UNIVERSITY OF TWENTE.

Impact of Benthic Species on River Morphology

MSc. Project

Impact of Benthic Species on River Morphology

Author

Felipe Alberto Elizondo García

Supervisors

Ir. B.W. Borsje
Dr. D. Augustijn
Dr. R. Leuven

Civil Engineering & Management
Water Engineering & Management

PREFACE

This master thesis comprehends the final stage of my master education in Water Engineering and Management at the University of Twente, The Netherlands. The project addresses the impact that benthic species have on sediment dynamics and thus river morphology. Hereby I would like to equally thank all the people who helped me during this long process.

Education

I thank Dr. Denie Augustijn for his helpful suggestions, feedback and interest in my research, also for the given opportunity to return and finish my master education in this institution. I would like to thank my daily supervisor Ir. Bas Borsje for answering my (literally) daily questions and for helping me getting acquainted with the Delft 3D program. In addition, I thank Dr. Rob Leuven of the Radboud University Nijmegen for the information regarding the current habitat conditions of the benthic species in the River Waal and Dr. Rolien van der Mark of Deltares for providing the Delft 3D model for this study and for her valuable help to understand how does the Delft 3D model works in river systems.

Family and Friends

I thank Dr. Estela María del Rosario García Sandoval (mom) for providing motivation throughout the year and for funding this long-term project. I also would like to thank Miguel Alfredo, Sandra Elizabeth, Rubén, Liz, Beto, Ruben Felipe, Ana Laura, Betito, Diego, Cheli for their interest in my education and career. Additionally, I am very grateful to Sharon, Tyler and Chantz and the rest of the Hebert Family for teaching me English, which opened me an international door. And Finally, I would like to thank all my friends regardless their nationality.

Felipe Albert Elizondo García

Enschede, August 2011

There are six academic disciplines in the world: Humanities, social science, natural science, formal science and applied science. The engineering discipline can be divided among more than 20 other branches; one of these is civil engineering. I define civil engineering as the discipline that deals with the design, construction, management and maintenance of infrastructure that allows societies to fully develop. Within civil engineering there are several sub-disciplines, some are: construction engineering, environmental engineering, structural engineering, transport engineering and water engineering…of this last one, I know a bit.

Felipe Elizondo 2011

ABSTRACT

The invasion of benthic exotic species in aquatic systems has increased in the last couple of decades due to the increase of human activities in waterways (e.g. ballast water transport, attachment to boat hulls). Many studies have been done on the interaction between benthic organisms, sediment dynamics and thus morphology of aquatic systems. Nevertheless, these studies have been mainly conducted in marine and estuarine systems, involving different sediment and hydrodynamic conditions. Until now no studies are known on the impact benthic species on river morphology.

The main objective of this Master Thesis is to investigate, by using the Delft 3D model, the influence of benthic species on sediment dynamics, and the possible changes on river bed morphology due to the presence of benthic species. Delft 3D is a numerical modelling system developed by Delft Hydraulics, fully applicable for 3-dimensional computations of hydrodynamics and morphodynamic simulations of coastal, river and estuarine areas. The study considers three exotic bivalve species in the River Waal: the *Corbicula fluminea, Dreissena polymorpha* and the *Dreissena bugensis*, where through the alteration of the erosion threshold, the *C. fluminea* living in the groyne field are the only species exerting a direct impact on sediment. Literature shows that the effect of the benthic activity on sediment dynamics may result in an increase/decrease of the erosion threshold, merely depending on two mechanisms: the bioturbation caused by benthic communities and the formation of biofilms (EPS) that “sticks” the sediment together.

In order to model the possible benthic effects, three scenarios were investigated: One scenario subjected to sediment biostabilization (high erosion threshold), another one to biodestabilization (low erosion threshold) and finally a scenario that accounts for the anticipated maximum possible biostabilization in rivers. When using the transport formulation developed by Van Rijn (84), the erosion threshold is proportional to the median grain size D_{50}, and therefore, in this study this value is locally increased/decreased inside the groyne fields in order to introduce the benthic effects into the Delft 3D model. The results show that under steady hydrodynamic conditions, the benthic effects do not exert significant changes in morphology. Contrary to this, the impact of changing hydrodynamic conditions and navigation are expected to alter the sediment processes within the groyne fields and therefore the benthic impact. These were not quantitatively considered in this study, however, are highly recommended for future research due to the importance of groyne fields for the sediment exchange in a river.

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1 INTRODUCTION

1.1 Problem Definition

The invasion of exotic species in aquatic systems has increased in the last couple of decades due to the connection of previously separated water systems, intensive shipping across international water and international trade. Freshwater ecosystems have been affected by human activities leading to a decline of native species together with a replacement by non-native species (Sousa et al. 2008), causing economic and environmental concerns. Benthic species cause economic damage through clogging of water pipes of industries and power plants, loading of boat hulls causing an increase in transportation costs, and fouling on other firm surfaces leading to extra costs for their removal (MacIsaac 1996). Furthermore, they may cause major ecological problems by elimination or decrease of native species (Thorp et al. 1998).

Dutch rivers and canals play an important role in the Dutch economy. Currently 33 % of the goods arriving at the Port of Rotterdam are transported via inland shipping, the goal is to increase this percentage to 45 % (Dierikx 2011). For this reasons, the Dutch rivers have been modified, creating a friendly environment for non-native species like Asian clams *(Corbicula fluminea)*, Zebra mussel *(Dreissena polymorpha)* and Quagga mussels *(Dreissena bugensis)*. In addition to the economic and ecologic impact, benthic species can stabilize or destabilize sediment depending on their habitat preferences and life style. Biostabilization can result from the removal of particles from the water column, afterwards being excreted in the form of extracellular polymeric substances (EPS) and increasing sediment cohesiveness (Vaughn and Hakenkamp 2001; Paarlberg et al. 2005) or by physical coverage of the river bed (Widdows et al. 2002). On the other hand, biodestabilization is caused by the movement of bivalves searching for food, which increases mixing (bioturbation) and porosity, and thus facilitate sediment motion.

Many studies have been done on the interaction between benthic organisms and morphodynamic processes (Van de Koppel et al. 2001; Widdows and Brinsley 2002; Paarlberg et al. 2005). The studies yield similar results, showing a dependency between the biological and sediment processes. However, these studies have been conducted in marine and estuarine systems, naturally involving different sediment conditions (e.g. cohesive), hydrodynamic conditions (e.g. waves and tides) and benthic species (e.g. *Mytilus edulis* and *Macoma balthica*), no studies are known on the impact of benthic species on river morphology.

Due to the constant human intervention in the Dutch rivers and canals, it is likely that the population of non-native species will increase in the near future. Up to now, there is a lack of research on the interaction between benthic species and river processes, and even though one can expect the benthic activity to modify the morphologic processes as in marine and estuarine systems, a study must be performed in order to confirm this hypothesis and magnitude of this impact. The investigation of these biological processes will serve as a first inventory of the effect of benthic organisms on sediment and hydraulic processes in order to increase the accuracy of future river models and thus enhance the economic and ecological assessment of the river system.

1.2 Research Objective and Research Questions

The main objective of this Master Thesis is the following: *Investigate, by using a Delft 3D model, the influence of benthic species on water and sediment dynamics, and the possible changes on river bed morphology due to the presence of benthic species.* Based on this objective, the following research questions are formulated:

1. How do benthic organisms influence sediment dynamics in river system?
2. How can the biological processes be parameterized in order to include them in Delft 3D?
3. What is the impact of the Asian clams, Zebra mussels and Quagga mussels on bed load and suspended sediment transport, bed roughness, flow velocity, water level and erosion/deposition?
4. To which biological parameters are the physical processes more sensitive?

1.3 Methodology

The representation of a river branch will be made with the aid of the computer program Delft 3D provided by Deltares. Delft 3D is a 3-dimensional computer program developed to perform simulations of diverse aquatic systems. The model should have characteristics of Dutch rivers and should include all the relevant data for the objective, such as: bathymetry data, flow velocity, bed roughness and grain size among others. Moreover, the incorporation of groynes is crucial for the study because they provide suitable locations for benthic accumulation. In Delft 3D is not possible to incorporate the benthic species directly, therefore, the user must find a way to represent the benthic activity of the species in equations already incorporated in Delft 3D. In this study the impact of benthic species was parameterized according to field and laboratory experiments of different researches for similar benthic species to the ones considered in this study (Widdows and Brinsley 2002; Neumeier et al. 2006) and was included in Delft 3D by manually modifying the erosion threshold on the areas with biota.

The proposed scenarios will have a temporal scale of 13 years, due to the sudden changes that the hydrodynamic boundaries generate on sediment dynamics during the first time steps. This temporal scale is necessary for the prediction of reliable results as the temporal scales between processes differ from each other (Van de Koppel et al. 2001; Morales et al. 2006), see table 1-1. Biological and hydrodynamic processes change on a daily basis, e.g. higher discharge due to rain or the difference in discharge summer-winter. This is not the case for morphological process which has larger time scale ranges e.g. from days in case of dunes (Paarlberg et al. 2007) and even decades in case of river meandering.

Table 1-1 Different scales on river morphology.

PROCESS	TEMPORAL SCALE
Biological process	Small time scale with seasonal variations
Hydrodynamic process	seasonal variations
Geomorphologic processes	Large time scales

1.4 Study Area

The Rhine River originates in Graubünden in the eastern Swiss Alps and flows through Germany, until it reaches the North Sea coast in the Netherlands. The Rhine extends for over 1,200 km and connects large cities through its course, which makes it one of the most important waterways in Europe (see Figure 1.1 A). Consisting of rainfall and snowmelt, the average discharge of the river at the Dutch-German border is 2,300 m^3 s^{-1}, with an average peak discharge of 7,000 m^3 s^{-1} every 4 years (Julien et al. 2002). Nevertheless, the river has experienced higher discharges, such as the ones in 1993 and 1995, when the discharge went up to 11,000 and 12,000 m^3 s^{-1}, respectively.

In the Netherlands, the Rhine River follows a straight pattern, with an average sinuosity of 1.1 (Julien et al. 2002). At river kilometer 867.2, the bifurcation point, better known as the Pannerdensche Kop, divides the Rhine River into two branches: (1) the Pannerdensche Kanaal, which flows to the north and (2) the Waal, which flows to the west (see Figure 1.1 B). This second branch (Figure 1.1 C) is the study area for this research and consists of a river reach of 23.8 kilometers, which extends from the Pannerdensch Kop (867.2 km) until the outskirts of the city of Nijmegen (891 km). The Waal's average depth is 5 meters (Ten Brinke et al. 2004), the average discharge is approximately 2/3 of the Rhine's discharge (≈1500 m^3 s^{-1}) (Julien et al. 2002) and has an average suspended sediment concentration of 30 mg l^{-1}, with values up to 120-180 mg l^{-1} for high discharges (Asselman 1999). Furthermore, the river gradient between the Pannerdensche Kop and Nijmegen is 1.1 x 10^{-4}, and the median grain size D_{50} is 2.5 mm (Julien et al. 2002).

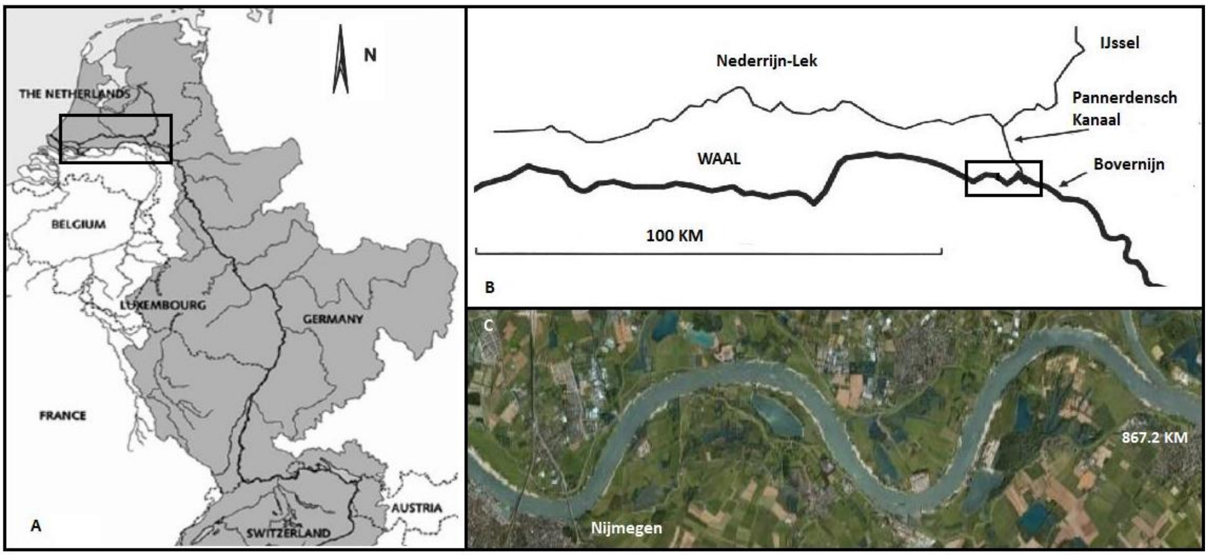


Figure 1.1 Study Area: A) Rhine River catchment area, B) River Waal, C) Study area.

