear stress that lies under the threshold of motion for gravel. The fines will get sucked out of the bed [23]. The mobilization of gravel is only necessary when the aim is to remove sediments from a layer deeper than one time the diameter of the coarse gravel. This shows again that it is important to specify clear goals.

However, the later the flushing, the more sediments remain in the system. Even if the upper layer is removed and the fish are able to further clean their redds, it is shown that the redds slowly fill up with fines if these are available in the surroundings [17].

Deposition on Channel Bars The idea was to point out the area that could benefit from a flushing event. However, as seen from figure 3.15, only a few cells are defined as suitable according to this specific habitat goal. It is clear that in this application, the coarse grid size of the model plays an important role. This results in some areas drying up, while others experience less deposition than would maybe happen in real life. Adding to this is that these areas are overgrown by some vegetation, which is known to affect the flow and therefore the deposition of sediments a lot. The model does not include this and is therefore not considered appropriate for this evaluation.

3.4.5. Integration with MesoHABSIM

MesoHABSIM, being a modelling technique that is currently in development, has the potential to create a close link with hydro-(morpho)logical modelling. It would be valuable to test the suggested approach in this chapter on a simulation that makes use of a real bathymetry, e.g. the Avisio River. Thereby it can be investigated which level of overlap can be reached between the MEM classification and classification performed visually in the field. The high spread of flow depths and velocities as shown in figure 3.1b, suggest that a classification conditioned by these physical attributes will be different from the in field measurements. It is however very well possible that a simulation results in less variety due to more averaging in space. Therefore, the modelling results might have a closer relation between hydromorphological units and physical attributes, than the field measurements suggest.

3.4.6. Validity

The presented approaches are based on the hydro-morhpodynamic model as presented in chapter 2 which needs validation on the base of measurements before it can be applied to any specific reach. However these evaluation approaches are based on this model that is not fully validated, the approach could be applied to any further developed morphodynamic model of a specific reach. To apply the MEM procedure, the calibration should be done based on classification surveys performed in the field. A validation step can then be included based on further measurements.

The choice to introduce a threshold for sediment thickness and to define the change in substrate based on this layer is extremely difficult to validate, as many factors play a role in the suitability. It is not feasible to isolate this effect and measure the amount of e.g. fish. Probably the best way to validate, is to do further literature research and talk to many experts.

The only way this method can be validated based on a meso habitat suitability model for a specific space, would be to find a species that is very sensitive to fine sediments, possibly a macroinvertebrate that only occupies the reach when fine sediments are present. This is further discussed in the recommendations

Operation Scenarios

The preceding chapters give an insight in the effects that can occur due to a flushing event. It is concluded that a clean water peak flow have a high influence on the effects of sedimentation and erosion, as opposed to the base flow. This makes that the boundary conditions that are imposed by the dam operation, play an important role in the deposition and removal of fine sediment. This chapter aims to investigate the sensitivity to these boundary conditions. First, the characteristic elements that define the shape of a hydrograph are investigated, by analysing additional data of the Avisio river and other alpine rivers. The findings are presented in section 4.1 and are translated into typical hydrographs. These are imposed on the morphodynamic model which helps to understand how the operation of the dam can influence the morphodynamics. Thereby this chapter aims to answer the last sub-question:

How can operation be changed in order to optimize the most affected physical habitats?

The modelling results are evaluated according to the approaches as presented in chapter 3 and presented in section 4.2. A discussion follows in section 4.3, which presents the main conclusions that are drawn from these results and puts them in perspective to the real situation.

4.1. Scope of Scenarios

In section 2.2, the operation of the Pezzé dam on the Avisio river and the restrictions resulting from the design of this dam were discussed. These restrictions impose limitations to the scenarios and thereby set the scope for this chapter:

- During the flushing event, the discharge is equal to the inflow into the reservoir. The turbidity can be controlled by making use of the middle gates giving some control in the sediment load.
- After the flushing event when the reservoir is filled up with water again, a clean water peak can be imposed by increasing the flow through the diversion pipe that leads to the turbines. The maximum capacity is unknown, but is assumed to be 30 *m*3/*s*.
- Due to the presence of a spillway, big rainfall events could increase the water level of the reservoir to such a level that the full magnitude of inflow into the reservoir, directly runs over the spillway into the downstream reach.

The reference run was based on values as used in the thesis of Rabitti (2014) which represent the flushing event in 2012, see section 2.3.4. From the flushing event in 2016, the only available data originate from measurements performed above the dam and are shown in figure 4.1. These data therefore do not include the influence of the dam operation. In addition, they do not include the inflow of two important tributaries that contribute to the Avisio flow downstream of the dam and upstream of the reference reach. They can therefore not be used as a direct comparison, but will be used to further characterise the flow in this chapter. This characterisation forms the background to the setup of more realistic scenario runs with the aim to investigate the sensitivity to the different flows.

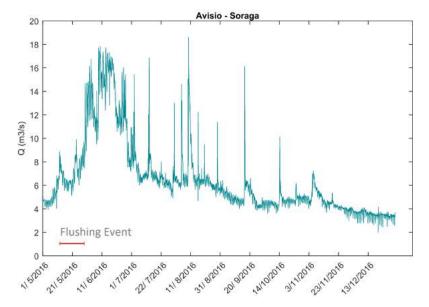


Figure 4.1: Flow data of the Avisio as measured above the Pezzé dam during and after the flushing event [?].

4.1.1. Clean Water Peak

As described above, a clean water peak can either occur as a result of a rainfall event that increases the discharge over the spillway, or as a result of an increased flow through the diversion pipes. Both are discussed in this section.

Rainfall Runoff Peak The first will be considered as a rainfall runoff peak, as it is assumed that in this situation the magnitude of flow over the spillway equals the inflow into the reservoir. Therefore, the hydrograph results from a normal rainfall-runoff relation. This section aims to set up realistic hydrographs that represent such a flow, and therefore analyses the hydrographs of several alpine rivers. They are selected if they have a baseflow of less than $20 \ m^3/s$ and contain a rainfall-runoff peak that increases the flow above $20 \ m^3/s$. These hydrographs are shown in figure 4.2. They show the discharge for thirty days between the end of august and the end of September 2017 [26]. These peaks are all rain events inducing a high runoff. They can be seen as exponential functions, increasing from baseflow to peak flow within a day. Also the falling limb can be approximated by an exponential function, although less steep with a time scale that is closer to two days. The peak itself is steep, which means that the highest discharge never occurs for a long time.

The flow peak induced by a rainfall event can be approximated by an exponential curve in the form of:

$$Q = Ve^{-t/k} (4.1)$$

where V stands for the peak volume, t for time and k for a characteristic time [$\mathbf{?}$]. The increasing limb is described with a characteristic time of 0.25, while the falling limb has a characteristic time of 0.5 to represent an increasing limb of 1 day and a decreasing limb of 2 days respectively. In this way more realistic hydrographs are generated that are described in section 4.1.4.

This shape also corresponds to the natural flow of the Avisio River, as can be seen from figure 4.3 which shows a part of the hydrograph presented in figure 4.1. Two rainfall events are included and the steep character of the rising limb in comparison to the falling limb can be observed. Also the time-scales are corresponding.

As seen in the previous chapters, the magnitude of the flow is of importance to the effects of sedimentation and erosion. Therefore the discharge of the peak flow is varied between 30 m^3/s and 100 m^3/s with the aim to include a flow that fully emerges the bars.

As the peaks are of short duration, and not the full capacity of the discharge magnitude is used, it is investigated whether multiple peaks have a cumulative effect, or do not supplement each other at all. This is done with the idea that multiple rainfall events normally occur.

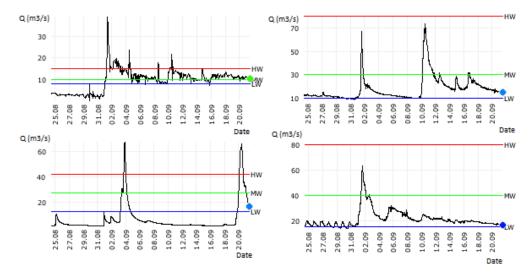


Figure 4.2: Several hydrographs containing a high water peak due to rainfall [26]. All are alpine rivers with a base flow of less than $20 \, m^3/s$ and show that the increase in discharge occurs on a shorter time scale than the falling limb.

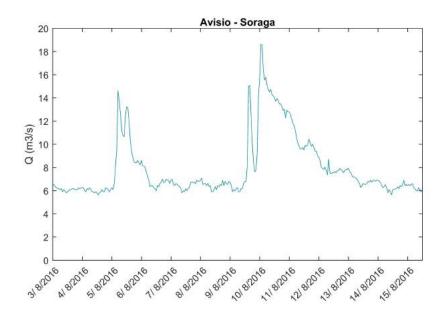


Figure 4.3: Flow data of the Avisio as measured above the Pezze dam covering two rainfall events [34].

Imposed Discharge Peak In the reference run, the discharge was increased for five days representing a peak flow that is imposed by the dam operators. This duration proved long enough to establish an equilibrium situation where no more sediments are cleaned due to this peak. It thereby represents the full capacity of a peak that has this discharge. Even if the magnitude is not realistic, it shows a useful comparison with a short, rainfall runoff peak. The imposed peaks in the reference run represent an abrupt change. To make these peaks more realistic, a similar exponential increase and decrease are imposed as also these peaks will not arrive instantly.

4.1.2. Daily Fluctuations

When analysing the Avisio data further, a daily fluctuation can be observed. The ranges are larger when flows are higher, fluctuating with a range close to five m^3/s compared to only one to two m^3/s during lower flow. Figure 4.4 zooms into a few days of the Soraga discharge measurements to illustrate this daily fluctuation. This daily fluctuation likely originates from snowmelt, which is dependent on a daily fluctuation of temperatures. It could influence the cleaning of the reach. Also during the flushing event, one can assume that the flow is not exactly constant but fluctuates. When the flushing operation occurs in spring time, the effect of fluctuation due to snow melt is even bigger. Whether this daily fluctuation is of any influence, is investigated through imposing a fluctuating discharge on the model, as described in section 4.1.4.

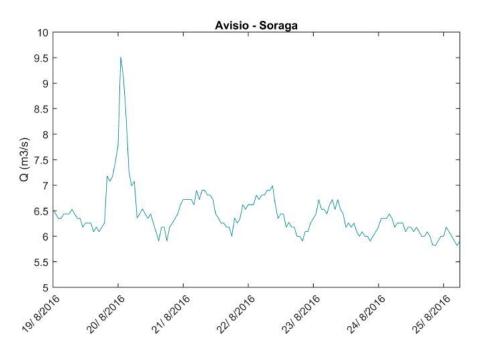


Figure 4.4: Flow data of the Avisio as measured above the Pezze dam showing the daily fluctuating character of the Avisio River [34].