1.5 Outline

In this master thesis, the 2nd Chapter is a description of the biological considered in this study, in addition to their effect on sediment dynamics. Chapter 3 is a summary of the equations used in Delft 3D to model the hydrodynamic and morphodynamic processes. In Chapter 4, the quantitative estimation of the impact of benthic organism on sediment processes takes place, as well as the parameterization of these processes into formulations recognized by Delft 3D. Chapter 5 describes the abiotic and biotic scenario set-up, including the bathymetry and boundary conditions and Chapter 6 displays the result of the study. Chapter 7 discuss the procedure and assumptions within the project and finally Chapter 8 answers the research questions and gives recommendations for future research.

2 BENTHIC INTERACTION WITH RIVER SYSTEMS

2.1 Introduction

The Asian clam, Zebra mussel and Quagga mussel, are known for their ability to invade and spread rapidly throughout new aquatic systems. These species have successfully established in different aquatic systems throughout North America and Eurasia. Records of these invasive species include the Mississippi, Hudson and Ohio River (Mellina and Rasmussen 1994) in North American, and the Rhine and Thames River in Europe (Elliott and Ermgassen 2008). The introduction and subsequent dispersion is the result of the increase of human activities in waterways such as: ballast water transport, utilization of specimens as fish baits, and juvenile attachment to boat hulls; among others (Sousa et al. 2008). These non-indigenous invasive species have been recorded in the Dutch rivers and due to their preference for the conditions of the Waal they have become dominant in this river system, which may alter the abiotic sediment processes of the river.

The burrowing and feeding activities of these benthic species are able to alter the transport processes in the river bed by altering sediment erodability, increasing deposition and changing bed roughness (Le Hir et al. 2007). In order to predict the impact of these species on river morphology, one must understand how these species interact with their environment. Therefore, the chapter first gives an insight of the habitat conditions, morphology, life style characteristics and behavior of the three species involved in this study. Finally, section 2.3 summarizes the benthic effects on morphodynamics and the prone location for high benthic accumulation.

2.2 Characteristics of Selected Bivalves Species

2.2.1 Asian clam *(Corbicula fluminea)*

The Asian clam, *Corbicula fluminea,* is recognized as one of the most important non-indigenous invasive species in fresh water aquatic ecosystems (Sousa et al. 2008), particularly in sandy and muddy bed substrates that have been modified by human activities such as dredging and sedimentation, or alteration of the flow regime by dams or bifurcations. Apart from this, human disturbances have resulted in a decline of native mussels, leaving an open habitat for Asian clams to colonize (Cooper 2007).

Figure 2.1 Asian clam (Wyoming game and fish department 2002). http://gf.state.wy.us/fish/AAC/Mollusks/Exotics/AsianClams/index.asp.

Life cycle

The Asian clam has a life span of 1 to 5 years, with a reproductive mode considered both hermaphroditic (species with reproductive organs normally associated with both male and female sexes) and dioecious, although studies performed in the Rhine River demonstrate that the species in this river are mainly dioecious (Sousa et al. 2008). The spawning season lasts about 6 weeks (USGS 2001) and afterwards the larvae are released into the water and buried in the substratum.

By the time the Asian clam reaches its juvenile age (Figure 2.2 c), it will already have grown to an average size of 250 microns. Furthermore it will have developed a shell, adductor muscles, food and a digestive system (Sousa et al. 2008). In general, these juveniles can be re-suspended by turbulent flow and easily transported downstream, either through the water column or attached to boats. The maturation stage takes place between the 3rd and 6th month (Figure 2.2 d, 2.2 a), with shells developing up to 40 mm in size. Asian clams reproduce twice a year; however, evidence suggest that the reproduction period could in fact take place up to 3 times a year, depending on the water temperature (Hornbach 1992) and food availability in the ecosystem. Like other bivalves species, *C. fluminea* has a high fecundity ($\approx 10^5$), counteracted by high mortality when adult.

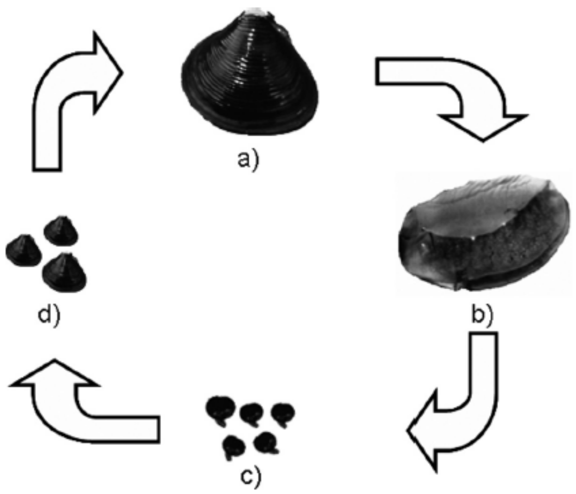


Figure 2.2 Illustrative representation of the life cycle of *C. fluminea*: a) Adult specimen; b) inner demibrach with larvae; c) small juveniles recently released and d) small adults. (Sousa et al. 2008)

Habitat conditions

Asian clam densities and biomasses vary dramatically depending upon diverse environmental factors such as flow speed, food availability, water quality, temperature, salinity etcetera. Diverse authors argue that the Asian Clam densities vary among water systems (Karatayev et al. 2005), with higher densities found in rivers and small streams, where they can reach values of 3000 Ind m^{-2} (Hornbach 1992; Karatayev et al. 2005; Sousa et al. 2008). Asian clams are usually found in mean annual biomasses in the order of hundreds (e.g. 160.00 gDW m^{-2} (Sousa et al. 2008) and 115.00 gDW m^{-2} (Cooper 2007)).

The species is tolerant to salinities between 10-17 %, have an upper temperature limit of 36 -37 ^{o}C and a lower limit of 2 ^{o}C (Werner and Rothhaupt 2008). The Asian clams are infaunal bivalves (Mackie 1991), which means that they live on soft substrate in the river bed, preferably in mixed sediments of sand, silt and clay. In addition, its pedal feeding activity requires them to live buried in the substratum.

Life style

The species is catalogued both as filtrate and pedal feeder, indicating that it not only causes changes in the sediment balance of the invaded ecosystem through its filtration rate from 0.018 (Cohen et al. 1984) to 1.0 l ind^{-1} hr^{-1} (Elliott and Ermgassen 2008), but it also alters the abiotic characteristics of the top sediment layer due to its crawling and pedal feeding activities (Vaughn and Hakenkamp 2001).

Filtering from the water column is the main process subjected to the survivorship of *C. fluminea.* Filtration by bivalves can lead to a decrease of nutrients and sediments in the water column. When this species occur in high densities, their high filtration rate has been found to filter the daily stream discharge (Vaughn and Hakenkamp 2001). The filtration rate depends upon factors such as temperature, filtration increases for warmer temperatures due to metabolic changes, or particle concentration. *C. fluminea* is able to adjust its filtration rate in order to reach an optimal rate of particle concentration. In addition, the species is able to change its orientation with respect to the flowing water in order to save energy utilized to pump water; this suggests that filtration rate is also influenced by flow velocity (Vaughn and Hakenkamp 2001).

Figure 2.3 depicts the potential impacts on ecosystems by burrowing bivalves. Pedal feeding is a form of deposit feeding which uses a foot to collect buried nutrients from the substrate. Typically, only one third to half of the shell is buried into the substratum as the rest is used for basic needs as respiration and feeding (Mackie 1991). Biodeposition is defined as the excretion of feces and pseudofeces onto the sediment, which changes sediment properties. Burrowing bivalves bioturbate the sediment as they crawl through the bed searching for food. Deposit feeding activity increases sediment mixing and facilitates erosion. Finally, the physical presence of colonies on the river bed may locally protect the sediment from erosion. Spaces between shells may provide refugee and food, as well as stabilize fine-grained sediment, therefore increasing habitat suitability (Vaughn and Hakenkamp 2001).

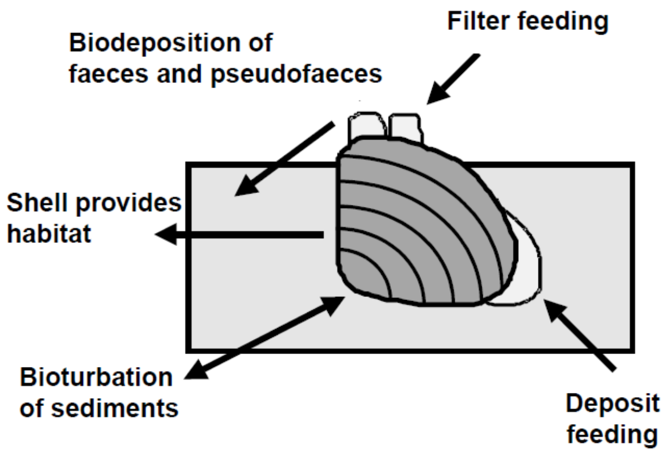


Figure 2.3 Potential impact on ecosystems performed by burrowing bivalves in water systems. (Vaughn and Hakenkamp 2001)

2.2.2 Zebra mussel *(Dreissena polymorpha)*

Zebra mussel is a small freshwater bivalve native of the Ponto-Caspian region. The species are catalogued as ecosystem engineer due to the strong influence on physical modification of habitats and the effects on other species and ecosystem processes (Jones and Lawton 1994). The *Dreissena polymorpha* has successfully established throughout Eurasia and its presence in North America includes the whole Mississippi River and Great Lakes (Stepien et al. 2002).

Life cycle

With a high die-off after the second year, the Zebra mussel has a maximum life expectancy of 5 years (Mackie 1991). The species are dioecious and similar to the Asian clam, they have two reproduction periods throughout the year, in which females can deposit up to 40,000 eggs per year during their third and fourth year. Typically, these organisms are sexually mature after reaching 8 to 10 mm in length (Mackie 1991), which means that they can reproduce during the first year of life.

The larval stage of the Zebra mussel takes about 4 weeks to complete (Mackie and Schloesser 1996). This period is divided into 3 stages: *the veliger stage, the post-veliger stage* and *the settling stage,* Figure 2.4 displays the life cycle of the Asian Clam. All these stages occur in the planktonic state, and they end once the young mussel has attached itself to any kind of surface; at this point the mussel enters the benthic state and starts its adult life. Once an adult, the Zebra mussels grow at a rate up to 0.5 mm d^{-1}, reaching shell sizes of up to 15 mm in the first year and 30 mm after the second year. Schöl et al. (2002) found a mean shell length of 15 mm for the Rhine, suggesting that the population is mostly consisting of juveniles.

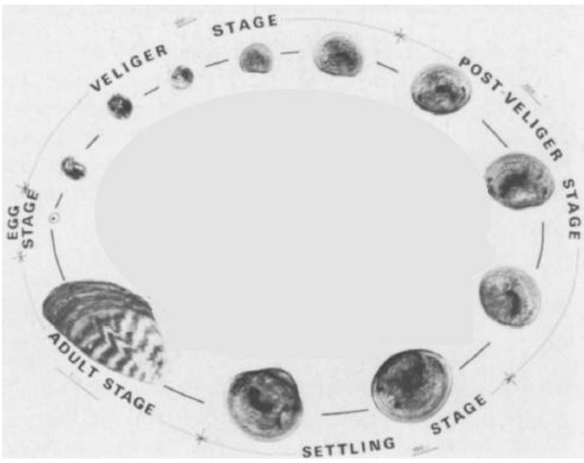


Figure 2.4 Life cycle of the D. polymorpha bivalve (Mackie 1991)

Zebra mussels travel along the water body during their larval stage. As veligers, the larvals are subject to the flow velocity, where velocities higher than 1 m s^{-1} will prevent veligers from travelling in the upstream direction (Mackie 1991). As adults, the mobility of the mussels is based on byssal and/or mucous threads. This transport is facilitated by a long thread that increases viscous drag, thus making it difficult for the weak current to drag Zebra mussels throughout their adult stage (Beukema and Devlas 1989).

Habitat conditions

The density of Zebra mussels, as well as other bivalves, is highly depending on the characteristics of the water system. The population is proportional of the availability of solid substrates, which in the Netherlands is high due the existence of structures (e.g. groynes) for flood protection and navigation purposes (Van der Velde et al. 1994). In 2002, Schöl et al., estimated the mean density in the Rhine to be 575 Ind m^{-2}, with a biomass of 4.2 gDW m^{-2}, which agrees with Caraco et al. (1997), who found densities of 590 Ind m^{-2} and a biomass of 5.3 gDW m^{-2} in the Hudson River. However, higher densities have been found in others aquatic systems and industrial installations: for instance, 3150 Ind m^{-2} in reservoirs (Karatayev et al. 2005) and up to 70,000 Ind m^{-2} at a power plant in Michigan (Benson and Raikow 2010).

Zebra Mussels are epifaunal, which means that, in spite of Mackie (1991), who states that this species are able to live in clumps in mud, they do in fact permanently live on solid surface such as: rocks, groynes, breakwalls, dams, ships, floating, sunken logs or larger living invertebrates. Moreover, in the absence of hard substrates, shells of unionid clams (e.g. Asian clam) are ideal substrates for zebra mussels and are often used as a starting point for mussel colonization (Mellina and Rasmussen 1994). This suggests that they will probably become the dominant bivalve in water systems (Mackie 1991). However, Karatayev et al. (2005) mention that, in rivers, Zebra Mussel's densities are reduced by the disturbance caused by periodic flooding, which are common in the Netherlands. Possibly the greatest impact of the Zebra mussels on invaded aquatic systems is associated with mussel biofouling, which is enhanced by its perfectly adapted morphology to live on hard substrates and submerged structures (Mackie 1991). The intensity of the biofouling depends on the substrate type and flow velocity. In general, materials used to construct dams, retaining walls and pipelines (e.g. concrete, iron and PVC) are suitable substrates for high densities of Zebra Mussels. However, flow velocities exceeding 1.5 m s^{-1} decrease mussel settlement on hard substrates (MacIssac 1996).

Life style

The Zebra mussel is a filter feeder bivalve. Similar to other benthic species, the filtration rate of the zebra mussels depends on various environmental factors such as: temperature and flow velocity. Filtration rate is maximal at temperatures between 5 and 20°C, with an optimal at 12.5°C (MacIssac 1996), declining fast at both higher or lower temperatures. The filtration rate ranges from 0.18 to 0.32 l Ind^{-1} h^{-1}. At velocities of 0.1 m s^{-1} clearance rates are highest, and at higher velocities than 0.2 m s^{-1} clearance rates are reduced (Ackerman 1999).

The particles selected for ingestion are based on size and consist mainly of suspended clays, silts, and large phytoplankton cells which are entrained in the inhalant current, sorted on the labial palps, enveloped in mucus and excreted as feces and pseudofeces. This process can improve water quality and decrease turbidity. High concentrations of suspended particles tend to decrease the filtration rate exponentially. The species will maintain a maximal and constant filtration rate below incipient limiting level (2 µg C ml^{-1}), but will decrease as soon as this level is reached (MacIsaac 1996). Figure 2.5 shows the potential impact of Zebra mussels on freshwater aquatic systems.

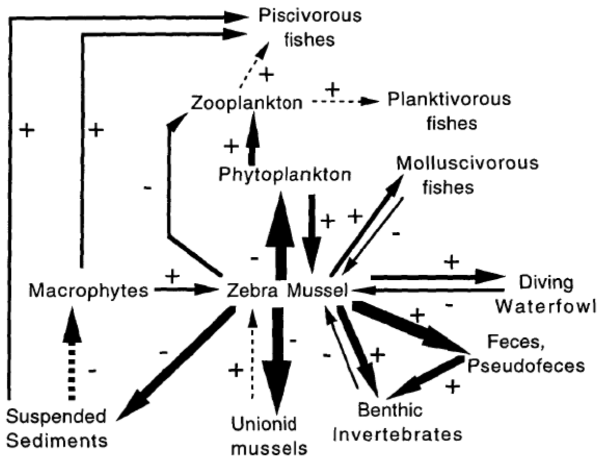


Figure 2.5 Schematic of observed (solid line) and potential (dotted line) impacts of the Zebra Mussel on freshwater communities. Taxa benefiting from Zebra Mussel invasion are indicated with a + symbol, and those affected adversely by a – symbol. Strong interactions are denoted by thicker arrows. (MacIsaac 1996)

2.2.3 Quagga mussel (*Dreissena bugensis*)

The Quagga mussel is an invader species which originated from the River Volga. The species has invaded the Great Lakes in the United States and has reached the Rhine-Meuse estuary in the Netherlands (Van der Velde et al. 1994). Due to its similar life style, spawning and diet as the Zebra mussel *(Dreissena polymorpha)*, the Quagga mussel is often compared with this species in literature. The principal differences between the Zebra and the Quagga mussel are: the filtration rate of 0.12 to 0.40 l Ind^{-1} h^{-1} (Ackerman 1999), the larger length of their shell (40 mm) (see Figure 2.6), the preferable type of substrate and their tolerance to certain environmental conditions (e.g. salinity and temperature).

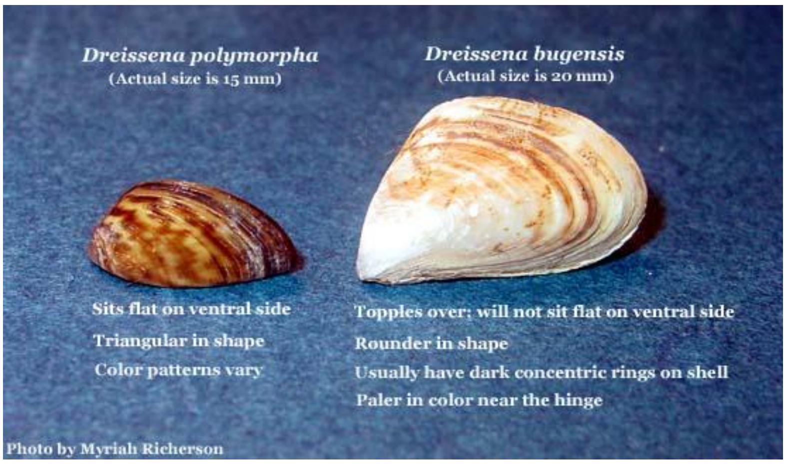


Figure 2.6 Comparison between Zebra and Quagga mussels (photo by Myriah Richerson. U.S. Geological Survey) (http://nas.er.usgs.gov/taxgroup/mollusks/zebramussel/zebra_gallery.aspx)

Habitat conditions

Although Quagga mussels live like Zebra mussels on solid substrates, this species has also been found to live in clumps and individually in mud (Mackie and Schloesser 1996). In 1996, Mills and Schloesser conducted an investigation on the Dnieper-bug estuary, where they found a high population of *Dreissenas* (Zebra and Quagga) in sands and silty sands. The results showed that Quagga mussels can occupy deeper (40 m) and colder water than Zebra mussels, suggesting that the species can survive in softer substratum (sand and sandy silt), in presence of less oxygen and in lower food conditions (Van Der Velde 2007).

The tolerance range of *Dreisennas* to salinity varies depending on the water system and continent. For the inland seas, in Euroasia, this level ranges from 2 to 12 ppt, but only 0.5 ppt in estuaries on the Dutch coast (Mills et al. 1996). Nevertheless, evidence suggests that the salinity tolerance of Quagga mussels is lower than that of the Zebra Mussel. Since salinity depends on the run-off, this means that at periods of large run-offs when salinity decreases, Quagga mussels will increase in abundance, provided that the flow velocity is low enough not to detach the Quagga Mussel from the substrate.

Density and biomass of bivalve species depend upon the characteristics of the water system. However, research has demonstrated that as a consequence of the competitive advantages of the Quagga mussels, it is likely that this species will overtake the territory occupied by the Zebra mussel, leading to a reduction in the population of the Zebra mussel. In the 1960s and the 1970s, the Quagga mussel almost entirely displaced the population of Zebra mussels at Zaporozh'ye (reservoir on the Dnieper River) (Mills et al. 1996). In the hydropower plant at the Dnieper River, the fouling population of *D. bugensis* with respect to the total *Dreissenas* was 7 % in 1964, 15 % in 1966, and 98 % by 1973. Records suggest that the Quagga mussel will increase in population over the Zebra mussel. However, the extent to which the Quagga mussel has spread over the Dutch rivers is still unknown.

2.3 Interaction between Benthic Species and Morphodynamics

The interaction between benthos and sediment dynamics has been well documented and plays an important role on morphological processes of marine systems (Van de Koppel et al. 2001; Paarlberg et al. 2005; Le Hir et al. 2007). Research demonstrates that despite sediment transport is primarily ruled by hydrodynamic forces, the biological components localized within the area can locally influence morphodynamics (Le Hir et al. 2007). The aim of this section is to provide an insight in the processes exerted by the benthic species on hydrodynamics and sediment transport.

According to a literature review, the activity of benthic organisms may change the river processes in several ways (Figure 2.7), some are: the feeding activity, which decreases the suspended sediment concentration (MacIsaac 1996); the creation of biofilms, that changes the characteristics of the upper sediment layer; And the presence of benthic beds, which increases bottom friction and may alter flow direction and velocity (Le Hir et al. 2007; Van Leeuwen et al. 2010). Apart from that, each species can have a different impact on sediment stabilization or destabilization. For instance, benthic beds may be formed by a mixture of several organisms, leading to infinite options of modifications of the river bed, making it very difficult to account for in a morphodynamic model.

In this section the stabilization-destabilization concept is introduced, which is commonly used in biological engineering literature (Paarlberg et al. 2005). The next section explains how benthos chooses their location in the river bed, which is an important factor for modelling. And finally, the effects on sediment fluxes are described in the sub-sections of biodeposition and erosion.

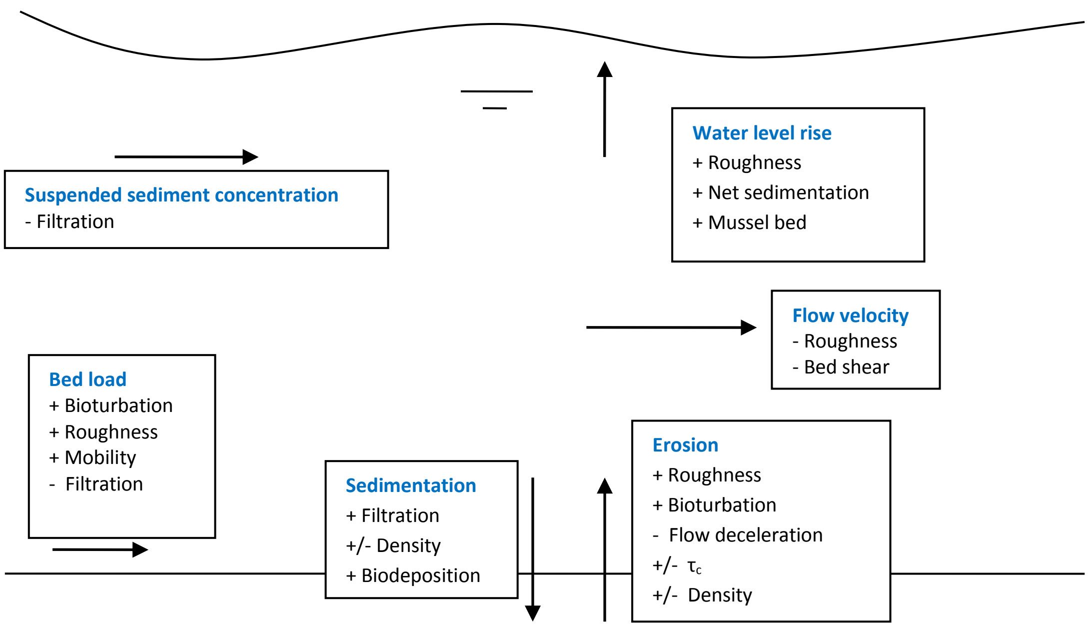


Figure 2.7 Impact of biological species on river processes. +/- indicates an increase/decrease in the given process.

2.3.1 Biostabilization and biodestabilization concept

In literature, the interaction between benthos and morphology is commonly described in terms of biostabilization and biodestabilization. In general biostabilization is related to sediment stabilization due to an increase of grain cohesiveness and critical bed shear stress. Whereas, biodestabilization is used when biological species decrease the critical bed shear stress due to their constant activity on the river bed.

Biostabilization and biodestabilization influence two sediment transport parameters: the critical bed shear stress and the erosion coefficient. Changes in these two parameters result in a different bed level and bed composition (Paarlberg et al. 2005). Bed shear stress is proportional to the mean squared velocity and benthic species strongly impact the flow by extracting momentum from the fluid via hydrodynamic drag, causing a reduction in the current velocity and hence bed shear stress. In contrast, an increase in bottom roughness is produced by the physical characteristics of the species which generates turbulence around their shells and clumps (Miyawaki et al. 2008).

Benthic species can stabilize or destabilize sediment depending on their life style (Paarlberg et al. 2005). Destabilization is caused by benthos through deposit/pedal feeding (e.g. Asian Clam) which increases mixing due to bioturbation, defined as "all processes implying sediment particle displacements generated by benthic organisms in order to satisfy their vital needs"(Le Hir et al. 2007). Bioturbation can change the strength of the top sediment layer by increasing porosity, leading to sediment destabilization. Moreover, the excretion of pseudofeces into the water column by deposit feeders contributes to resuspension of material (Graf and Rosenberg 1997). Pseudofaeces are "fluffy" and mainly composed of fine material, which enhance resuspension (Jones and Lawton 1994; Le Hir et al. 2007).

On the other hand, the excretion of filter feeder bivalves tends to increase sediment cohesiveness. Considering the fact that the Asian Clam is both deposit and filter feeder and taking into account the filtering activities of Zebra and Quagga mussel, it is expected that, in the Dutch rivers, the biological interaction rather than contribute to destabilization, will exert a stabilizing effect on the sediment layer, which would result in a net sedimentation and thus water level elevation.

2.3.2 Biodeposition and filtration rate

Biodeposition is defined as the deposition of the excreted material by the benthic population in form of extracellular polymeric substances (EPS) (Paarlberg et al. 2005). The related species for this study are catalogued as filter feeders, which feed by filtrating organic matter and sediment particles that afterwards are being excreted back into the system. This filtering process changes the particles properties (Le Hir et al. 2007) by enhancing flocculation and thus increasing settling velocity.

In Graf and Rosenberg's article (1997) about bioresuspension and biodeposition, it is stated that the settling velocity of the fluffy material excreted by benthos increases by a factor of > 100, which indicates that this material will be deposited closer to the source and hence reduce the net flux of material between the sediment and the water column. In addition, the closer biodeposition enhances the formation of colonies, as research has shown that molluscs will attach easily to substrates in present of biofilms (Van de Koppel et al. 2001). The following explains the properties of the biodeposited material by benthos.

Properties of biodeposition

The properties of these EPS, also called biofilms, differ depending on the filtration process they were subjected to and can be divided into two main groups: faecal pellets (faeces) and pseudofeces (Berg et al. 1996). Biodeposition enhances the material flux from the water column to the river bed, resulting in accumulation of particles that in natural conditions might be deposited elsewhere (Taghon et al. 1984). This section, explains the differences in properties (e.g. size, density) and production between the faecal pellets and pseudofaeces.