4.1.3. Controlled Turbidity

As presented in section 2.2, dam operators try to limit the impact to the environment by controlling the turbidity of the outflow during the flushing event. This is aimed at reducing the direct impact of the flushing event which results from a high concentration of fine sediment in the flow. It is difficult to say whether a decreased turbidity also results in a reduced effect on the physical habitats, as bed load cannot be directly related to turbidity which consists to a large extent of wash load. It is assumed that the direct outflow (before mixing with the cleaner water) is at full capacity, as it is capacity limited. It can therefore be said that, when mixing the outflow of the reservoir with cleaner water from the middle gates, the bed load transport capacity increases, resulting in a supply limited system. This influence is investigated by imposing half the amount of sediment, as well as double the amount (the full capacity was not reached yet).

A second way in which the bed load transport is influenced, is due to the processes that occur in the reservoir during flushing. In principle, the sediment influx is assumed to be at a level of full capacity of the flow. This transport capacity calculation however assumes an equilibrium state which is not the case during a flushing event. The bed is constantly changing inducing variations in flow velocity over time and in space. The system therefore constantly adapts which in its turn results in fluctuating bed load transport.

In addition, erosion processes are not limited to the erosion that occurs due to a higher transport capacity than the incoming sediment load. A second process that occurs in the reservoir during flushing and is probably of higher influence, is the process of bank erosion. Parts of the bank collapse suddenly resulting in an increased amount of sediment. The photo taken of the reservoir during the flushing operation in figure 4.5 makes it easy to imagine that this collapsing of the banks occurs, as the banks get very steep. This pro-



Figure 4.5: The Soraga reservoir during flushing. The photo shows how a river flow cuts through the sediments that were trapped in the reservoir. From the Autonomous Province of Trento (2017)

cess increases the possible fluctuating character of the fine sediment load and the effects of this fluctuation are therefore investigated. As the reach is about ten kilometres downstream of the dam however, it is not expected that the bed load is higher than full transport capacity, as otherwise the fine sediments would have settled before.

4.1.4. Scenario Runs

Based on the above discussions, several hydrographs are imposed as an upper boundary condition in the model. The aim is to investigate the sensitivity to flow patterns (more natural vs. abrupt changes) and varying sediment loads (fluctuating and in size). The runs represent:

- a constant flow during the flushing event and a constant peak flow of 30 m^3/s that lasts for 5 days with abrupt change (Reference run/L000) and exponential increasing and decreasing flows (L001),
- a daily discharge fluctuation around the reference discharges (L002),
- rainfall runoff peaks in stead of a constant peak with a peak volume of 30, 50 and 100 m^3/s (L003, L004 and L005 respectively),
- combinations of peaks; a peak of 30 m^3/s followed by a peak of 50 m^3/s , the same peaks in reverse order and two peaks of 30 m^3/s (L006, L007 and L008 respectively),
- a daily fluctuating sediment input (L010), and
- doubled and halved magnitudes of sediment input (L011 and L012 respectively).

In appendix E the varying discharges (L000 - L008) are presented in figure E.1 and the varying sediment loads are presented in figure E.3.

4.2. Results of Scenario runs

The results are compared in three ways. First, a quantitative analysis is done by comparing the volume of sediments that have accumulated in the reach. Secondly, the sedimentation is analysed per class as specified based on the MEM procedure (see chapter 3), to see whether a change in operation could benefit certain habitats. Static classification is applied for the flushing flow discharge, as this has the clearest relation to the habitats. Finally, the results are evaluated based on the functional habitat goals as described in section 3.3. Figure 4.6 shows the comparison of accumulated volume. These graphs support most of the observations. The reader is referred to appendix E for a complete overview of the results that consider the sediment cover per class. Only the significant comparisons are included in figure 4.7. The observed influences are discussed below:

- Neither a fluctuating sediment load nor a fluctuating discharge are of big influence to the deposition of sediments. Fluctuations are observed but are just small around the average (figure 4.6a and 4.6d). The simplification to constant loads and discharges is therefore justified.
- The only observed difference between abrupt changing boundary conditions and an exponential increasing an decreasing flow, is explained by the setup of the hydrograph in combination with the imposed bed load. The latter is namely decreased to zero at t=0, where also the abrupt discharge is brought back to base flow. For the exponential decrease however, a short period remains where the discharge is higher and therefore the transport capacity is higher. This explains the difference between t = 0 and t = 10 days in figure 4.6a.
- The duration of the clean water peak is of influence, as sediments need time to leave the system. This is apparent when comparing L000 to L003. In the latter more sediments remain even though the peak magnitude is equal (figure 4.6a). This effect will be even higher if longer stretches are considered.
- The rainfall induced clean water peak of 50 m^3/s has a result that is very comparable to the long peak of 30 m^3/s (figure 4.6a and 4.6b). As stated above however, this might change for a longer stretch where a longer but lower peak might be more favorable.
- The higher the clean water peak, the more sediments are removed. With a flow of 100 m^3/s , all sediments leave the system (Figure 4.6b).
- All clean water peaks are capable of fully removing the sediments that cover the fast runs and the riffles (the high energy classes) except from the rainfall induced peak of 30 m^3/s (see appendix E).
- The effectiveness of a combination of peaks is mostly dependent on the magnitude of the highest peak as can be seen by the volume of removed sediments (figure 4.6c). However, when having a closer look to where these last sediments remain, it becomes apparent that the order of clean water peaks could have an influence on the spatial patterns. Figure 4.7 compares run L006 to L007 which contain the same clean water peaks of 30 and 50 m^3/s , but in a different order. If the higher peak is followed by the lower peak (L007 showed on the right), more dry area remains covered. The difference however remains small and it can be doubted whether this difference is of any significance.
- Big differences are found when the sediment load is altered. With double the load, the system reaches an equilibrium much faster and the total volume of accumulated sediments during the event is much higher. This mainly results in a higher cover of the fast runs. Even though the total accumulation is higher, the imposed clean water peak removes all sediments from the high energy classes. Only slightly more runs and dry area remains covered. A higher negative impact can be expected if only short clean water peaks are available or the impacted reach gets longer (see figure 4.6d and appendix E).
- A decreased sediment load results in a lower volume of accumulated sediment and the riffles and fast runs are hardly affected. The final result is still very similar to the reference run, though the cover on the runs is almost zero (see figure 4.6d and appendix E).

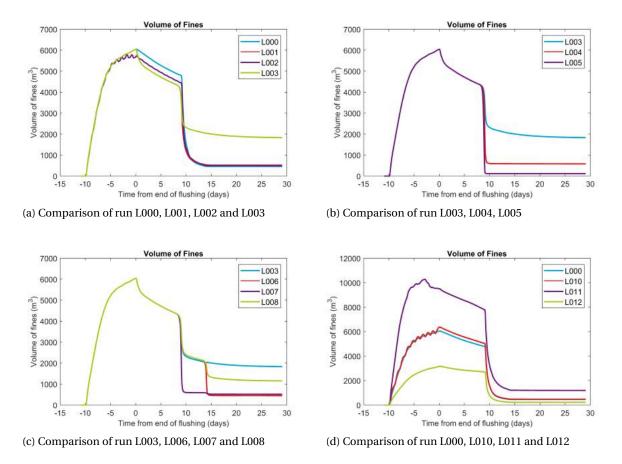


Figure 4.6: The total volume of accumulated sediments compared over time for the different scenarios, grouped as described in section 4.1.4. In the top left figure the abrupt change in flows is compared to more natural increases and decreases, a daily fluctuating flow and a (short) rainfall induced peak. The top right image compares three magnitudes of rainfall induced clean water peaks. The bottom left image compares combination of peaks and the bottom right image compares variations in sediment load.

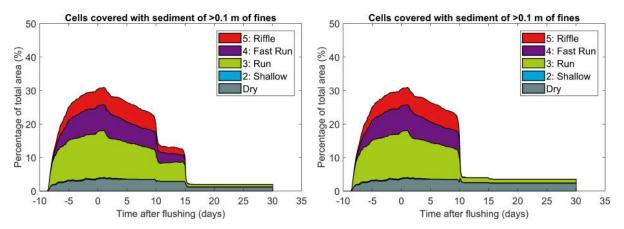


Figure 4.7: The images show the percentage of cells covered with a layer of fines thicker than 0.1 meters, divided into the classes as classified according to the MEM procedure during flushing flow discharge. On the left the results for run L006 where a peak of 30 m^3/s precedes a peak of 50 m^3/s and on the right the results of run L007 with the same peaks but in opposite order.

Peak Flow	Percentage of	Percentage of
	Suitable Area*	Total Area
10	0 %	1 %
15	4.7 %	6.2 %
20	22.3 %	15.0 %
30	48.4~%	28.8 %
50	96.1%	58.2 %
100	99.9%	81.2 %

*As defined during baseflow

Table 4.1: Percentages of area that is recovered by the mobilization of gravel due to a clean water peak

4.2.1. Recovery of Spawning Habitat

The results as discussed above already indicate that the fine sediments get flushed out of the high energy classes, as classified during flushing discharge. In order to assess the impact caused to the spawning habitat however, the classification should be done during base flow, as this is the flow under which the spawning takes place. Following the micro-scale approach as presented in chapter 3, the different scenarios are evaluated with the functional goal of recovering the spawning habitat of the trout. As of the area that gets covered with a full layer of fines is already very small even without a clean water peak, the focus here lies on the mobilization of the gravel, and the percentage of suitable area that is recovered due to different magnitudes of clean water peaks. The geometrically suitable area is defined as the area with velocities in the range of 0.3 and 1 m/s and depths in the range of 0.1 to 1 m during base flow. The gravel gets mobilized when the velocity exceeds 1.5 meter as calculated for the principle of incipient motion. The area that is recovered after a clean water peak is presented in table 4.1, as a percentage of geometrically suitable area and as a percentage of the total area. The duration of the peak is not of importance in this analysis, as the gravel only needs to be rummaged and not transported.

Table 4.1 shows that already with a flow 30 m^3/s , almost half of the geometrically suitable area is fully recovered, quickly increasing to almost 100 % with a flow of 50 m^3/s . As this definition of mobilization of gravel was on the safe side, it can be stated that any considered peak flow is capable of recovering at least half of the suitable area, which is a considerable amount. In the same areas one can be sure that the transport capacity is high enough to also remove the fine sediments.

4.2.2. Improvement of Channel Bar Habitat

As seen in chapter 3, the evaluation of the improvement of channel bar habitat seems to suffer from the coarse character of the grid. Therefore a quantitative analysis will be invaluable. The results as presented in section 4.2 are however discussed qualitatively in reference to this functional goal in the following section.