Pseudofeces are filtered particles that were not ingested by the benthos, generally as a result of exposure to high seston concentrations. Research by Berg et al. (1996) reveals that these particles are covered by a mucous layer and return, in bigger sizes, into the water column via the inhalant siphon. Despite the fact that these pseudofeces are clumps of finer particles and that the increase in size and density through aggregation increases their settling velocity, pseudofeces are easily broken down and might be transported as suspended material (Ten Brinke et al. 1995).

In principal, the mussel production of pseudofeces and faecal pellets depends on a threshold of seston concentration (Ten Brinke et al. 1995; Schneider et al. 1998). Below this threshold the sediment is turned into faecal pellets, and above this level, the filtered sediment is transformed into pseudofeces. Figure 2.8 shows a schematization of the biodeposition process of the Zebra mussels, which due to their similar characteristics, can be assumed to be in the same order of magnitude for the Asian clams and Quagga Mussels. This concentration threshold is usually low for mussels, which suggest that most of the filtered material is transformed into pseudofaeces rather than faecal pellets. In 1995, Ten Brinke et al. performed a study of the Oosterschelde tidal basin and suggested that for the marine mussel, *Mytilus edulis,* the threshold concentration is 5 mg l^{-1}, whereas Schneider et al. (1998) state that in the case of the Zebra mussel, this value is 3 mg l^{-1}. For the Oosterschelde tidal basin, the biodeposition resulted in a net sedimentation, in which only 20-30 % of the upper sediment was composed by faecal pellets, suggesting that the rest was transformed into pseudofeces and transported as a suspended load.

According to Berg et al. (1996), "faecal pellets are made up of non-digestible remnants of absorbed material and substances that have been passed unabsorbed through the gut". In contrast with the pseudofeces, these faecal pellets are ejected via exhalant siphon, and due to the digestive process, these particles have not only increased in size and density, but they are also strongly bound together as a result of a mucous layer, resulting in a material much more resistant to erosion (Ten Brinke et al. 1995)

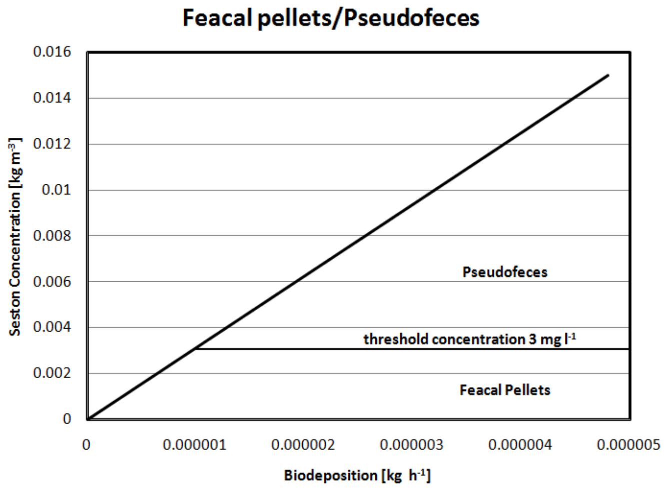


Figure 2.8 Schematization of the biodeposition process of the Zebra Mussels.

Size and density of the deposited sediment play an important role in determining the extent to which the flow velocity influences sediment transport. Up until now, there has been a lack of research on these parameters for the benthic species involved in this study. Jones and Lawton (1994) indicate that faecal pellets of deposit feeders can increase the sediment grain size from fine mud to fine sand, that is, from 16 µm to 250 µm. In addition, Taghon et al. (1984) found that the density of the faecal pellets, expelled by the tube-dwelling *A. scaphobranchiata,* is in average 1180 kg m^{-3}.

Filtration rate

The rate of biodeposition is proportional to the filtration rate, which in case of the Asian clam, Zebra and Quagga mussel ranges between 0.12 and 1.0 l Ind^{-1} hr^{-1} and can lead to large removal of phytoplankton and suspended sediment from the water column (Vaughn and Hakenkamp 2001). The filtration rate of each species depends on several variables such as flow conditions, temperature, sediment concentration and mussel size (MacIsaac 1996; Thorp et al. 1998; Ackerman 1999). Ackerman (1999) demonstrated that the filtration rate is strongly related to the shell size and formulated an empirical equation to calculate the filtration rate of mussels (equation 2.2 and 2.3). In general, the largest filtration rates are associated with the largest individuals of the Zebra and Quagga mussels. In addition, the study compares the filtration rate for mussels of 11 and 32 mm length (see figure 2.9), in which the differences between values indicate the susceptibility of filtration rate to other factor and conditions.

$$Fr = 6.82DW^{.88} \quad (2.2)$$

$$DW = 1.54\times10^{-5}\, SL^{2.42} \quad (2.3)$$

Where,

Fr= filtration rate, DW= dry weight, SL=shell size (mm)

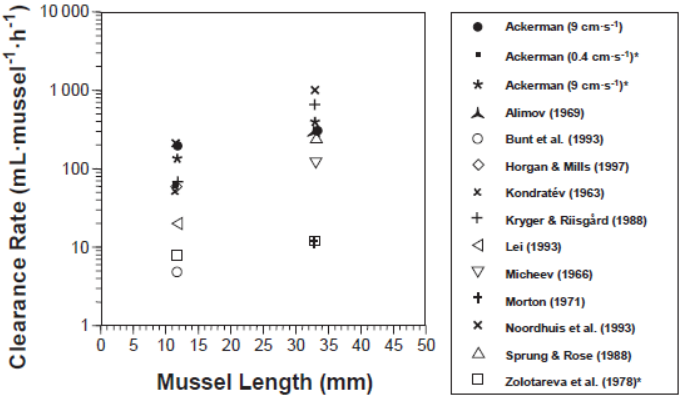


Figure 2.9 Comparison of clearance rates of different researchers for small (11 mm) Ackerman (1999)

The filtration rate of large mussels (32 mm) was approximately 1.5-3 times the rate of small mussels (11 mm). Ackerman (1999) concluded that the filtration rate of the Zebra and Quagga mussels is also dependent on flow velocity. For these species the flow velocity has a positive effect up to velocities of ~ 0.09 m s^{-1}, beyond this point, increasing the velocity causes a reduction of the filtration rate, leading to a lowest and constant filtration rate at velocities of ≈ 0.19 m s^{-1}. Furthermore, MacIsaac (1996) states that high concentrations of suspended particles tend to decrease the filtration rate of the Zebra mussels exponentially.

2.3.3 Erodability of benthic bed

Sediment erodability, which varies spatially and temporally, is the incapacity of sediments to stay in place when submitted to hydrodynamic forces (Le Hir et al. 2007), and is defined in terms of the erosion threshold and mass sediment eroded (Widdows and Brinsley 2002). Erodability is dependent on the interaction between hydrodynamic processes, sediment properties and biological activity, which can be divided into two main groups, bio-stabilizers and bio-destabilisers (Paarlberg et al. 2005).

As mention before, the production of EPS by benthos forms biofilms at the river bed. The properties of this material are known to cement the sediments and thus enhance sediment stability through an increase in the erosion threshold. Several authors have attempted to quantify the impact of EPS on the erosion threshold, however, until now there is no exact value that correctly determines the effect of EPS on the sediment erosion: Le Hir et al. (2007) states that the erosion threshold can increase by a factor of 5, Van de Koppel et al. (2001) found factors between 1.25 and 20, Grabowski et al. (2011) reveals an increase of one order of magnitude for mud in estuarine systems and an increase between 20 – 120% for marine systems, whereas De Brouwer et al. (2005) indicates, for an intertidal mudflat, an increasing factor of 10. The biofilm acts as a skin protecting the sediment, the larger the sediment size, the higher the amount of biomass needed to stabilize the sediment. In addition, once the biofilm layer is broken, sediment erodability is back governed by hydrodynamics forces (Le Hir et al. 2007).

Another important factor contributing to erosion is the covering percentage of a mussel bed. Figure 2.10 shows the dependency of erosion on current speed and mussel cover density. At 0 % the sediment is uniquely affected by the flow velocity and the mass eroded is the lowest. But, as soon as the coverage percentage increases, erosion takes place, reaching its highest at coverage percentages between 20 % and 35 %. Beyond this point, the sediment layer begins to be protected by the benthos and the erosion decreases, until at 100% coverage it reaches approximately the same values for 0 % coverage. This indicates that the covered percentage of bed plays an important role in the initiation of sediment motion, furthermore, Widdows et al. 2002 state that high densities of *Myilus edulis* can diminish the erodability of a sandy substrate.

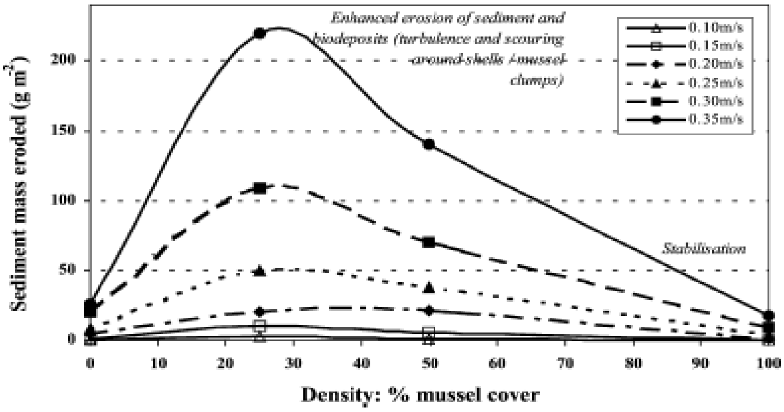


Figure 2.10 **Effect of Mytilus edulis density on erosion (Widdows et al. 2002)**

2.3.4 Distribution of bivalves in river systems

Not only benthic activity has an impact on hydrodynamics, but also hydraulic variables also play an important role in benthic behaviour and in their localization on the river bed (Morales et al. 2006; Miyawaki et al. 2008). Morales et al. (2006) reveal that conditions with lower bed shear stresses are more suitable for benthic activities. This conclusion agrees with Widdows et al. (2002) and Allen and Vaughn (2011) who argue that flow velocity has a direct impact on mussel feeding and bed stability and that mussels are able to organize themselves in order to acclimate to flow conditions.

During the first stage of their life cycle the Asian Clam, Zebra Mussel, and Quagga Mussel will travel through the water column until they have reached conditions that allow them to be deposited in the river and start their benthic stage (Mackie 1991; Sousa et al. 2008). The settling velocity of an individual can be modelled by the Van Rijn (1993) equation for suspended particles: Morales et al. (2006) reported a settling velocity of ≈ 0.0003 m s^{-1}. This result indicates that the settlement of these species will take a long time and that they are unlikely to be deposited in locations where particles sizes ≥ 0.25 mm are being transported in suspension. This also suggests that the settlement of organisms will take place on locations with lower flow velocities and hence lower bed shear stresses

Morales et al. (2006) found a successful method to identify the possible areas for mussel colonization. The method is based on substrate stability and a non-dimension parameter, the bed shear stress ratio (RSS), expressed as:

$$RSS = \tau_0/\tau_c \tag{2.1}$$

Where τ_0 is the bed shear stress caused by the flow velocity, and τ_c is the critical bed shear stress necessary to onset sediment motion. RSS > 1 destabilize the substrate and creates erosion. The hypothesis is that high mussel densities would be found in RSS < 1, however, mussels can tolerate RSS as high as 2 (Allen and Vaughn 2010), due to possible resistance of mussels to higher flow velocities.

Morales et al. (2006) used a 3-dimensional hydrodynamic model of a navigation pool in the Mississippi River, developed by the Iowa Institute of Hydraulic Research. The results were compared with observations of mussel colonies in 1981 and showed good agreement (Figure 2.11). This indicates that benthic species would occupy locations with lower flow velocities such as the edge of the river or islands. Moreover, the lifestyle of the colonies located in these places will benefit in several ways. For instance, lower flow velocities prevent detachment of mussels, increases filtration rate (Ackerman 1999; Vaughn and Hakenkamp 2001; Widdows et al. 2002) and increases biodeposition (Ten Brinke et al. 1995), which creates a suitable environment for benthic organisms.

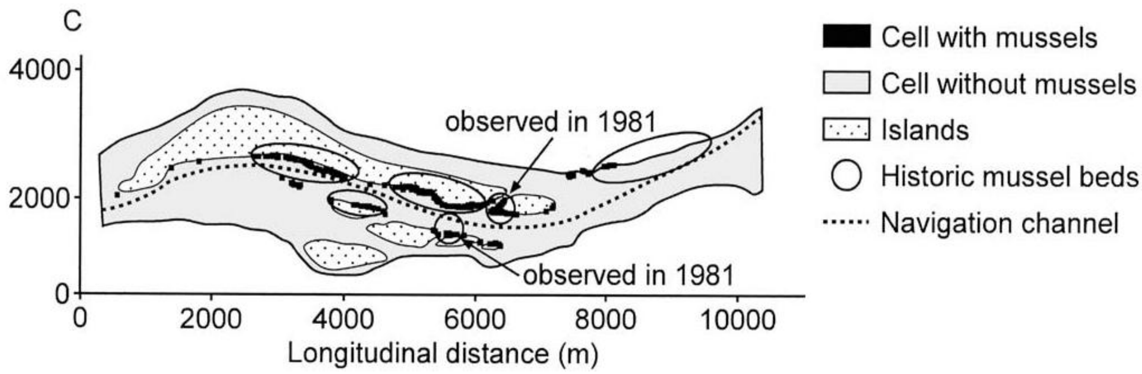


Figure 2.11 Simulation results of the mussel dynamic model for estimating the spatial distribution of mussel bed in the navigation pool 16 in the Mississippi River (Morales et al. 2006)

Summary of Chapter 2

The introduction of exotic species has increased due to the connection of previously separated water systems and the increase of water shipping trade, which provides the species the opportunity to migrate to locations that are friendlier for its particular characteristics. This is the case with the Asian Clam *(Corbicula Fluminea),* the Zebra Mussel *(Dreissena polymorpha)*, and the Quagga Mussel *(Dreissena Bugensis)*, whose presence have been recorded in the Dutch Rivers, creating concerns due to the economic and ecologic damage that these species have caused in other water systems.