4.3. Discussion: Operation Scenarios

The results presented in this chapter direct towards one simple conclusion: the impact of fine sediments on the physical habitats are minimized by imposing a peak flow of either a high magnitude (10 times the base flow) or a lower magnitude with a longer duration (roughly 6 times the base flow for several days). Even a short peak of $30\ m^3/s$ cleans out most sediments. These results seem to suggest that little harm is done to the physical habitats, but all originate from model runs that were set up to investigate the sensitivity to different clean water peak characteristics (mainly duration and magnitude). What if such a clean water peak does not occur at all? This is what happened on the Kern River in California:

"On the Kern River, California, sand was flushed from a small diversion dam during base flow in 1986 in anticipation it would be transported away the next winter. However, a series of dry years followed, and the flushed sand remained on the bed for several years because the river did not experience a sufficiently large flow to transport it away"

- Kondolf et al. (2014)

In the case study of the Avisio River in Italy, this question seemed irrelevant at the start as peak flows up to $50 \ m^3/s$ were observed after the flushing event in 2012 [35]. When however analysing the discharge data as presented in figure 4.1, which were measured above the dam and therefore represent the natural inflow of the

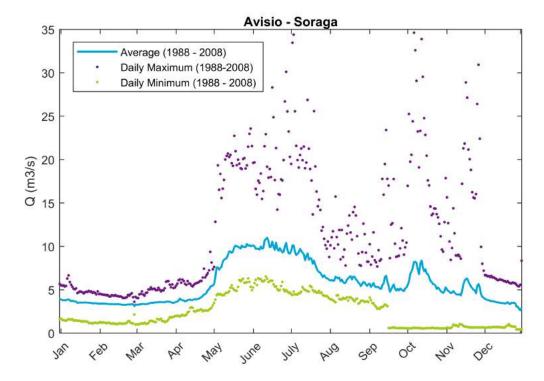


Figure 4.8: The minimum, average and maximum flow per day of the year as measured over the years 1988 until 2008 at Soraga, which is upstream of the reservoir [34].

reservoir, the assumption of having high water peaks might have to be refuted. Figure 4.8 gives the per day maximum discharges as measured at Soraga over a period of 20 years (1988 to 2008). The highest discharge measured was lower than 35 m^3/s which shows that the possibility of operating the dam in such a way that a clean water peak is induced for several days is not realistic.

At the same time, the rainfall induced peak is probably more realistic than expected with the prerequisite that the reservoir is full before the rainwater peak arrives. The reason for this is that two important tributaries contribute to the Avisio river downstream of the dam but upstream of the reference reach. Although no continuous discharge data are available of these tributaries, several flood flow simulations indicate that one in 30 year floods exceed values of 80 m^3/s easily, with values up to 160 m^3/s [34]. These discharges, added to the flow coming from Soraga, makes it highly assumable that rainfall induced peaks clean the reach every year. Note however that such events are unlikely to happen in the winter season, while the highest discharges are expected in the months of May to July, when also snow melt contributes. Furthermore, these peaks cannot be controlled by improved dam operation.

Where for most habitats it is considered beneficial when the fine sediments flush out of the system, the channel bar habitats were assumed to improve when a layer of fine sediments settles. However the grid is too coarse to make a quantitative judgement, the results as presented in this chapter and in appendix E, give some insight in the potential of this application. At first the results suggest that the cover of dry cells is sensitive to the magnitude of the peak flow and a high flow that overtops the bars is certain to flush away all sediments. However, if the reach would be longer, it is still imaginable that this concept works with a very short, relatively high peak. Secondly, and more surprisingly, the results suggest that even though the order of peaks does not make a big difference in total volume that is cleaned from the reach, but the covered dry area seems to be larger when the higher peak precedes the lower peak than when the order is opposite. Before meaningful conclusions can be drawn, this should be investigated further.

In addition, in relation to the discussion above, which indicates that the control due to the operation of the dam is smaller than assumed before, it is nearly impossible to exactly induce such combination of peaks that would improve this channel bar habitat.

Conclusions

Flushing events can be considered as a temporary, anthropogenic disturbance of the river system. Their impact on downstream ecosystem functions and processes is a highly sensitive issue for river managers. This study focused on developing a predictive approach of the potential effects of fine sediment flushing from artificial reservoirs on the downstream physical habitats for fish. To this aim, a morphodynamic model has been applied to an idealised channel morphology loosely inspired on a reach of the Avisio River in North-East Italy. Model applications proved a useful tool to increase the understanding of fine sediment dynamics and to explore ways to relate these dynamics to the ecologically relevant meso-scale. With the obtained knowledge, this chapter summarises the answers to the research question, which was formulated as follows:

What are the spatial and temporal dynamics of fine sediment in gravel bed rivers in relation to flushing operations and what are their implications for the physical habitats at the meso-scale?

The answer is summed-up, divided into the sub-questions below:

Which spatial patterns occur in the deposition and removal of fine sediments in a gravel bed river in the presence of bars and what are the governing processes?

- During a flushing event a large amount of fine sediment is introduced on a coarse river bed characterised by an alternate bars morphology. Under the assumption that this coarse bed does not move significantly during the flushing event, a simplified model simulation shows that the fines deposit upstream and, to a higher extent, downstream of the bars. Spatial variety in thickness of accumulated sediment is consequent to the variability in transport capacity, which is to a large extent influenced by the flow velocity. As long as bars are (partly) emerged, low flow areas exist, maintaining areas where fines deposit or stay in place.
- Downstream of the bars, secondary flow is found to direct sediment transport towards the higher regions of the bars, magnifying the spatial patterns that already exist due to a variety in flow velocities. This results in larger fine sediment patches downstream of the bars than upstream.

Which meso-scale physical habitats are most affected by the deposition and removal of fine sediments?

- In-field meso-scale habitat suitability models regard the variety in magnitude of physical attributes within meso-scale habitat units. This gives an advantage over a micro-scale approach as it better accounts for the behaviour of organisms. The Meso-scale Evaluation Method (and similar classification methods) undermine the advantage of assessment at the meso-scale as, strictly spoken, a micro-scale approach is taken.
- Such a micro-scale classification method can however, if based on flow depth, flow velocity and shear stress, distinguish between classes that do relate to the meso-scale habitats. The division in low and high energy classes provides a meaningful prediction of areas that are affected most during a flushing event.

- This research shows that such classification (based on flow velocity, flow depth and shear stress) is expected to shift as a result of a flushing event, as the geometry changes. This shift is however not significant, as the bars do not change. On the other hand, the classification is very sensitive to an altering discharge, as consequently flow velocities and flow depths change. This makes such classification method useful to estimate the discharge needed to clean specific areas, as a high energy class is favourable to removing fine sediments.
- Focusing on fish, the habitat of the spawning trout is most sensitive to the deposited fine sediment, as it needs a coarse river bed for reproduction. This research suggests that spawning habitat is not affected severely as it is considered a high energy class. A clean water peak might be necessary to rummage the gravel in order to thoroughly recover the spawning habitat.
- Deposition of the fine sediments onto the channel bars could have other eco-morphodynamic effects besides fish habitats, as e.g. it may support colonization of vegetation by retaining moisture, seeds and organic material. The set-up of this research however does not provide enough information to give a quantitative measure of such effects.

How can operation be changed in order to optimize the most affected physical habitats?

- The impact of fine sediments on the physical habitats are effectively minimized by imposing a peak flow of either a high magnitude (order of 10 times the base flow) or a lower magnitude with a longer duration (order of 5 times the base flow for several days). Even a short peak of this lower magnitude cleans out most sediments in the high energy habitats, but some sediments remain in the low energy areas. Only with high discharge peaks, one can be sure to rummage the coarse material, ensuring full cleaning of the fines.
- The feasibility of imposing any high water peak depends on the hydrology of the reservoir's catchment. In the reference case at the Avisio, the inflow into the reservoir is not of such quantity that an imposed clean water peak can be induced through operation. In other cases however, especially a moderate peak of longer duration could be a feasible opaterion scenario.
- Rainfall events can also provide runoff peaks that clean the reach. The reference reach benefits from several important tributaries that flow into the Avisio river downstream of the dam but upstream of the reference reach. These rainfall runoff peaks originate from different catchments and appear sufficient to ensure a clean water peak multiple times throughout the high water season. If the flushing operation is timed at the start of this high flow season, which lasts from May to July, it is highly probable that the spawning ground is recovered before the next spawning season, which occurs in winter. If it is timed later in the season, this probability is reduced significantly.

Recommendations

In this chapter, recommendations following from the research are given in three themes. The first section discusses what is needed to successfully make use of hydro-morphodynamic models for habitat suitability studies at the meso-scale. The second section aims at the validation of these studies. The third section focuses on the recommended operation of dams, and the possible ways to limit the impacts on the downstream physical habitats. The final sections discuss the applicability of the research method to other river systems and puts the conclusion in perspective of the larger system.

6.1. Morphodynamic Modelling as a Tool for Habitat Suitability Studies

As many situations exist where morphological change has an effect on habitat suitability, the use of morphodynamic modelling for habitat suitability studies has a high potential, which is still largely unexplored.

Model Improvements A quantitative analysis of fine sediment accumulation still presents large uncertainties within the current setup of state-of-the-art morphodynamic models. Closure relations that link (i) sediment entrainment thresholds, (ii) local roughness and (iii) local, transport-effective near-bed shear stresses to the fine sediment cover of the coarse riverbed are based on little experimental evidence and need improvements. Very sensitive parameters are the bed slope parameter, controlling the steepness of the deposition, the erosion threshold, influencing the magnitude and the speed of adaptation towards the new equilibrium configurations. These processes are of key importance for an adequate quantitative evaluation of the effects on the habitats. It is recommended to continue research, particularly in mountain rivers with low relative submenrgence for which the standard formulations of these parameters are often not valid.

Hydrodynamic modelling as a starting point As the fine sediment dynamics over a fixed bed are related to the physical flow parameters, it is plausible to give a first indication of the areas where sedimentation is expected, based on a hydrodynamic model. Also the areas of mobilization can be roughly indicated by a simple post-processing step on hydrodynamic modelling results, as long as no significant changes in the bed topography are expected.

Habitat classification methods based on numerical modelling results do not yet satisfy the same advantages that in-field classification on sight does, and suitable methodologies extracting mesoscale habitats from hydraulic simulations still need proper development and testing. It is therefore recommended to perform an initial classification on site, especially at lowest discharges which often ensure wadable conditions. Hereafter, hydrodynamic modelling can be used to classify low energy classes that are prone to sedimentation under numerous discharge scenarios.

Meso-scale classification The potential of a meso-scale classification method that is based on hydro- (morpho)dynamic modelling results is high. It is suggested to direct the development of such a method to considering neighbouring computational cells to reflect the patchiness properties of the meso-scale physical habitats. Another suggestion is to automatically extend the habitats to the river banks, as this could help to approximate the hydromorphological units.

6.2. Validation 61

The MEM-approach combines flow velocity, flow depth and shear stress data for its classification. Experts in the field use these characteristics to make the classification, but consider many more visual characteristics that are not so easily modelled. One example is the change in slope, which is often defined as a border of the meso-scale units. It is recommended to incorporate this information in the classification method, either as a preliminary routing to determine the potential borders, or combined with the first routing where velocity, depth and shear stress are accounted for. Such developments could significantly reduce the amount of field days.