The major differences between the species are in the location they occupy in the river cross-section, feeding characteristics and their filtration rate. Table 2.1 gives a comparison of the characteristics of these three species. Asian Clams *(Corbicula Fluminea)* are found in sand and muddy substrates, and this species presents the highest filtration rate among the three species (0.03 - 1 l Ind^{-1} h^{-1}). Apart from this, it is the only species able to feed as a pedal feeder, which causes destabilization of the upper sediment layer. The Zebra Mussel *(Dreissena polymorpha)* lives mainly on hard substrates, although unionid clam colonies, such as Asian Clam, can also be utilized as substrates to colonize (Mackie 1991). This species has the lowest filtration rate (0.18-0.32 l Ind^{-1} h^{-1}). Quagga mussels show capabilities to adapt to different substrates, like sand, silt and solid, nevertheless, a hard substrate is often preferred. The filtration rate, which for all the bivalves varies according to its shell size, temperature, particle size and flow regime, can reach values between (0.12-0.4 l Ind^{-1} h^{-1}).

Table 2-1 Comparative table between the Asian Clams, Zebra Mussels, and Quagga Mussels. The current velocity favorable velocity for highest filtration rate. Biodeposition values are based on feces deposited by the filter feeders.

	Asian clams	Zebra mussel	Quagga mussel
Mean densities River Waal (Ind m^{-2})	130	560	18
Max densities River Waal (Ind m^{-2})	645	910	107
Biomass (gDW m^{-2})	115-160	5.3	5.3
Habitat (substrate)	Sand-mud	Solid	Sand-silt
Life span (y)	5	5	5
Spawning (individuals)	35000	40000	40000
Length (mm)	40	30	40
How they feed	Filter- pedal	filter	filter
Filtration rate (l $ind^{-1}h^{-1}$)	0.03-1	0.18-0.32	0.12-0.4
Current velocity (cm s^{-1})	-	10	10
Biodeposition (g $m^{-1}h^{-1}$)	0.002-70	60	60

Zebra Mussels present some characteristics not seen in the Asian clam which makes them better colonizers: 1. they can live on top of burrowing bivalves colonies, 2. they are able to filter a much broader range of particles and 3. the byssate features of adults allows them to be transported upstream by attachment to the hull of boats. Data and field measures suggest that the Quagga Mussel will prevail over Zebra Mussel populations. This brings us to the conclusion that, over time, the Quagga Mussel will have the largest colonies in the Dutch rivers. However, the current situation in the River Waal shows relatively low densities for the Quagga Mussel (mean 18 Ind m^{-2} and max of 110 Ind m^{-2}). Different is the case for the River Meuse, which has records of 1895 Ind m^{-2} on groynes. In addition, the canal connecting the Meuse and Waal River presents densities of up to 940 Ind m^{-2}. This information, provided by Dr. R.S.E.W Leuven of the Radboud University in Nijmegen suggests that the invasion of Quagga Mussel is taking place from west to east and therefore it is highly probable an increase of Quagga densities in the River Waal in the upcoming years.

The presence of benthic species in rivers has an effect on the water and sediment processes. The cohesion of superficial sediment is strongly related by the secretion of EPS, which protects the sediment from erosion. The movement of benthic species searching for food, or for a better location, can destabilize the sediment by bioturbation (Le Hir et al. 2007). Benthic organisms enhance sediment fluxes between the water column and the river bed, through filtration of particles, biodeposition, or by rejection of faeces and pseudofaeces (bioresuspension) (Graf and Rosenberg 1997). Furthermore, the protuberance generated by benthos can change the bed roughness, and in case of high densities, waves and current may be damped due to the biologically increased bottom friction.

3 MORPHODYNAMICS IN DELFT 3D

The development of new computer programs has allowed scientists and engineers to estimate physical processes that would be impossible to simulate in experimental conditions. The simulations of these computer programs, which are based on mathematical models, play an important role in engineering and must never be overlooked during the design stage. The modelling exercise on this study is performed by a previously calibrated Delft 3D model of the River Waal provided by Rolien van der Mark.

Delft 3D is a numerical modelling system developed by Deltares, fully applicable for 3-dimensional computations of hydrodynamics and morphodynamic simulations of coastal, river and estuarine areas (Deltares 2009). The program is able to conduct simulations of flow, sediment transport, waves, water quality, morphological development, which makes it a very suitable tool for this study and therefore will be used herein. In this program, the physical processes are modelled by a system of equations that consists of two hydrodynamic equations, the continuity equation and the momentum horizontal equations, and one transport equation for conservative constituents. In this chapter the governing equations that Delft 3D uses to model the hydrodynamic and morphological changes of the river are described. Section 3.3 gives an overview of how the sediment transport is utilised to update the bed level changes in time.

3.1 Hydrodynamic Continuity and Momentum Equation

The Delft3D-flow module performs the hydrodynamic computations by solving the Navier Stokes' equations for shallow water in two (depth-averaged) or three dimensions, under the hydrostatics pressure assumption, which neglects the vertical acceleration due to buoyancy effects or changes in bottom topography (Lesser et al. 2004). For the modelling, the user may choose to solve the equations in a Cartesian, orthogonal curvilinear, or spherical grid, however, for 3D simulations the σ coordinate system introduced by Phillips (1957) is applied. This system divides the computational area in layers of equal size, in which a set of coupled conservation equations are solved for each layer, nevertheless, the given model was calibrated for only one layer.

The depth-averaged continuity equation is given by (Lesser et al. 2004):

$$\frac{\partial \zeta}{\partial t} + \frac{\partial [HU]}{\partial x} + \frac{\partial [HV]}{\partial y} = S \tag{3.1}$$

Where, S represents the contribution of the discharge of water, evaporation and precipitation per unit area. ζ stands for the water level and H is the water depth.

And, the momentum equations in the x- and y- directions are given by:

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} + \frac{\omega}{H}\frac{\partial U}{\partial \sigma} - fV = -\frac{1}{\rho_0}P_x + F_x + M_x + \frac{1}{H^2}\frac{\partial}{\partial \sigma}\left(\nu_V \frac{\partial u}{\partial \sigma}\right)$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + \frac{\omega}{H}\frac{\partial V}{\partial \sigma} - fU = -\frac{1}{\rho_0}P_y + F_y + M_y + \frac{1}{H^2}\frac{\partial}{\partial \sigma}\left(\nu_V \frac{\partial v}{\partial \sigma}\right) \tag{3.2}$$

In which, U and V are velocity components in the x and y direction, respectively. ν_v is the vertical viscosity, ω is the settling velocity and f is the Coriolis force. In addition, the terms P_x and P_y, are the so-called barotropic pressure gradients for water of constant density, with the account of the atmospheric pressure ρ_0 (see Lesser et al. 2004), F_x and F_y are the horizontal Reynold's stresses, determined by the eddy viscosity concept. And finally, M_x and M_y represent the discharge or withdrawal of momentum due to the contribution of external sources such as hydraulic structures, discharges of water, wave stresses, etcetera.

3.2 Advection-Diffusion Equation

Delft 3D calculates the transport of sediment by solving the three-dimensional advection-diffusion equation for suspended particles (equation 3.3) (Deltares 2009). In which, the flow velocities and eddy diffusivities are calculated from the hydrodynamic equations 3.1 and 3.2. In addition, the program is able to adjust the density of water in relation to temperature and salinity (see Deltares 2009) and differentiates the settling velocities and sediment fluxes between cohesive and non-cohesive particles (see section 3.2.1 and 3.3.1).

$$\frac{\partial c}{\partial t}+\frac{\partial Uc}{\partial x}+\frac{\partial Vc}{\partial y}+\frac{\partial (w-w_s)c}{\partial \sigma}-\frac{\partial}{\partial x}\left(\varepsilon_{s,x}\frac{\partial c}{\partial x}\right)-\frac{\partial}{\partial y}\left(\varepsilon_{s,y}\frac{\partial c}{\partial y}\right)-\frac{\partial}{\partial \sigma}\left(\varepsilon_{s,z}\frac{\partial c}{\partial \sigma}\right)=0 \tag{3.3}$$

Where,

C	= Depth averaged suspended sediment concentration	[kg m^{-3}]
U, V,	= Flow velocity components in the x- and y- direction	[m s^{-1}]
w_s	= Settling velocity	[m s^{-1}]
$\varepsilon_{s,x,y,z}$	= Eddy diffusivities in three directions	[m^2 s^{-1}]
w-w_s	= “assumption that the settling velocity with respect to the flowing water is the same that in stagnant water” (Ribberink 2010).	

The settling velocity for cohesive and non-cohesive sediment is calculated in relation to the concentration (Deltares 2009). In high concentrations, the presence of other particles reduces the settling velocity of a single particle. In order to account for this hindered effect, Delft 3D follows a formulation introduced by Richardson and Zaki (1954) and determines the settling velocity as a function of the sediment concentration. However, the model is calibrated for a reference density (CSOIL) of 1600 kg m^{-3} and if according to Asselman (1999), the average sediment concentration in the Rhine River is 30 mg l^{-1}, the hindered settling effect can be neglected and the settling velocity for non-cohesive sediment can be modelled by the Van Rijn (1993) formulation. Moreover, the temperature effect that alters the viscosity of water and increases particle settlement at higher temperatures is neglected.

3.2.1 Settling velocity

The settling velocity of non-cohesive sediments can be modelled by the Van Rijn (1993) formulation, which depends upon a representative sediment diameter, D_s. The formulation is of relative importance for this study as the model is calibrated for the Van Rijn’ 84 equation which, in Delft 3D, requires the settling velocity as an input value.

$$w_s = w_{s,0} = \begin{cases} \dfrac{(s-1)gD_s^2}{18v} & 65\mu m < D_s \leq 100\mu m \\ \dfrac{10v}{D_s}\left[\left(1+\dfrac{.01(s-1)gD_s^3}{v^2}\right)^{.5}-1\right] & 100\mu m < D_s \leq 1000\mu m \\ 1.1[(s-1)gD_s] & D_s > 1000\mu m \end{cases} \tag{3.4}$$

And,

$$D_s = \begin{cases} 0.64 D_{50} & for\ T \le 1 \\ D_{50}\left(1 + .015(T - 25)\right) & for\ 1 \le T \le 25 \\ D_{50} & for\ 25 \le T \end{cases} \tag{3.5}$$

s = relative density ρ_s/ρ_w of the suspended sediment fraction
D_s = representative diameter of sediment fraction [m]
D_{50} = median grain size of bed material [m]
v = kinematic viscosity coefficient of water [$m^2\ s^{-1}$]
T = non-dimensional bed shear stress

3.2.2 Deposition and erodability on Delft 3D

The model quantifies the sediment entering the flow due to an upward diffusion (erosion) and the sediment dropping out of the water column due to the settling velocity of particles (deposition). The sediment fluxes between the bed and flow are based on modelled approximations by sink and source terms acting on a layer above the reference height *a* developed by van Rijn (1993), named in Delft 3D as the *kmx layer* (Figure 3.1). The concentration approximation follows a standard Rouse profile from the reference height *a,* to the centre of the *kmx layer* (see Deltares 2009). Shortly, the deposition and erosion flux through the *kmx layer* can be expressed as follows:

Deposition flux:

$$D = w_s c_{kmx} \tag{3.6}$$

Erosion flux:

$$E \approx \varepsilon_s \left(\frac{c_a - c_{kmx}}{\Delta z}\right) \tag{3.7}$$

Where,
w_s = settling velocity [$m\ s^{-1}$]
ε_s = sediment diffusion coefficient evaluated at the *kmx layer.*
c_{kmx}= sediment concentration at the *kmx layer* [$kg\ l^{-1}$]
Δz = difference in elevation between the *kmx layer* and the van Rijn's reference height *a* [m]

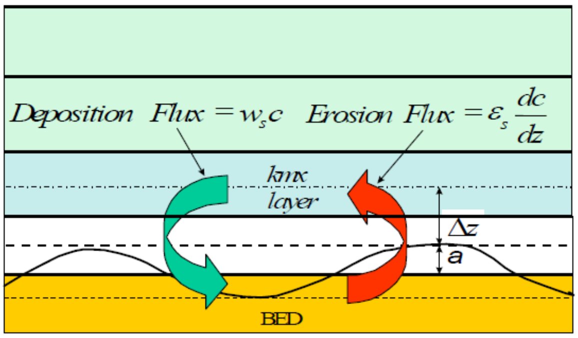


Figure 3.1 Schematization of flux on the kmx layer (Deltares 2009).