Care must be taken however to the validity of the MEM-procedure under varying modelled discharges, as the calibration must in principle be coherent with the governing discharge during data collection. The difference between the classification performed under baseflow and flushing flow conditions in this research, for which the classes were conditioned in the same way, showed that mismatches can occur if the modelled discharge is different from the discharge on which it was calibrated.

The importance of clear goals — In order to assess the actual implications to the ecology, functional habitat goals are necessary. They are implicitly specified by using a habitat suitability model that considers a target species. Before performing any classification, whether performed visually in the field or by using numerical modelling results, it is recommended to determine which habitat suitability model will be applied. This is a prerequisite for choosing a discharge (or season) at which the classification is performed, as this situation needs to be in accordance with the goals of the habitat suitability assessment.

In addition, only when understanding the sensitivities of such biological model to e.g. substrate size, it is possible to set up a hydro-morphodynamic model that provides the right information to assess the impact. An example that comes forward in this thesis, is the evaluation of the improvements to the channel bar habitat. In this case it would be necessary to apply a more detailed grid and to extend it to where the flow could potentially come during high discharges. Possibly, flexible mesh could be a valuable method.

6.2. Validation

As described in the discussions per chapter, this research can be improved significantly when implementing a validation step. This section discusses several options.

Monitoring Sediment Transport In several studies, turbidity is used as a measure to quantify sediment transport. It can be easily monitored and operation can be adapted to real time values. However, with the aim to quantify sediment accumulation and therefore bed material load transport, turbidity data lack relevant information. They represent wash load together with suspended load, but do not include bed load. The wash load part does not interact with the bed and travels faster than the bed material load. It is therefore recommended to set up a measuring campaign during the next flushing event in order to investigate the relation between turbidity and bed material load transport, by sampling the deposited sediments as well as the sediments in suspension. In addition, the bed load transport can be monitored by bed load samplers, which is more aimed at the speed and distance that the bed load travels in comparison to the suspended load (and therefore, the measured turbidity). These measurements can then be used to calibrate a morphodynamic model of the flushing event (e.g. the erosion threshold), rather than turbidity measurements that lack information to calibrate the full extent of the model.

Monitoring Sediment Accumulation A better understanding of the relation between bed material load and turbidity, can aid in the calibration of the model, but does not yet validate whether the spatial patterns are realistic. To do so, the locations where most accumulation occurs need to be determined in a real case. Instead of mapping the whole reach, certain points can be chosen that are expected to have higher and lower values of accumulation. This can for instance be done preliminary by distinguishing in high and low energy classes according to the MEM-procedure.

To the writers knowledge, the only measuring campaign that was aimed at assessing these spatial patterns in fine sediment deposition, was performed on the Arc en Maurienne River in France by Camenen et al. (2016). This research could give valuable input in the design of a new meauring campaign. 7

Macroinvertebrate Sampling Macroinvertebrates are increasingly used as an indicator to assess the instream ecological quality [9, 38, 40]. Monitoring the presence of macroinvertebrates can give a more direct indication that certain habitats are recovered. Their presence does not depend so much on the time they

6.3. Operation 62

need for recovering, as they can fly in from other rivers. If the right macroinvertebrate is considered, this can be used to validate the recovery of e.g. gravel habitats.

6.3. Operation

Based on this research, the following recommendations are given in terms of operation of the dam at the Avisio river, and comparable dams that use flushing operations to clean their sediments.

Timing It is recommended to release the flushing event at the start of the high water season which lasts from May to July. Also October and November know high rainfall events in this Alpine area, but planning the flushing event prior to these imposes a higher risk as some years come out much drier than expected. Climate change adds to this uncertainty. The Pezzè reservoir on the Avisio river was flushed in October in 2012, which shows that this is still common practice. Note that it is definitely dissuaded to flush during the dry season which lasts form December to February, as eggs occupy the gravel habitats and would suffer direct mortality.

Residual flow reach The Avisio river depends on its tributaries to provide clean water peaks that clean the reach from fine sediments. A reach of several kilometres does however not benefit from these peaks, as it is situated upstream of the confluences. When aiming at this reach, a clean water peak needs to be released directly from the dam.

Dam design In this research, the dam design was considered a prerequisite and the operation scenarios are coherent with the functionality of the dam. Already in the design phase, improvements can be made that result in better operation of the dam. As the peak flow is found so effective in cleaning the downstream reach, it is recommended to implement the possibility to impose such a peak flow, even if the inflow in the reservoir is not high enough. Possibly the middle gates can serve this function. This is useful with the aim to clean the residual flow reach.

Reduce Impact during Flushing One measure taken to reduce the direct impact of a flushing is environmental flushing, as highlighted in chapter 4. Without dams, rivers also know high water events with increased turbidity. Fish are relatively resilient to these. One of the reasons is that they escape the event by hiding in tributaries. They know when to hide as they experience warning peaks that are caused by disturbances of the river profile upstream. When such a warning peak can be imitated this could direct fish into safe zones before the flushing event takes place. Further research is necessary to see whether this effect can be reached.

Different frequency Possibly, the frequency of flushing can be changed. The time required to fully recover the life stage pyramid of fish is considered to be five years, which makes a once in three year flushing event destructive. Considering that also natural peaks contain increased sediment loads to which a fish is resilient, it is an option to adopt a yearly flushing event, to which the ecosystem can adapt. A benefit could be that the fines are less harmfull as they spent less time on the bottom of the reservoir. Also this research showed that a decreased sediment load will result in a decreased deposited volume, though the remains after a peak flow are comparable to a higher load. Further research should point out whether this is an option.

Less frequent flushing on the other hand, gives the ecosystem more time to recover, which could be beneficial for the biodiversity.

No flushing The best solution for the downstream ecology is without doubt to refrain from flushing. Examples exist where the ecological values became more important than the economical values of the hydropower and it was decided not to flush any more. In Baden-Württemberg, a new, swamp like ecosystem developed in the sedimented reservoir. The hydropower plant is still in use, but cannot serve hydropeaking demands anymore [25].

6.4. Broader Applicability

Different River System This research is based on the reference case of the Avisio River in the Alpine region of North-East Italy. However a large part of this river is channelised, the section that contains most variation in bed topography was selected. This reach is however simplified to an alternate bar topography. This also

generalised the research. The relevance of this research concerns any river that has a variable bed topography that results in significant spatial variety in sediment dynamics. This includes but is not limited to braided rivers and meandering rivers. Steep mountain rivers however, that result in supercritical flows or that contain e.g. step-pool sequences, are excluded as too many uncertainties arise when applying morphodynamic modelling in these settings.

Different Morphological Alterations The applicability of this research is not limited to flushing events. Also naturally increased sediment fluxes occur, e.g. as a result of flooding or land slides. Furthermore, anthropogenic land use changes as deforestation can by increased sediment loads result in deterioration of instream ecological integrity [41]. In the light of the Water Framework Directive which directs more attention towards these effects, having methods to evaluate possible measures is considered useful.

6.5. Integrated Water Resource Management

This research aimed at the effects of a flushing event at a specific reach, downstream of the dam. The river is part of a larger system and the recommendations given, need to be considered in this larger system.

Catchment Hydrology Chapter 4 considers different scenarios and discussed the feasibility within the hydrology of the catchment. This shows that possibly, tributaries are of higher influence on the downstream reach than the operation of the dam. This level of control differs for every dam and must be considered during the design phase of the dam, when designing for the peak flow operation.

Multi functional dams Within the thesis, it is assumed that a rainfall runoff peak that originates from the reservoir's catchment, can be imposed on the downstream reach. This requires that the reservoir fills up completely before the peak arrives in order to lead the increased discharge over the spillway. However possible, other dam functions (e.g. flood protection) could be jeopardized which should therefore be considered.

Stakeholder Involvement This research is aimed at improving the habitat conditions after a flushing event. It is shown that the operation of the dam has an influence on the effects. As further research is planned, it is recommended to involve the dam operators to have a clear insight in the extent of control that can be taken. This involvement will bring them in a position where they are more willing to implement operation scenarios that result in less impact.

A second group that should be involved, are the fishermen. This is the group that is most vocal about the impact of the flushing event. Their expertise, originating from years and years spent at the river side, can be of valuable input to the development of adequate models that address the real impacts.

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From Basin to Local Scale

Spatial patterns in sediment transport, erosion and deposition can be observed at several spatial scales. These patterns at various scales influence each other, and the considered meso-scale is affected by the larger and smaller scale. It can be said that the larger scale patterns define the geometry of the meso-scale, while smaller-scale patterns could cause 'disturbances' in this geometry. Figure A.1 names several processes that happen at the basin (macro) scale, reach (meso) scale and local (micro) scale.

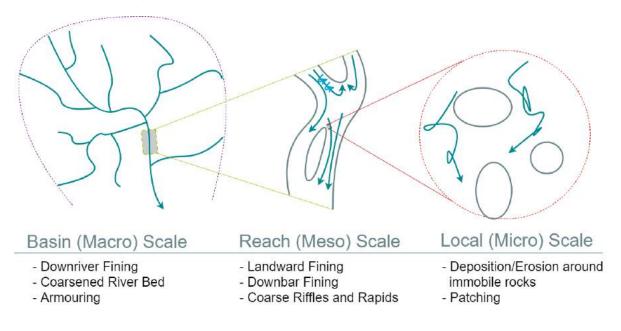


Figure A.1: The processes result in spatial variety of morphological characteristics which occur at different scales, but all have their influence on reach scale.

A.O.1. Basin (Macro) Scale

In general, rivers are the steepest in at the sources in the mountains, and ease of towards the sea. This goes hand in hand with a reduction in flow velocities which results in a gradually decreasing transport capacity for large fractions. Only the finer sediments are transported further down resulting in a fining of the river bed downstream. This is enhanced due to breaking of the particles due to collision.

When looking at spatial patterns on the macro scale, which would be the full length of a river and therefore covering the whole basin, a large variety in river bed substrate can be observed. Starting in the mountain streams, the further down you go, the finer the substrate gets. A main factor is the declining slope, decreasing the transport capacity of the river which causes larger sediments to drop sooner. Only the smaller sediment

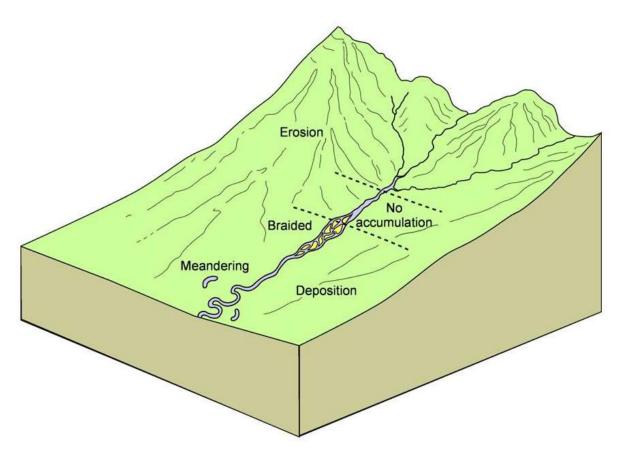


Figure A.2: The sedimentation and erosion processes can be evaluated on the macro-scale [41]

reaches further downstream. This declining slope in combination with decreasing sediment size, causes different processes to occur, resulting in different spatial patterns over the river length. Figure A.2 gives a good idea of these differences, showing that erosion takes place up in the mountains, the river then gets a braided character and further downstream meandering patterns could occur.