3.3 Morphodynamics

The bed evolution is based on the sediment continuity equation (3.8), where the first term expresses the changes in bed level in time (Tonnon et al. 2007)**.** Whereas, the second and third terms are the sediment fluxes (bed and suspended load) in the x- and y- directions. The equation states that the bed level evolution in time is depended on the suspended and bed load gradients in the x and y directions.

$$\frac{\partial z_b}{\partial t} + \frac{\partial (S_{b,x} + S_{s,x})}{\partial x} + \frac{\partial (S_{b,y} + S_{s,y})}{\partial y} = 0 \tag{3.8}$$

Where,

$S_{b,x,y}$	= bed-load transport in x- and y- direction .	[kg m^{-1} s^{-1}]
$S_{s,x,y}$	= suspended-load transport in x- and y- direction.	[kg m^{-1} s^{-1}]
z_b	= bed level.	[m]

3.3.1 Suspended and bed load transport

The suspended and bed load transport are computed by standard sediment transport formulations defined by the user (e.g. van Rijn (1993), Engelund-Hansen (1967), Bijker (1971), Soulsby, etc), which subsequently are corrected for bed-slope effects, upwind bed compositions and sediment availability (Deltares 2009). The Van Rijn' 84 formulation is able to calculate the suspended and bed load transport separately and distinguishes between the transport mode according to the reference height *a*. Above the reference height the concentration is catalogued as suspended load and below as bed load. In river systems, as the particles are bigger, the settling velocity of particles is higher than in other aquatic systems, therefore one could forecast the River Waal to be governed by bed-load transport mode.

The latter can be confirmed with the aid of the Rouse Number *P*, which is a non-dimensional number that defines the transport mode of the sediment. See equation 3.9

$$P = \frac{w_s}{\kappa u_*} \qquad \begin{array}{cc} P > 2.5 & \text{Bed Load} \\ 0.8 < P < 1.2 & \text{Susp. Load} \\ P < 0.8 & \text{Wash Load} \end{array} \tag{3.9}$$

Where, `

u_*	= critical shear velocity	[m s^{-1}]
κ	= von Kármán constant, typically 0.40	[-]
w_s	= Settling velocity, (0.1 m/s, calibrated Delft 3D model)	[m s^{-1}]

According to the Van Rijn' 84 formulation (Deltares 2009), the critical shear velocity u_* is determined by:

$$u_* = q\sqrt{\frac{f_{cb}}{8}} \tag{3.10}$$

Where,

q = depth average velocity, 1 m s^{-1}

and, f_{cb} is a friction factor expressed as (Deltares 2009):

$$f_{cb} = \frac{0.24}{\left[\log_{10}\left(\frac{12H}{3D_{90}}\right)\right]^2} \tag{3.11}$$

With,
H = water depth, 5 m (Ten Brinke et al. 2004)
D_{90} = 1.5D_{50}
D_{50} = 2.5 mm (Julien et al. 2002)

Finally, we can use these representative values of the River Waal to calculate the Rouse number, which indeed confirms that in the River Waal the main transport mode is bed-load (eq. 3.12). The water depth and the depth averaged flow velocity might be spatially and temporally variable, however, the fact that the species are located within the groyne fields (R.S.E.W Leuven, personal communication) increases the Rouse Number even more. Therefore, the suspended sediment transport can be neglected for the purpose of this study.

$$P = \frac{.17}{.40 * .05} = 8.3 > 2.5 \tag{3.12}$$

3.3.2 Bed load transport: Van Rijn 84

For simulation without waves, the magnitude of the bed load transport is calculated according to Van Rijn' 84 equation, for which the model is calibrated:

$$S_b = \begin{cases} .053\sqrt{(s-1)gD_{50}^3}D_*^{-0.3}T^{2.1} & for\ T < 3.0 \\ 0.1\sqrt{(s-1)gD_{50}^3}D_*^{-0.3}T^{1.5} & for\ T \geq 3.0 \end{cases} \tag{3.13}$$

Where, S_b is the bed load transport rate (kg m^{-1} s^{-1}) and D* and T are the shear velocity, non-dimensional particle size and the non-dimensional bed-shear stress respectively (specified by van Rijn' 84). With,

D* Non-dimensional particle size:

$$D* = D_{50}\left[\frac{(s-1)g}{v^2}\right]^{\frac{1}{3}} \tag{3.14}$$

T Non-dimensional bed-shear stress:

$$T = \frac{\mu_c \tau_{b,c} - \tau_{cr}}{\tau_{cr}} \tag{3.15}$$

In which, the critical bed shear stress τ_{cr} is written based on the Shields parameter which is defined as a function of the non-dimensional particle parameter *D**:

$$\tau_{cr} = (\rho_s\text{-}\rho)gD_{50}\,\theta_{cr}$$

$$\theta_{cr} \begin{array}{ll} =0.24D_*^{-1} & \text{for } 1<D_*<4 \\ =0.14D_*^{-.64} & \text{for } 4<D_*<10 \\ =0.04D_*^{-0.1} & \text{for } 10<D_*<20 \\ =0.013D_*^{0.29} & \text{for } 20<D_*<150 \\ =0.055 & D_*>150 \end{array} \tag{3.16}$$

Where, the formulas to calculate the bed shear stress are:

$$\tau_{bc} = \frac{1}{8}\rho_w f_{cb} q^2 \tag{3.17}$$

$$\mu_c = \left(\frac{18log\left(\frac{12H}{\xi_c}\right)}{C'}\right)^2 \tag{3.18}$$

$$f_{cb} = \frac{0.24}{\left[\log_{10}\left(\frac{12h}{3D_{90}}\right)\right]^2} \tag{3.19}$$

Where ξ_c is the reference level, for which the given calibrated model assumes a value of 0.3 m and in which the Chézy coefficient *C'* is expressed as a function of the grain size D_{90}, interpreted in Delft 3D as $1.5D_{50}$. The equation is written as:

$$C' = 18\log\left(\frac{12h}{3D_{90}}\right) \tag{3.20}$$

Summary of Chapter 3

Delft 3D is a numerical modelling systems developed by Deltares to perform coastal, river, sea, and estuarine simulations of flow, sediment transport, waves, among others. Delft 3D models the hydrodynamics processes according to the continuity and momentum equation, whereas, the transport of sediment is modelled by the three-dimensional advection-diffusion equation. The settling velocity for non-cohesive sediment is modelled in Delft 3D according to the Van Rijn' 93 formulation, which depends upon the sediment concentration and the representative sediment diameter $D_{s,}$ function of the median grain size D_{50}. The model quantifies the amount of sediment entering the water column due to an upward diffusion (erosion) and a downward settling velocity (deposition) passing through the *kmx layer* (figure 3.1).

The bed evolution in time is based on the sediment continuity equation (3.8), where the bed elevation in time is a function of the suspended and bed load transport gradients within each grid. This study only considers the bed load transport because the Rouse number (non-dimensional number that defines the transport mode) of the River Waal indicates the bed load as the principal mean of sediment transport. In this study, the Van Rijn' 84 equation for bed load transport is utilised. The formula is commonly used for situations without waves and calculates the bed load transport rate according to the non-dimensional particle size and the non-dimensional bed shear stress.

4 PARAMETERIZATION OF BIOLOGICAL PROCESSES

From literature study was concluded that through their benthic activity, the Asian clams, Zebra and Quagga mussels might impact river morphology in several ways, for instance: altering the erosion rate, changing the flow velocity and direction, increasing deposition, etcetera (Widdows et al. 2002; Le Hir et al. 2007). Nevertheless, in order to perform the parameterization of the Asian clams, Zebra mussels and Quagga mussels, it is assumed that the impact on sediment dynamics, product of these species, are the result of mainly three biological processes: the benthic coverage percentage, the creation of biofilms due to the deposition of excreted material (biodeposition) and the filtration rate. This chapter details the followed procedure to determine the impact of the benthic species on river morphology. Moreover, it offers the parameterization of the benthic processes in order to implement them into the Van Rijn 84 equation.

4.1 Impact of Benthic Species on Erosion Threshold

Due to the complex parameterization of benthic organism as a result of the relatively large grid cells size in the model provided by Deltares, in comparison with the smaller size of the benthic organisms (see Chapter 5), a method that accounts for the overall impact on the erosion threshold caused by the bio (de-) stabilization effect of the benthic species is introduced. The method multiplies the impact on the abiotic erosion threshold of the three main biological processes affecting sediment dynamics (see Equation 4.1) and returns the expected alteration in the abiotic erosion threshold for a complete area. The parameterization of each process will be discussed below. Furthermore, the parameterization of the species only considers the Asian clams, Zebra and Quagga mussels are neglected in this study because they live on the groyne fields and do not directly impact sediment dynamics (See section 5.4.1 for further discussion)

$$\tau_{bio} = (Cp, B, Fr)\tau_o \tag{4.1}$$

Where,

τ_{bio} = Biotic erosion threshold [N m^{-2}]
τ_o = Abiotic erosion threshold [N m^{-2}]
Cp = Coverage percentage factor
Fr = Filtration rate factor
B = Biofilms factor

4.1.1 Coverage percentage factor

Up to now, no study has investigated the changes in sediment erodability produced by the shell roughness and communities of *Corbicula fluminea*. However, Widdows et al. (2002) conducted a study to investigate the changes on sediment erodability, as a result of an increase of turbulence (bioturbation) and scouring around *Myilus edulis* communities*.* The study was performed over a sandy substrate with the aid of annular flume and the similarities between the *Myilus edulis* and the *Corbicula fluminea* (shell size, burying behavior, and self-mussel orientation) are believed enough to assume similar results for *Corbicula fluminea* communities. Since the effects of biofilms was avoid by "siphoning the feces from the flume" the study only takes into account the erosion caused by the bioturbation around the mussels (Widdows et al. 2002).

Widdows et al. (2002) concluded that the velocity at which erosion (U_{crit}) occurs ranged from 0.23 m s^{-1} for bare sand, 0.12 m s^{-1} for 25% mussel cover, to 0.17 m s^{-1} for 50% and 0.29 m s^{-1} for 100% mussel cover. With the aid of these values and the erosion formula $\tau=\rho U^2$ (Chang 1988), the coverage percentage factor *Cp,* on a sandy substrate, can be calculated (see table 4-1). Figure 4.1 shows the non-linear relationship between erosion threshold ratio and the mussel bed density on a sandy substrate. Clearly, biodestabilization is more likely to take place within a mussel bed with coverage percentages between 0 and 73%. The biostabilization effect takes place for coverage percentages above 73 %, which, assuming the natural position on substrates (partially buried and with their posterior shell edges and siphons above the substrate), is reached for Asian clam densities of approximately 2300 Ind m^{-2}.

Table 4-1 Coverage percentage factor *Cp*.

Coverage (%)	U_{crit} [m s^{-1}]	τ_{crit} [N m^{-2}]	Cp [τ_{bio}/ τ_0]
0	0.23	54.5	1
25	0.12	14.8	0.27
50	0.17	29.8	0.55
100	0.29	86.6	1.59

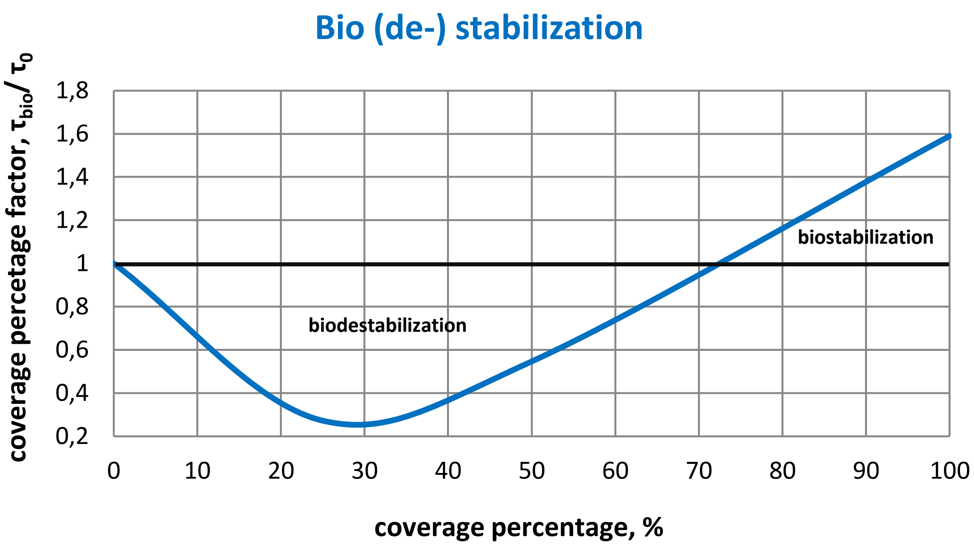


Figure 4.1 Non-linear bio (de-) stabilization between erosion threshold ratio and the mussel bed on a sandy substrate.

4.1.2 Biofilm factor

As discussed in previous sections, there is a lack of data and research in relation to the effect of biofilm on sediment erodability for sandy substrates. Researchers have found correlation between sediment erodability and chlorophyll *a* (Widdows and Brinsley 2002) and water content (Neumeier et al. 2006). The increments of the erosion threshold τ_0 on these studies ranged between 1 and 10-fold (Neumeier et al. 2006; Le Hir et al. 2007), and therefore these ranges are expected in this study. Table 4-2 lists the four assumed factors. However, the study considers that in reality, biofilms do not always fully developed: The bioturbation caused by clams, in addition to the different physical characteristics between feces and faecal pellets prevent the complete deposition of biofilms (Ten Brinke et al 1995; Neumeier et al. 2006)(see Sections 2.2.3 and 4.2).

Table 4-2 Expected linear effects of biofilms for sandy substrates on aquatic systems (τ_{bio}/ τ_0).