Coarsened River Bed When flows become supply limited, all the fines erode and Only course enough sediments stay in position or move only slightly, resulting in a coarsened river bed. This is often the case after the construction of dams as sediments are trapped in the reservoir. The Pezzé dam on the Avisio is just an example.

Armouring A process that is more difficult to describe by the formulae and the earlier described basics, is armouring. In principle, the fine sediments flush away sooner than the coarse sediments, but here the top coarse layer functions as a blanket, protecting the lower lying fine sediments.

A.O.2. Reach (Meso) Scale

On reach scale, the following patterns can be expected.

Landward Fining Due to higher flow velocities in the middle of the river, these channel beds become more coarse than the near bank river beds, as smaller particles can be moved in the channels but will be deposited near the banks.

Downbar Fining Adding to landward fining, downbar fining can be expected due to higher flow velocities at the upstream end of a bar, and lower flow velocities at the downstream end. This pattern is enhanced by the secondary flow process, which directs the near bed flow towards the bars and transports the smallest particles the furthest.

Coarse Riffles and Rapids The flow over riffles and in rapids is generally faster than in glides or pools due to the steep river bed. These riffles and rapids are therefore the coarsest parts of the river.

A.O.3. Local (Micro) Scale

Also some micro scale processes can result in sediment patterns which can be visible on the meso scale.

Sediment Patches Immobile rocks can influence the near bed flow and cause local sediment scours upstream of the rock (horse shoe) and sediment deposits downstream. If multiple immobile rocks are clustered together, this can result in fine sediment patches and could become the start of a new bar.

Sensitivity Analysis

This chapter contains further clarifications to the modelling choices explained in chapter 2.3. First, the sensitivity analysis is presented that forms the base of the parametrisation described in section 2.3.5.

The following sections describe the sensitivity to the bed slope effect, the choice of roughness coefficient, the threshold for drying and flooding and the different sediment sizes. It finalises with some main conclusions.

B.0.4. Bed Slope Effect

When the river bed has a slope, sediments will move down the slope easier than they would on a flat surface. Looking at a single particle, this is explained by the concept that the pivoting point is lower, making it easier for a particle to tumble over and therefore move down the slope [30]. Equation 2.9 shows the way that Delft3D accounts for this bed slope effect. A_{Sh} is considered the most sensitive parameter that is normally calibrated in combination with the ESPIR keyword, which accounts for secondary flow. Here, three values of A_{Sh} are compared. The value of 1.3 is chosen based on equation 2.11 with D_{50} of 1 mm and h_0 of 0.6 which is roughly the average depth when a flow of 20 m^3/s runs through the initial bathymetry. The value of 1 is the value used for creating the initial bathymetry. The value of 0.7 is based on equation 2.11 with D_{50} of 0.1 mm instead.

Volume of sediment in figure B.2.

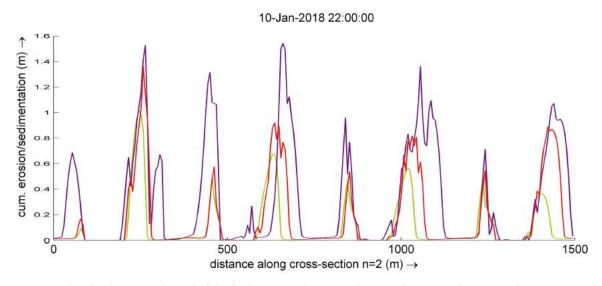
Takeaways Figure shows the accumulated sediment at the end of the flushing as well as 20 days after the flushing. REF ($A_Sh=1$) is shown in red, A1P3 ($A_Sh=1.3$) in purple and A0P7 ($A_Sh=0.7$) in green. It is clear that the higher the parameter, the higher and the larger the sediment patches. The patterns are generally the same, but some disturbances seem to occur for $A_Sh=1.3$ after the flushing event. Probably this can be solved by halving the timestep. The preference is given to the most extreme effect so the scenario runs will be performed with $A_Sh=1.3$, using half the times step.

B.0.5. Roughness Coefficient

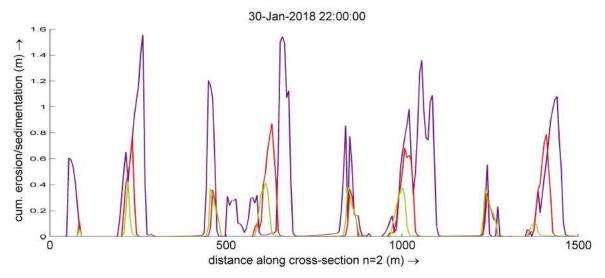
To get an idea of the potential difference, first two runs are performed with Chezy values that belong to the deepest part of the river and to the shallowest part of the river respectively. Let's say, 10 cm and 1 meter. If the Chezy value of 25 is considered to belong to a depth of 1 meter, Manning's coefficient would be 0.04. Calculating Chezy again for this Manning's coefficient, but with a depth of 10 cm, gives a Chezy coefficient of 17. So with this value the run is performed again and will show the difference.

$$C = -\frac{1}{n}R^{1/6} \tag{B.1}$$

where n is Manning's coefficient and R is the hydraulic radius which is roughly the same as the depth. Keeping Manning constant at 0.04, C will become 17 for a water depth of 0.1 meter. 0.04 is also from literature a realistic number, as it hangs between the value for normal channels, less than 30 meters wide with some weeds and stones (0.035) and the value of mountain streams, cobbles and boulders (0.05)[49].



(a) Accumulated sediment at the end of the flushing period. REF ($A_Sh=1$) is shown in red, A1P3 ($A_Sh=1.3$) in purple and A0P7 ($A_Sh=0.7$) in green.



(b) Accumulated sediment 20 days after the flushing event.

Figure B.1: REF ($A_{Sh}=1$) is shown in red, A1P3 ($A_{Sh}=1.3$) in purple and A0P7 ($A_{Sh}=0.7$) in green.

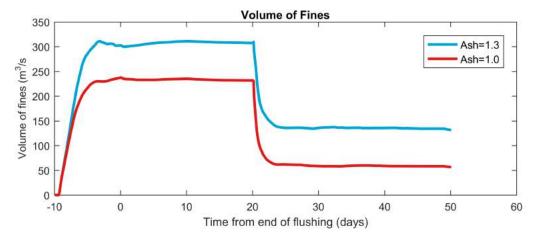


Figure B.2: The deposited fines at the end of the flushing, one and three days after the flushing and after the clean water peak.

The transport capacity (and with that, the deposition and erosion) depends on the flow velocity, sediment size and roughness coefficient. In many studies, the roughness coefficient is a calibration coefficient based on the flow velocity and the discharge. It is therefore taken as a constant which is sufficient for reach averaged calculations like sediment budgets or celerities. When however looking at the spatial distributions, this approach might be over simplified. Instead of using Chezy as a constant roughness coefficient, Manning can be used which is dependent on the depth. Chezy's coefficient relates to Manning's coefficient as follows:

$$C = \frac{1}{n}R^{1/6} \tag{B.2}$$

in which n is Manning's coefficient and R is the hydraulic radius, which is close to the water depth. The shallower the flow, the rougher the bed. Three runs are performed to research the effect of different roughness coefficients. The reference run (REF) in which Chezy is 25, one run uses in which the Manning's coefficient is applied with a value of 0.04, increasing the roughness for shallower area's (MN) and one run in which the overall roughness is increased by applying a Chezy value of 17 (CH17).

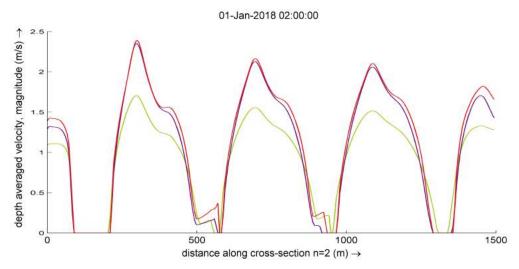
Takeaways The results are partly as expected. Before sediment computations, the velocity profiles look similar for REF and MN, while the overall increased roughness in CH17 clearly decreases the overall flow velocities which increases the water level making that the water reaches further and therefore velocities are higher on the bars in comparison. Comparing REF to MN, it can be seen that velocities are slightly lower in the shallower areas, though the difference does not seem significant (see figure B.3a).

The difference between REF and MN are neither big when looking at the first 4 hours of morphological change with fine sediment inflow (figure B.3b) although it can be seen that MN has the lowest deposition rate. The reason is that even though velocities are slightly lower in the shallower area's, the transport capacity is higher because of higher roughness. That CH17 has an overall higher deposition is explained by the lower velocities. The higher water level causes the fines to deposit higher up the bars.

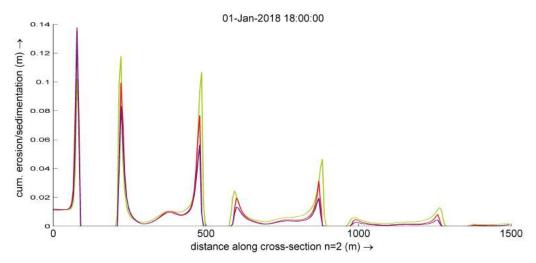
The biggest difference between REF and MN are found at the end of the flushing. Where the upstream side of the bars seems similar, on the downstream side of the bars, the accumulation seems to extend further.

Twenty days after the flushing, the results are again similar for REF and MN, which shows that the remaining fines are not so dependent on the choice of roughness coefficient. The difference with CH17 is bigger and mainly showing that sediments remain higher up the bars.

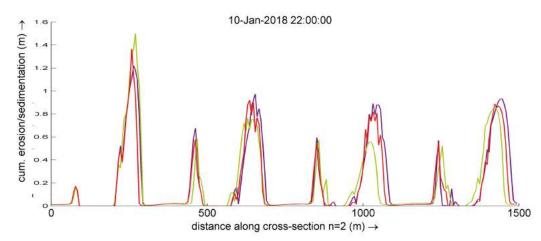
The differences between REF and MN are relatively small, showing that no problems arise due to using Manning's coefficient. As this is a more realistic approach, this will be applied in the further models. This is justified by the general observation that gravel on the top of the bars is often coarser [35], making the roughness higher.



(a) The velocity profile along longitudinal cross section at Y = 6 meters before morphological change



(b) Accumulated sediment along longitudinal cross section at Y = 6 meters after 4 hours of morphological change



(c) Accumulated sediment along longitudinal cross section at Y = 6 meters at the end of the flushing event

Figure B.3: Sensitivity to the choice of roughness coefficient. Legend: Red: Chezy's coefficient of 25, Green: Chezy's coefficient of 17 and Purple: Manning's coefficient of 0.04

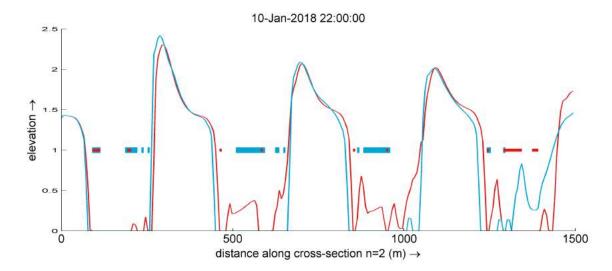


Figure B.4: When using a high threshold for flooding and drying (and sediment computations), cells fall dry relatively easily making the cells inactive for sediment calculations. The lines at y=1 indicate the dry cells at the end of the flushing. Red is for REF while blue is for TH10.

B.0.6. Threshold for Drying and Flooding

When sediment keeps accumulating, at some point the water depth becomes so small that barely any water reaches the place. Within Delft3D, the SedThr keyword sets a minimum water depth for sediment calculation, below which no sedimentation or erosion occurs. The DryFlc keyword sets a threshold for the water depth under which the cell is considered dry and becomes inactive. Two runs are performed to show investigate the effect of a higher threshold. Run REF has a threshold (for both keywords) of 1 cm, while run TH10 has a threshold of 10 cm.

Takeaways When applying a threshold of 10 centimetres, quite soon several cells fall dry. From this moment onwards, sedimentation and erosion calculations are only based on bank erosion processes that can be determined as a factor of the neighbouring cell erosion, in stead of physical processes included in the transport formulae. This is therefore in principal unfavourable. Figure B.4 shows the effect in reduced velocities for TH10 (in blue) with the inactive cells shown on the line y=1. As no problems occur when choosing a lower threshold, this is preferred over the larger threshold and will therefore be used in subsequent runs.

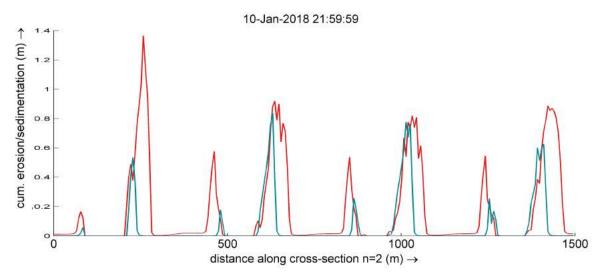
B.0.7. Different Sediment Sizes

As the flushing involves different sediment fractions, the influence of the choice of sediment size is explored. In run REF, sand with a sediment diameter of 1 millimeter is considered, while in run D0P1, a diameter of 0.1 millimeter is considered. The influx is kept the same.

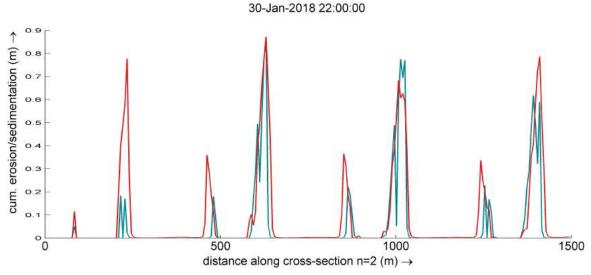
Takeaways Figure B.5a shows clearly that for coarser sediment, the patches become bigger. The easiest explanation is the difference in transport capacity with different velocities. As seen before, $S_0 \sim D_{50}^{-1}$ and the velocity dependent transport capacity for both sediment sizes is shown in figure B.6. The horizontal line indicates the transport capacity that is put in at the upstream boundary. The figure clearly shows that for a smaller sediment size, the flow is still able to carry this amount of sediment with lower velocities.

Considering that both sediment fractions are represented in the same category of MesoHABSIM modelling and that the coarser sediments of 1 millimeter have the largest effect due to highest deposition, it was chosen to focus on this size. The effect of smaller sizes will be smaller as well.

Note: when computing the transport of the fines sediment, a smaller time steps needs to be taken. This gives another reason to work with the slightly coarser sediments.



(a) The accumulated sediment at the end of the flushing event. The deposition of different sediment sizes follows the same pattern but clearly the larger sediment size creates larger patches.



(b) Also 20 days after the flushing event, the coarser sediment is present like larger patches, though less explicit.

Figure B.5: Sensitivity to the size of the sediment fraction: REF is shown in red while D0P1 is shown in blue.

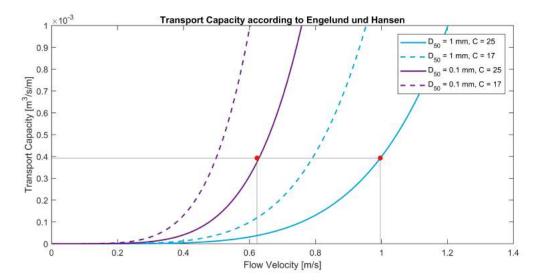


Figure B.6: The transport capacity as calculated by Engelund und Hansen for Chezy=25 and the different sediment fractions.

B.0.8. Main Conclusions

The main conclusions can be summarized as follows:

- The threshold describing the minimum water depth for sediment computation, as well as the depth at which cells are considered as dry (inactive) cells, is set at 1 cm. No problems occur with this relatively low threshold.
- The roughness coefficient described by Manning will be used in the computations, as it accounts for variability in roughness depending on the water depth. Differences are apparent but small with using a constant Chezy value. However using Manning gives a more realistic approximation, the deposition of fines might have an inverse effect, as it smooths the shallow area's instead of making them rougher.
- The smaller the sediment size, the smaller the amount of deposition. The tested sediment sizes belong to the same size category in MesoHABSIM. Therefore the D50 will be 1 mm, which will have the largest effect on the habitats within this category. In this way, the most extreme case is investigated.

MesoHABSIM Procedure

This appendix describes MesoHABSIM procedure, and the way it defines suitability from the measurements performed.

During a MesoHABSIM field survey, the reach is divided into Hydromorphological Units as defined in table C.1 and the outlines are mapped using a pocket PC running on ArcPAD software in order to get georef-erenced GIS polygons. This division is done visually and is therefore based on expert judgements. Observed characteristics that aid in this definition are smoothness of the water surface, changes in slope, water depth and flow velocities.

HMU	Description of characteristics					
Riffle	Shallow stream reaches with moderate current velocity, some surface turbulence and higher gradient Convex streambed shape					
Rapid	Higher gradient reaches with faster current velocity, coarser substrate, and more surface turbulence. Convex streambed shape					
Cascade	Stepped rapids with small waterfalls and very small pools behind boulders					
Glide	Moderately shallow stream channels with laminar flow, lacking pronounced turbulence. Flat streambed shape					
Ruffle	Dewatered rapids in transition to either run or riffle					
Run	Monotone stream channels with well-determined thalweg. Streambed is longitudinally flat and laterally concave					
Fast run	Uniform fast-flowing stream channels					
Pool	Deep water impounded by a channel blockage or partial channel obstruction. Slow. Concave streambed shape					
Plunge pool	Main flow passes over a complete channel obstruction and drops vertically to scour the streambed					
Backwater	Slack areas along channel margins, caused by eddies behind obstructions					
Side arm	Channels around islands, smaller than half river width, frequently at different elevation than main channel					

Figure C.1: Defenition of Hydromorphological Units (HMU's) from Parasiewicz (2007)

Subsequently, the different physical attributes from table C.2 are determined in three categories for each HMU: absent, present or abundant. The depth as well as the mean column velocity are measured at seven or more locations within each HMU. The locations for these measurements are chosen by the expert with the aim to represent the share of area that has similar characteristics and at the same time, include the variety that is observed within the HMU. From these measurements, the Froude Number is calculated. At all these locations, the choriotop is determined. It relates to the substrate and is therefore of importance in this thesis. It is divided according to the Austrian Standard ON6232 as described in table C.3. The aim is to determine the mean sediment size at the location (D_{50}), which is sometimes difficult as a combination of several fractions are present. It is up to the expert to include this variety by choosing the measuring locations well.

All information is collected in a database which is then evaluated using a biological computer model.

Attribute (value)	Categories			
Hydromorphologic units (yes/no)	(See Table II)			
Cover sources (no/some/much)	Undercut bank, woody debris, overhanging vegetation,			
	submerged vegetation, boulder, riprap, canopy cover shading, shallow margin			
Choriotop (% of random samples)	Pelal, psammal, akal, microlithal, mesolithal, macrolithal, megalithal,			
	phytal, xylal, sapropel, detritus (for exact definitions see Austrian			
	Standard ON6232)			
Depth (% of random samples)	6 classes in 25 cm increments (range 0–125 cm and above)			
Mean column velocity	8 classes in 15 cm s ⁻¹ increments (range 0–105 cm s ⁻¹ and above)			
(% of random samples)				
Froude number	Average			

Figure~C.2:~Physical~attributes~used~to~establish~logistic~regression~with~fish~absence~and~presence~from~Parasiewicz~(2007)

Nomenclature	Grain size range	Choriotop description				
Megalithal	>40 cm	Upper sides of large cobbles and blocks, bedrock				
Macrolithal	>20–40 cm	Coarse blocks, head-sized cobbles, variable percentages of cobbles, gravel and sa				
Mesolithal	>6.3-20 cm	Fist to hand-sized cobbles with a variable percentage of gravel and sand				
Microlithal >2-6.3 cm		Coarse gravel, (size of a pigeon egg to child's fist) with percentages of medium to fine gravel				
Akal >2 mm-2 cm		Fine to medium-sized gravel				
Psammal 0.063–2 mm		Sand				
Pelal	< 0.063 mm	Silt, loam, clay and sludge				
Biotic choriotop						
Detritus		Deposits of particulate organic matter; distinguished are: CPOM				
		(coarse particulate organic matter),				
		as for example, fallen leaves and FPOM (fine particulate organic matter)				
Xylal		Tree trunks (dead wood), branches, roots, etc.				
Sapropel		Sludge				
Phytal		Submerged plants, floating stands or mats, lawns of bacteria or fungi,				
		tufts, often with aggregations of detritus, moss or algal mats				
		(interphytal: habitat within a vegetation stand, plant mats or clumps)				
Debris		Organic and inorganic matter deposited within the splash zone area by wave motion and changing water levels, for example, mussel shells, snail shells				

Figure C.3: Natural Choriotop types describing river bottom (modified from Austrian Standard O NORN 6232 by Parasiewicz (2007))

Creation of the Biological Model In order to create the biological model, data were collected to calculate a function that relates these physical attributes to the fish absence or presence. Mostly this is done by electrofishing according to a method developed by Bain et al. (1985). The fish in the specific HMU's are counted and their size is measured.