Case	Factor	Description
Fully developed	10	Hydrodynamic forcing allow for the complete development of the biofilm (e.g. low flow velocity)
50 % developed	5	50 % of the excreted material being deposited
20-30% developed	2.5	For the Oorterschelde tidal basin, only 20-30 % of the upper sediment layer was composed by faecal pellets (Ten Brinke et al. 1995)
0 % wash off	1	No biodeposition due to high flow velocities

4.1.3 Filtration rate factor

The increase of biodeposition due to the filtration activity of benthos, can be mimicked in Delft 3D by altering the settling velocity of the material transported as suspended sediment (Van Leeuwen 2008). For this matter, the deposition equation 3.6 must be altered by the filtration rate: assumed uniform after ignoring the impact of flow conditions of the filtration rate and expressed in meter per seconds as a function of the benthic densities per square meter. Finally, the equation reads:

$$Biodeposition = (w_s + Fr)\ C \tag{4.2}$$

w_s = Settling velocity [m s^{-1}]
Fr = Filtration rate [m s^{-1}]
C = Concentration [kg l^{-1}]

The settling velocity can be calculated according to the van Rijn (1993) formulation (eq. 3.4), as a function of a representative diameter of the suspended sediment, D_s, which depends upon the median grain size of the bed material D_{50} and the dimensionless bed shear parameter T (see eq. 3.15). For an average bed material D_{50} of 1.7 mm (average D_{50} for the model provided by Deltares), the non-dimension parameter T has values below 1, meaning that the representative grain size can be determined as $0.64D_{50}$ (see eq. 3.5), resulting in a D_s=1.1 mm. Finally, with aid of the third term from equation 3.4 (assuming a specific density of sediment fraction of 2650 kg m^{-3}), one can calculate the settling velocity for D_s > 1000 µm, which leads to a settling velocity of 0.09 m s^{-1}. However, the model provided by Deltares has been calibrated for a w_s of 0.1 m s $^{-1}$.

Now, as mentioned above, in order to modify equation 4.2, one should express the filtration rates of the three species in meter per seconds. Table 4-3, gives the filtration rates of these species. The formulation is based on maximum possible values (current situation) for filtration rates, it neglects the hinder effects of the flow, sediment concentration and temperature on the filtration rate, and it assumes maximum densities for these species in the River Waal. Nevertheless, even considering these values, the filtration rate is so small in comparison to the settling velocity, that it can be neglected from this study, therefore:

$$Deposition = (w_s + Fr)\,C \;\approx\; w_s\,C \tag{4.3}$$

Table 4-3 Calculation of the ratio between the filtration rate and the settling velocity (w_s = 0.1 m s^{-1}). Filtration rate based on densities for the River Waal. Field data by Rob Leuven (personal communication, 2011)

Parameter	dimension	Asian Clam	Zebra Mussel	Quagga Mussel
Max. Densities	Ind m^{-2}	645	910	110
Filtration rate	l ind^{-1} hr^{-1}	1	0.32	0.42
Filtration rate	l hr^{-1} m^{-2}	643	292	43
Filtration rate	m s^{-1}	.00017	.0000810	.000012
Fr/w_s	%	0.17	0.08	0.012

4.2 Expected Alterations of the Erosion Threshold

Table 4-4 displays the expected biotic erosion threshold (eq. 4.1) caused by the Asian Clam communities according to the proposed parameterization. The table indicates the probable upper and lower changes in erosion threshold; a maximum increase of 15.9τ_o for Asian clams communities with 3200 Ind m^{-2} in which the all fecal pallets and pseudofaeces are being deposited, and a maximum decrease for communities that reach densities of 800 Ind m^{-2} and with no deposited faecal pellets. According to the table, the current colonization of the Asian Clam (130-650 Ind m^{-2}) could produce changes between 0.4 and 9.5τ_o in the infested zones.

Table 4-4 Expected impact of Asian Clam communities on the erosion threshold ($\tau_{bio}/\ \tau_0$).

Coverage: Density:	4% 130 Ind m^{-2}	20% 650 Ind m^{-2}	27% 800 Ind m^{-2}	73% 2350 Ind m^{-2}	100 % 3200 Ind m^{-2}
	Mean current scenario	Max. Current scenario	Max. Possible erosion	No impact on roughness	Max. possible density
100% biofilm develop	9.5	4	2.7	10	15.9
50% biofilm develop	4.75	2	1.35	5	7.95
20-30 % biofilm develop	2.85	1.2	0.80	3	4.77
wash off	0.95	0.4	0.27	1	1.59

Parameterization of the biotic erosion threshold in Delft 3D

The parameterization suggests that the effect of the benthic organism's lifestyle on sediment dynamics may result in an increase/decrease on the erosion threshold depending on the coverage percentage and biofilm factor. When using the transport formulation developed by Van Rijn (84), the erosion threshold is proportional to the median grain size D_{50} (see section 3.3.1), and therefore, in this study this value is locally increased/decreased in order to introduce the benthic effects into the Delft 3D model. Table 4-5 shows the needed increment of the grain size, in relation with the average D_{50} in that zone (1.56 mm) for the abiotic scenarios (see table 4-4). The grain sizes were carefully calculated according to the Shields parameter (eq. 3.16), furthermore, the over (under-) estimations of erosion due to the changes in roughness and grain sizes were avoided by using the trachytopes files (roughness files). These files were calibrated by Deltares and inside the groyne fields were set as Nikuradse value between 0.05 and 0.2 m, probably defining bed forms. Finally, the over (under-) estimations of settling velocities were avoided by setting this value to 0.1 m/s in the .tra file (sediment transport formula file).

Table 4-5 Increments on the median grain size D50 , based on the τbio index. Note: Increments proportional to Van Rijn 93 formulation to determine the critical bed shear stress.

Scenarios	4% 130 Ind m^{-2}	20% 650 Ind m^{-2}	27% 800 Ind m^{-2}	73% coverage 2350 Ind m^{-2}	100 % coverage 3200 Ind m^{-2}
	Mean current scenario	Max. Current scenario	Max. Possible erosion	No impact on roughness	Max. possible density
100% biofilm develop	7.7	4	2.9	8	11.45
50% biofilm develop	4.5	2.3	1.55	4.68	6.7
20-30 % biofilm develop	3	1.35	0.55	3.15	4.5
wash off	0.86	0.08	0.1	1	1.85

Summary of Chapter 4

Following the review of the selected species of this study, it was concluded that the Asian clams can impact the hydro and morphodynamics processes of aquatic systems in numerous ways such as: increasing/decreasing the erosion rate, redirecting the flow, increasing the water level and roughness, etcetera. (Widdows et al. 2002; Le Hir et al. 2007). In the parameterization, the impact of benthic activity on river systems was assumed to be caused by mainly three biological processes altering the erosion threshold: the benthic coverage percentage, the creation of a biofilms that sticks the sediment together, and the filtration rate that increases deposition..

Because no study has investigated the bioturbation effect of Asian Clams on a sandy substrate, the coverage factor was calculated according to the changes in sediment erodability (sand) due to bioturbation around *Myilus edulis* communities (Widdows and Brinsley 2002). The bioturbation caused by the *Myilus edulis* and the Asian Clam is believed to produce comparable results due to the similarities among the species. Figure 4.2 shows the potential effects of the Asian Clam on the erosion threshold assumed in this study.

The lack of precise documentation in relation with the effect of the biofilms on sandy substrates, forced the assumptions based on ranges of previous studies. The parameterization assumes that a fully developed biofilm may increase the erosion threshold by a factor of 10, however, due to the flow conditions of river, it is expected that only 20 to 30 % of the material expelled by the benthos will be deposited within benthic community, increasing sediment erodability by a factor of 3. Furthermore, the current colonization on the River Waal (130 - 650 Ind m^{-2}) suggests that the sediment stability is more sensitive to biofilm development (Figure 4.2) than for the turbulence around Asian clam communities. The filtration rate was discarded due to the low effects on the settling velocity of particles in the River Waal. Finally, the changes on the erosion threshold are made by changing the grain sizes inside the groyne fields of the model provided by Deltares

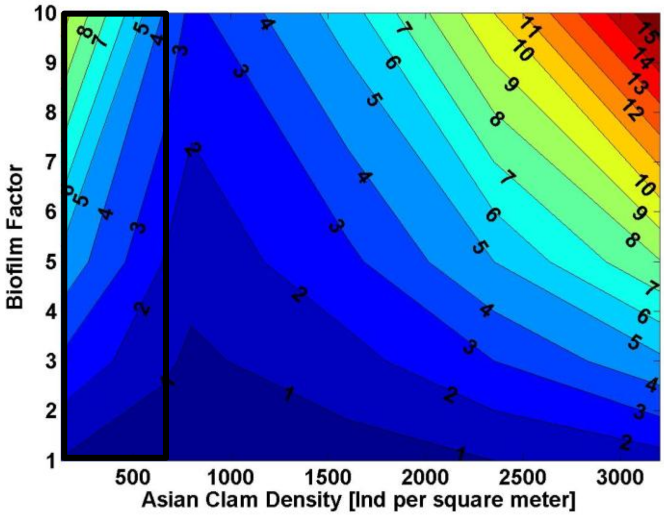


Figure 4.2 Expected biotic erosion threshold for Asian Clam communities. The rectangle indicates the zone of the current situation (average and maximum densities) in the River Waal (τ_{bio}/τ_0).

5 SCENARIOS

5.1 Computational Grid and Bathymetry

As mentioned in chapter 2, the invasion of the species involved in this study not only came from the east side of the Netherlands (through the Rhine River), but also from the west. This pattern has lead to records of Asian Clams, Zebra mussels and Quagga Mussels in the River Waal (R.S.E.W Leuven, personal communication), making the Waal an appropriate area for the purpose of this study. The Delft 3D model provided by Deltares represents the Waal after the bifurcation point at Pannerdensche Kop and extends until the city of Gorinchem. In order to decrease the computational time, the complete model was shortened to comprehend a river reach of 23.8 km, from the Pannerdensche Kop to the outskirts of the city of Nijmegen. Figure 5.2 shows this computational grid of the River Waal, one grid cell in the navigation channel is approximately 2000 m^2 (80 x 25 m). The bathymetry of the River Waal is illustrated in figure 5.3; the figure not only includes the navigation channel, but also the floodplains, dikes and adjacent ponds.

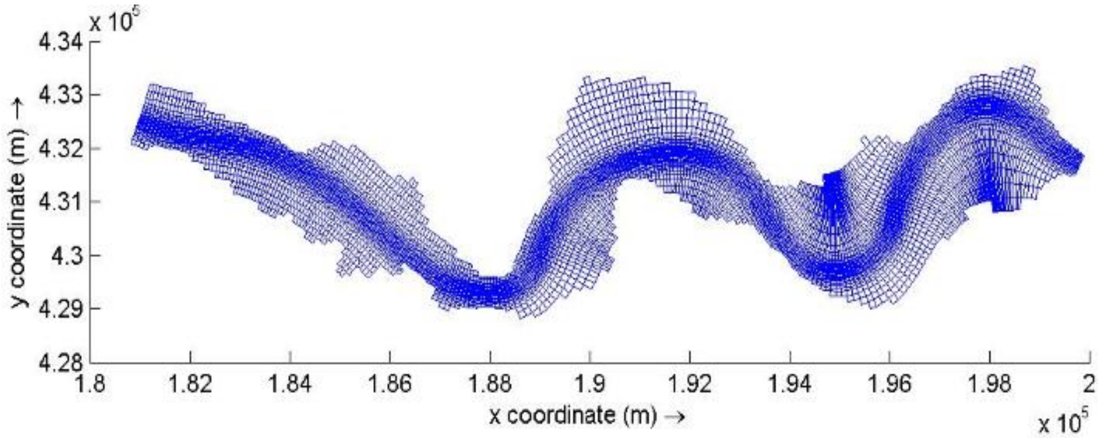


Figure 5.1 Computational Grid of the River Waal (Pannerdensche Kop - Nijmegen)

Figure 5.2 Aerial photograph from the River Waal, A) City of Nijmegen (Source: Google Earth May 2011.)