These fish data are used as dependent variables in combination with the environmental attributes that are used as independent variables in a regression model that looks like:

$$R = e^{-z} (C.1)$$

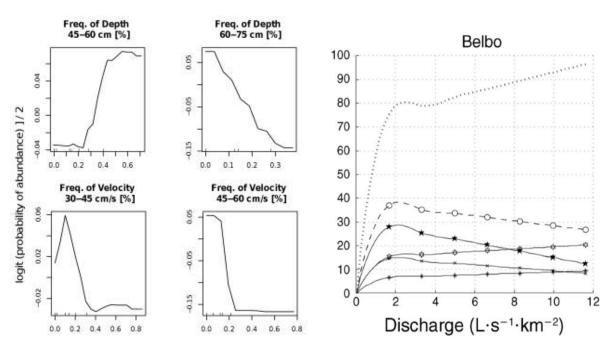
where $z = b_1 * x_1 + b_2 * x_2 + ... + b_n * x_n + a; x_{1...n}$ are significant physical variables; $b_{1...n}$ are regression coefficients and a is a constant. [31].

The probability of fish presence is then dependent as follows:

$$p = \frac{1}{1+R} \tag{C.2}$$

Currently the model is developed to make use of the random forest model. The basic idea is that multiple decision trees are created that divide a big database on a different characteristic at every node. An algorithm is then used that determines the best possible decision tree from this forest of trees. These fuzzy based rules can be translated in partial dependency plots like the ones in figure C.4a that aid the interpretation and can be analysed to understand the sensitivity to different variables. Note that they are based on the frequency of occurance which is how the meso-scale is addressed. Some models will show that a unit is only suitable if it has a minimum frequency of low flow velocity, but also a minimum frequency of high velocities.

Repetative Mapping A useful visualisation of the results of MesoHABSIM is the plotting of the percentage of suitable area over the whole area, depending on the flow. This can be done after repetitive mapping and results in a graph like figure C.4b. Such information can be the basis for defining environmental flow regimes.



(a) Example of partial dependency plots that describe the sensitivity to different attributes, based on the frequency of occurance.

(b) Example of the suitability curve depending on the discharge for a specific species from Vezza et al. (2013) $\,$ 47

Figure C.4: Examples of results generated by the application of MesoHABSIM

MEM procedure

This appendix expands on the Mesohabitat evaluation (MEM) procedure and how it is applied within this thesis. The MEM Method combines depth, flow velocity and shear stress data in order to classify the results of a hydrodynamic model into ecologically meaningful units at the mesoscale.

D.0.9. General Procedure

The evaluation method is based on the simulation results of the two-dimensional depth-averaged model Hydro_AS-2d. The results of Delft3D can be used in a similar way. The depth as well as the velocity values are divided into 5 categories, rating 1-5. The velocity value (NC_v) increases with increasing velocity while the depth value (NC_d) decreases with increasing depth. The limits dividing the categories is normally calibrated based on field measurements.

Subsequently, shear stresses are categorized into three classes ranging from 0 to 0.2 m^2/s , 0.2 m^2/s to 20 m^2/s and above, rated with values of 0, 1 and 2 respectively (NC_s).

The three categorizations are combined to give an MH rating according to:

$$MH = (NC_v + NC_d) * NC_s$$
 (D.1)

From the MH values, 5 main habitats can be distinguished: Pool (MH: 2-4), run (MH: 5-9), fast run (MH: 10–18) and riffle (MH: 20). The remaining cells have a value of MH=0 and are further divided into deep, low flow area's (MH=1) called backwaters and shallow, low flow area's (MH=0) called shallow water habitats. These are the first two routing steps. The full procedure is illustrated in figure D.1.

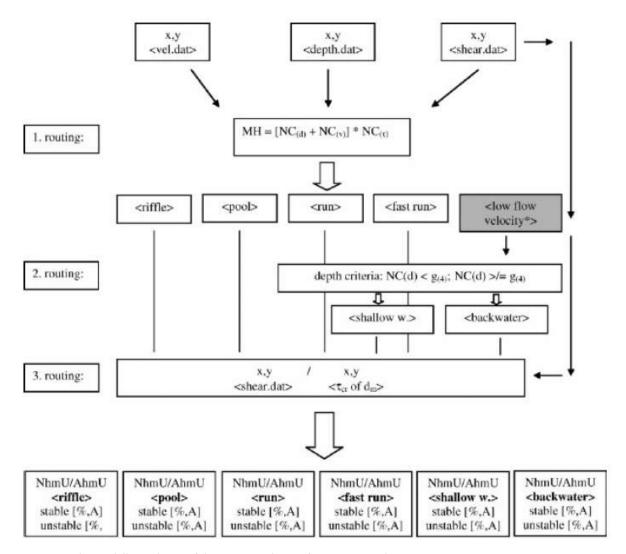


Figure D.1: The modelling scheme of the conceptual MEM from Hauer et al. (2008). $\,$ 18

D.0.10. Application of the MEM in this Thesis

The procedure is applied in this thesis in order to divide the idealized reach up into ecologically meaningful units on the mesoscale. Calibration is performed visually with the aim to distinguish the riffle-like habitats (shallow, but fast running) from the run-like habitats (deeper). This distinction should be clear in low flow (pre- and post flushing) as well as during the flushing flow. The calibration is performed before morphological change occurs due to flushing.

1st **Routing** According to the MH values derived from the MEM procedure, the only distinction made between a riffle and a run is when the depth is in the lowest class while the velocity is in the highest class. As a distinction within the range of the MEM runs is preferred, the MH values are slightly adapted as follows: Low Velocity (EH:0-1), Pool (2-5), Run (6-9), Fast Run (10-14) and Riffle (15-20). The ranges of calibrated velocities, depths and shear stresses are summarized in table D.1 and the resulting classification is shown in figure **??**. The model is classified according to this classification before the flushing event, which is shown in figure **??**.

Velocity Range	NC_v	Depth Range	-	Shear Stress Range	NC_d
0 - 0.3 m/s	1	0 - 0.2 m		$0 - 0.2 \ m^2/s$	0
0.3 - 0.6 m/s	2	0.2 - 0.4 m	4	$0.2 - 20 \ m^2/s$	1
0.6 - 0.9 m/s	3	0.4 - 0.6 m	3	$>20 m^2/s$	2
0.9 - 1.2 m/s	4	0.6 - 0.8 m	2		
>1.2 m/s	5	>0.8 m	1		

Table D.1: The ranges that categorize the velocities, depths and shear stresses into NC's.

 2^{nd} Routing The Low Velocity area's are not further divided as non of them are deeper than 0.5 m, making them all backwater habitats.

 $\mathbf{3}^{rd}$ **Routing** The third routing step was not applied in this thesis, but is very comparable to the step taken to check the mobilization of gravel. This was discussed in section 3.4.2.

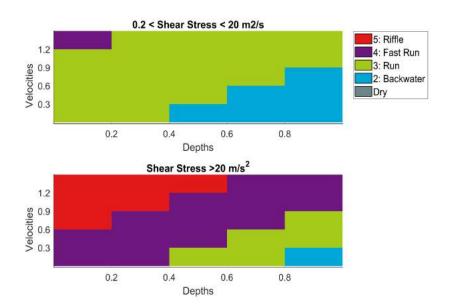


Figure D.2: The assigned classes based on the flow velocity and water depth in a cell. When cells have a depth smaller than 0.08 m, they are considered dry.

Scenarios

This appendix presents the boundary conditions imposed as the different scenarios. Consequently all results of the evaluation approach of chapter 3 are presented.

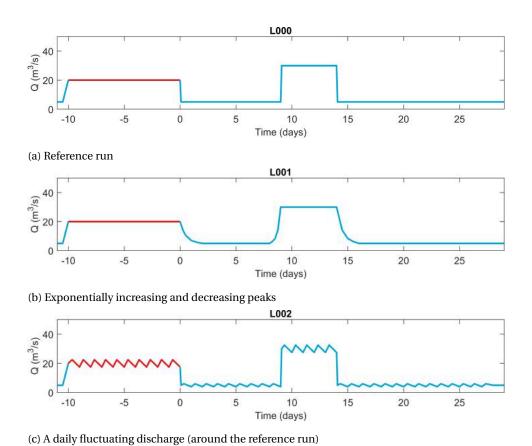


Figure E.1: The imposed discharges ran to investigate the sensitivity to more natural scenario's vs. abrupt changes and constant flows. The red line represents the time that fine sediments enter the system, the blue lines are clean flows.

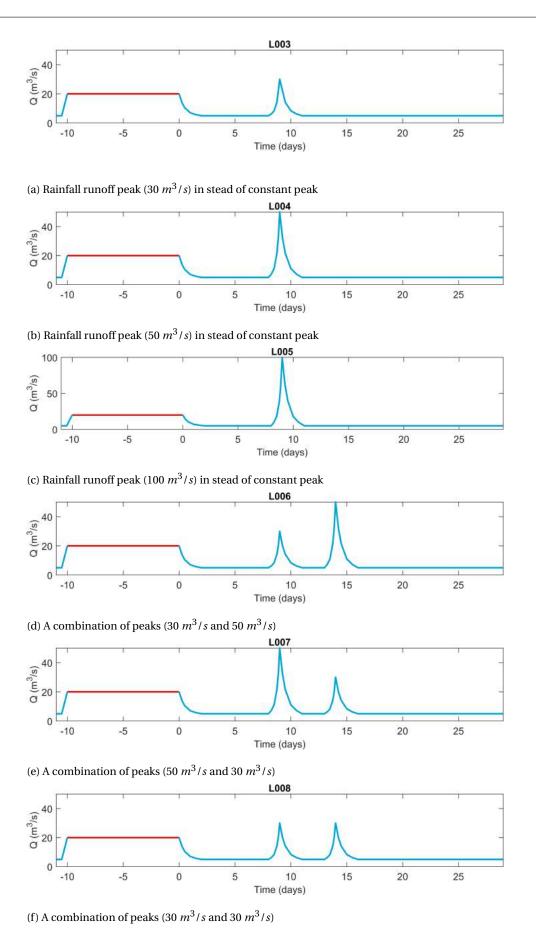


Figure E.2: The imposed discharges ran to investigate the sensitivity to more natural scenario's vs. abrupt changes and constant flows. The red line represents the time that fine sediments enter the system, the blue lines are clean flows.

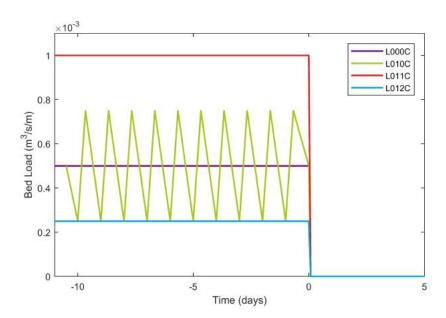


Figure E.3: Different sediment load scenarios

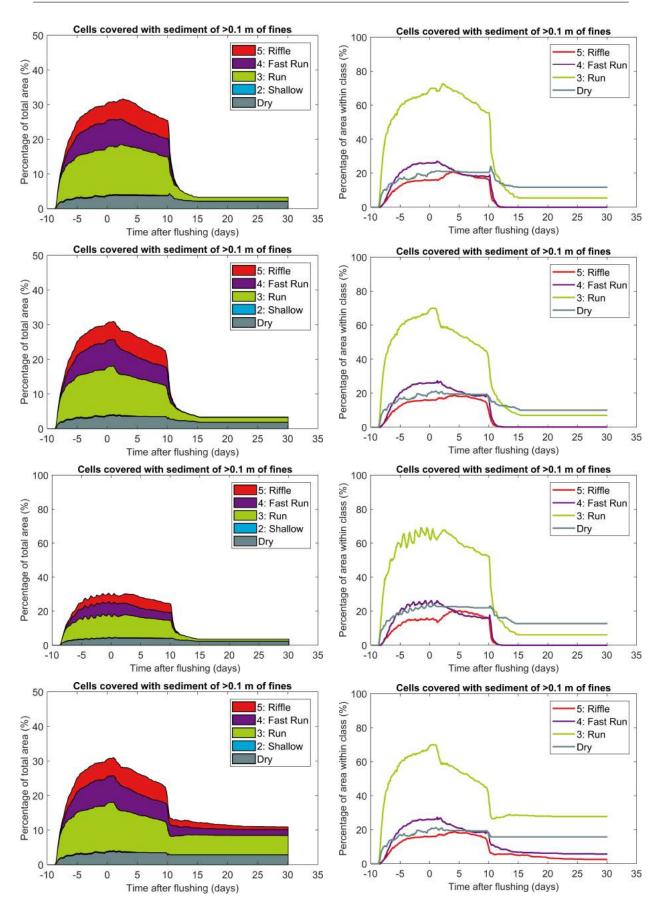


Figure E.4: The left images show percentage of cells covered with a layer of fines thicker than 0.1 meters, divided into the classes as classified according to the MEM procedure during flushing flow discharge. On the right side the percentage of covered area normalized per class. The top two images represent run L000, which is the reference run. Below that, the results of run L001 representing a more realistic increase and decrease of the flushing and peak discharges. Then the results of run L002, which represents a daily fluctuating discharge and the lowest images show the results of run L003, for which the clean water peak is induced by a rain event instead of a constant increased discharge.

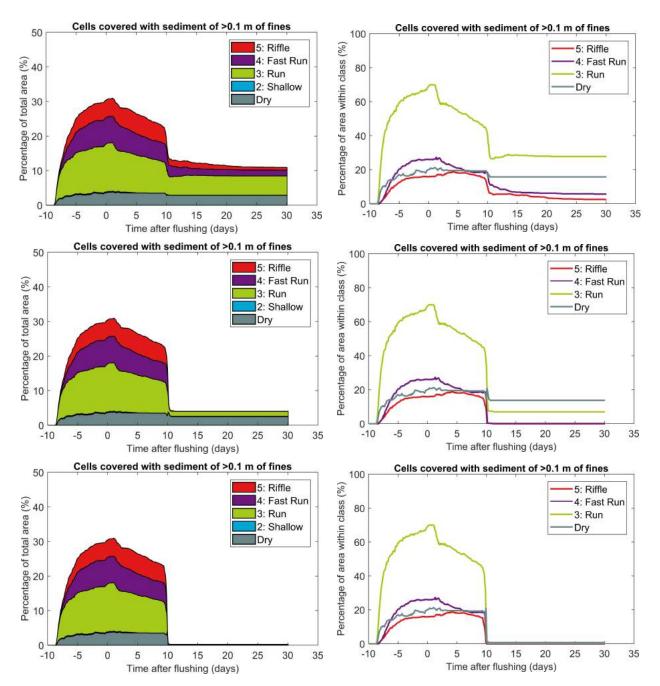


Figure E.5: The left images show percentage of cells covered with a layer of fines thicker than 0.1 meters, divided into the classes as classified according to the MEM procedure during flushing flow discharge. On the right side the percentage of covered area normalized per class. The top two images represent run L003, containing a clean water peak of 30 m^3/s . Below that, the results of run L004 containing a peak of 50 m^3/s . Then the results of run L005, with a peak of 100 m^3/s .

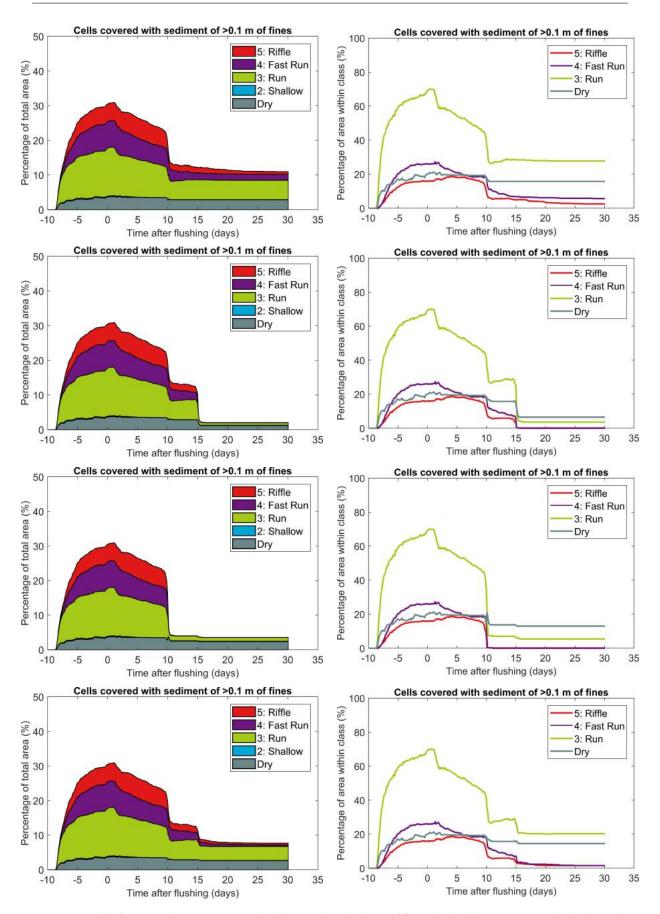


Figure E.6: The left images show percentage of cells covered with a layer of fines thicker than 0.1 meters, divided into the classes as classified according to the MEM procedure during flushing flow discharge. On the right side the percentage of covered area normalized per class. The top two images represent run L003, containing a clean water peak of $30 \ m^3/s$. Below that, the results of run L006 containing a peak of $30 \ m^3/s$ followed by a peak of $50 \ m^3/s$. Then the results of run L007, with a peak of $50 \ m^3/s$ followed by a peak of $30 \ m^3/s$ and the lowest images show the results of run L008 with two peaks of $30 \ m^3/s$.

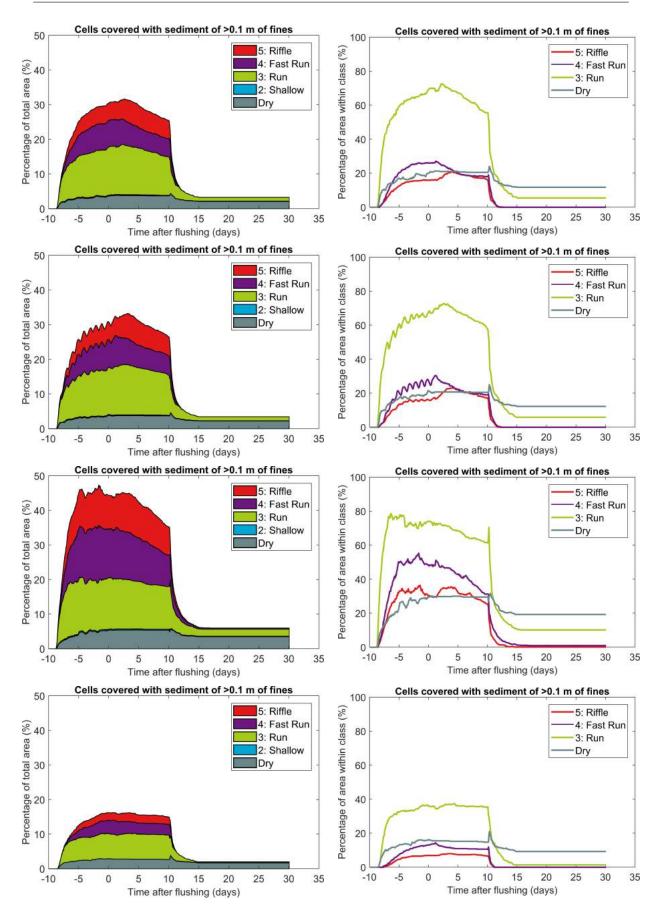


Figure E.7: The left images show percentage of cells covered with a layer of fines thicker than 0.1 meters, divided into the classes as classified according to the MEM procedure during flushing flow discharge. On the right side the percentage of covered area normalized per class. The top two images represent run L000, which is the reference run. Below that, the results of run L010 representing a fluctuating sediment load. Then the results of run L011, which imposes double the sediment load as compared to the reference run and the lowest images show the results of run L012 with half the sediment load as compared to the reference run.

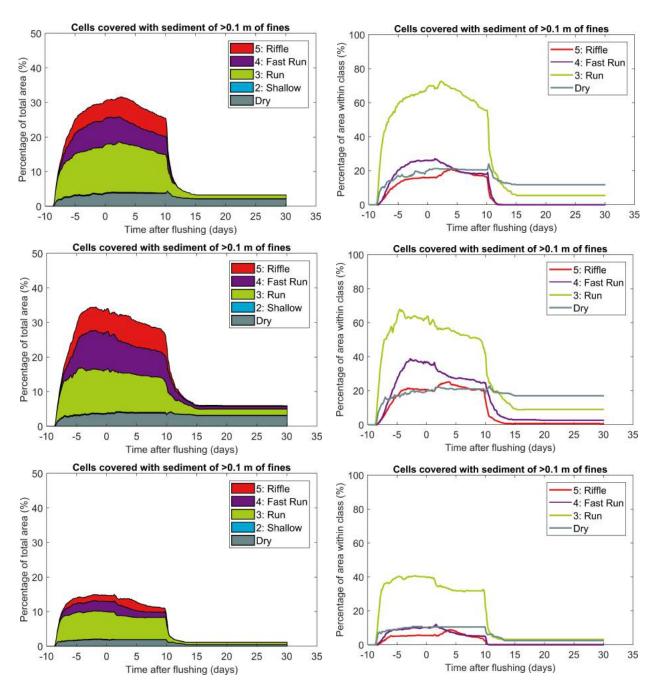


Figure E.8: The left images show percentage of cells covered with a layer of fines thicker than 0.1 meters, divided into the classes as classified according to the MEM procedure during flushing flow discharge. On the right side the percentage of covered area normalized per class. The top two images represent run L000, the reference run. Below that, the results of run N001 with a bed slope parameter $A_S h$ of 1.3. Then the results of run N002, with a bed slope parameter $A_S h$ of 0.7.