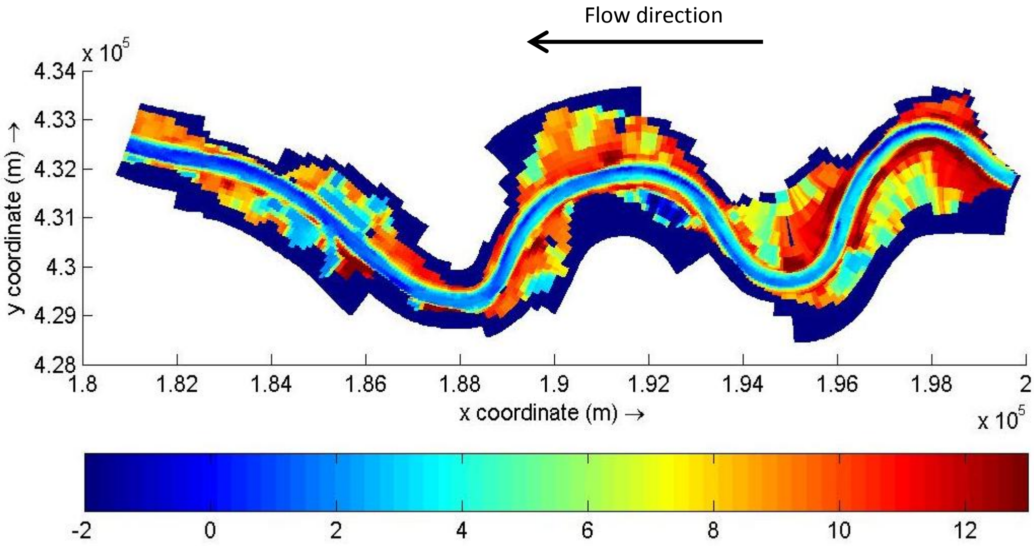
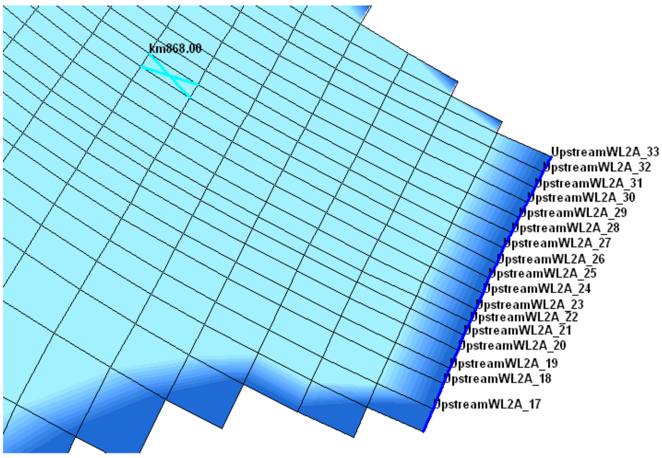


Figure 5.3 **Bathymetry of the River Waal in meters above Mean Sea Level.**

5.2 Boundary Conditions

The model is bounded by 15 active open boundaries: 14 upstream open boundaries, with a constant discharge per cell, which in total makes up a constant average discharge of 1640 $m^3 s^{-1}$ (see figure 5.4), and one downstream boundary condition. As mentioned before, initially the model extended from the Pannerdensche Kop to Gorinchem, however, the model was shortened by setting a unique downstream boundary condition (water level type) of 6.98 m, at approximately the 182 km in figure 5-3, consisting of the water level (at this specific point) reached after the stabilization of the hydrodynamic and morphodynamic processes. (for discussion about steady state see 7.3.1)



Upstream Boundary Conditions	Discharge
Upstream Boundary 20	2.95 $m^3 s^{-1}$
Upstream Boundary 21	41 $m^3 s^{-1}$
Upstream Boundary 22	76 $m^3 s^{-1}$
Upstream Boundary 23	98 $m^3 s^{-1}$
Upstream Boundary 24	133 $m^3 s^{-1}$
Upstream Boundary 25	126 $m^3 s^{-1}$
Upstream Boundary 26	138 $m^3 s^{-1}$
Upstream Boundary 27	150 $m^3 s^{-1}$
Upstream Boundary 28	156 $m^3 s^{-1}$
Upstream Boundary 29	167 $m^3 s^{-1}$
Upstream Boundary 30	171 $m^3 s^{-1}$
Upstream Boundary 31	172 $m^3 s^{-1}$
Upstream Boundary 32	148 $m^3 s^{-1}$
Upstream Boundary 33	61 $m^3 s^{-1}$
TOTAL	1640 $m^3 s^{-1}$

Figure 5.4 **Upstream boundaries conditions summoning a constant average discharge of 1640 $m^3 s^{-1}$. The Upstream boundary conditions are expressed as discharge per cell expressed in $m^3 s^{-1}$. Values were given by Deltares. Boundary 17-19 are not active and represent no discharge.**

5.3 Input Transport and Morphologic Parameters

When using the Delft 3D flow module, the user must define some parameters before the start of the computation, however, not all these values can be altered in the flow module interface and one must directly change them from their respective files. This is the case for the transport formulation and the morphological changes. This section explains the parameters utilized in this study to model the bed load transport and the morphologic changes within the area.

The Van Rijn' 84 equation has two input parameters: the settling velocity w_s and the reference level ξ_c. The settling velocity in the Van Rijn equation was calibrated by Deltares and set at 0.1 m s^{-1}, a value that is lower than the expected 0.17 m s^{-1} for D_{50} of 2.5 mm (see section 3.3.1), this is probably caused by the different grain size for which the model is calibrated, which apparently was obtained iteratively and gives a variable grain size throughout the river branch (see figure 5.5). However, no significant changes are expected in the model's results as the filtration rate is still negligible and the transport mode is mainly bed-load dominated (see section 3.3.1). In addition, the settling velocity of 0.1 m s^{-1}, ranges within the order of magnitude for non-cohesive sediments. The reference level ξ_c was set to 0.3 m.

In order to account for morphological changes, the Delft 3D model calls the morphologic update file (.mor). In this file the user may define several parameters so Delft 3D is allowed to dynamically calculate the bed elevation at each computational time-step, these are: the morphological scale factor (MorFac), the morphological delay (MorStt) and the morphological switch (BedUpd and CmpUpd). The morphological scale factor (MorFac) is the factor that Delft 3D uses to scale morphological developments in the same time scale typical for hydrodynamics flows. In rivers, "the morphological scale factor should be interpreted as a speed-up factor for morphological development without changing the order of events" (Deltares 2009).

Deltares has investigated the Morfac value and obtained reliable results for a Morfac of 720 (R. Van der Mark, personal communication), therefore, this value has been set to 720, meaning that for each hydrodynamic minute, the model is displaying the morphologic changes expected for 720 minutes (12 hours). Furthermore, the morphological delay (MorStt) is used to avoid the morphologic destabilization caused by the first time steps during each run; the MorStt is set as 1600. In addition, the model allows the update of the calculated depths at each time step by setting "true" the BedUpd and CmpUpd factor inside the .mor file.

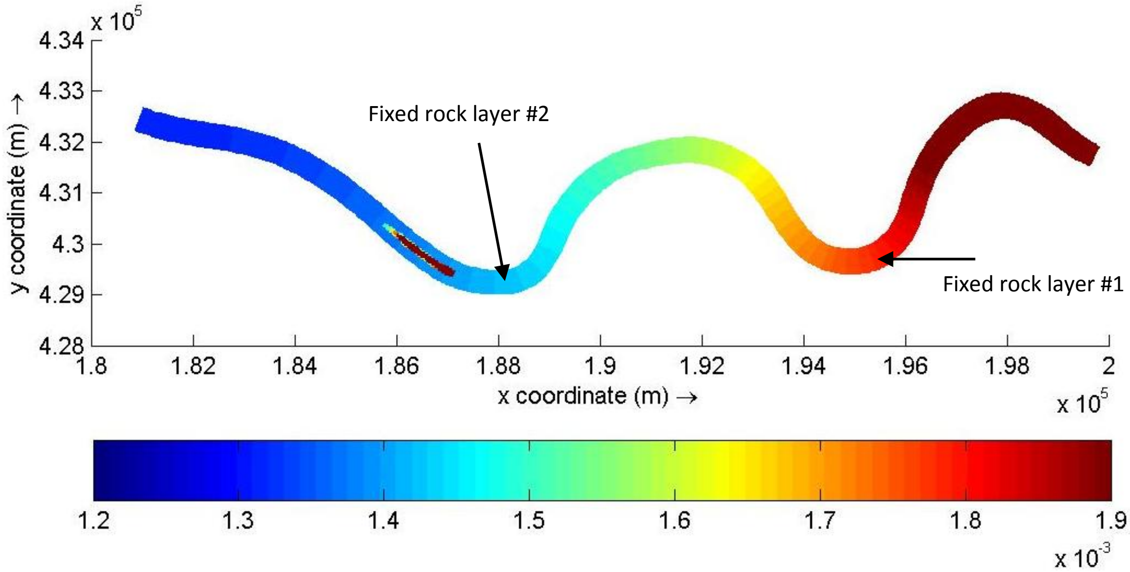


Figure 5.5 Grain size (D_{50}) distribution in the Navigation channel of the River Waal. According to the model provided by Deltares.

5.4 Biotic Scenarios

5.4.1 *Dreissena polymorpha and bugensis:* Reason to reject

From literature study was concluded that the Zebra and Quagga mussels are catalogued as epifaunal and despite that Mackie (1991) and Mackie and Schloesser (1996) state that the species are able to accumulate on top of mud and unionid shells, the data provided by Leuven (2011) demonstrates that the colonization of these species in the Dutch river system is limited to hard substrates such as groyne stones. From this information is concluded that the impact of these two species on river morphology is negligible. The following are the reasons for this conclusion:

The parameterization assumes that the biological impact on morphology is caused mainly by three biological processes: the benthic coverage percentage, the filtration rate and the creation of biofilms. However, in the biodestabilization zone (figure 4.1) the coverage percentage is governed by the bioturbation caused by the shell roughness (Widdows et al. 2002), which can be neglected because the groyne itself will have a major contribution on flow resistance, in the same way, the stabilization effect of this process is considerably small on these locations. Additionally, the material deposited by these organisms is expected to follow two paths: 1) be deposited (faecal pellets) in the groynes and therefore having no effect on sediment and 2) being expelled as pseudofeces and transported downstream within the water column (Ten Brinke et al. 1995), for any path, there will be no impact on morphology. And finally, the impact of the filtration rate can be neglected as mentioned in section 4.1.3. Due to these motives, it is assumed that the only benthic species expected to cause morphologic modification are the Asian Clams (*Corbicula fluminea).* The next explains the Asian Clam scenarios in this study.

5.4.2 Asian clam scenarios (*Corbicula fluminea*):

This section proposes the most likely scenarios for the River Waal. Within this section, the reasons for each Asian Clam scenario are explained. Table 4-4 shows the expected impact on the erosion threshold for several densities of Asian Clam communities regardless of the aquatic system. However, not all these scenarios may be representative for rivers and so, based on the following assumptions, the scenarios in which the biofilms are fully developed and washed off are discarded:

1. Fully (100 %) developed biofilms are unlikely to happen in rivers due to the different physical characteristics between faecal pellets and pseudofeces. Despite the fact that they are harder to erode (Jones and Lawton 1994; Ten Brinke et al. 1995), faecal pellets, represent only a small percentage of the complete material deposited by benthic communities (see Section 2.3.2). In addition, the relatively high flow velocity in rivers (compared with other aquatic systems), provokes that most of the biodeposition would be resuspended and transported downstream (Ten Brinke et al. 1995), thus, these scenarios will be neglected.

2. A complete wash off of the material deposited by the benthic community is also neglected. As already mentioned, zones with substrate stability are prone for benthic accumulation (Morales et al. 2006), which coincides with the current situation in the River Waal, where the Asian clam communities are solely localized in groyne fields. In the groyne fields, the flow velocity diminishes and therefore it is assumed that the flow velocity is not high enough to completely erode the biodeposited material.

Table 5-1 Impact of the erosion threshold, caused by Asian clam communities. Scenario based on the parameterization of the Asian Clam. Values inside rectangles are the most likely current situation for the River Waal.

Scenarios	4% 130 Ind m^{-2}	20% 650 Ind m^{-2}	27% 800 Ind m^{-2}	73% coverage 2350 Ind m^{-2}	100 % coverage 3200 Ind m^{-2}
	Mean current scenario	Max. Current scenario	Max. Possible erosion	No impact on roughness	Max. possible density
100% biofilm develop	9.5	4	2.7	10	15.9
50% biofilm develop	4.75	2	1.35	5	7.95
20-30 % biofilm develop	2.85	1.2	0.80	3	4.77
wash off	0.95	0.4	0.27	1	1.59

Table 5-2 proposed scenarios for the modeling of the Asian Clam on the River Waal

Scenario	Density	Biofilm	Coverage %	τ_{bio}
1	Current mean	25 % developed	4%	2.85 τ_o
2	Destabilization density	25 % developed	25%	0.80 τ_o
3	Maximum possible	100 % developed	100%	15.9 τ_o

Due to the before mentioned assumptions, table 4-5 contains the proposed scenarios for this study: Scenario 1 consists on the most likely current situation in the River Waal: According to the data provided by R.S.W.E Leuven (2011), containing the densities of Asian clams on several locations along the River Waal, the communities of these species have registered maximum values of 643 Ind m^{-2}, with an average density of 130 Ind m^{-2}. Interestingly, the increase of the erosion threshold in current scenarios show similar results as the results obtained by Neumeier et al. (2006) in the presence of cockles (*Cerastoderma edule)*, in which the overall effect of biofilm in conjunction with these benthic species (194 Ind m^{-2}) increased the erosion threshold by a factor of 2-3. Furthermore, the study considers a scenario (2) in which the overall effect of the Asian Clam destabilizes the sediment. At the moment this scenario is far from reality, as the invasion is yet not that critical. However, the river system in the Netherlands is not free of further colonization, making this scenario interesting for modelling. Finally, a critical stabilization scenario (3) is considered to determine the upper boundary of impact of the Asian clams on river morphology.

Location of benthic species

As previously mentioned, the invasion of the Asian Clams in the River Waal is believed to take place exclusively within the groyne fields. R.S.E.W Leuven (personal communication) mentioned that this is possibly caused by the shipping activity, in which waves impede the Asian Clams to migrate to deeper locations. This assumption is supported by Karatayev et al. (2006) and Sousa et al. (2008) who state that *C. fluminea* is intolerant to hypoxia, requiring well-oxygenate areas and therefore are usually found in the littoral and sublittoral zones of the river. Figure 5.6 shows the suggested location of the Asian Clams in the River Waal, the zone is prone to accumulation of benthic organism due to its low flow velocities and hence low bed shear stress τ (Morales et al. 2006), which may enhance their habitat conditions (see Chapter 2): The zones will allow the settlement of larvae and nutrients, decrease the detachment of juveniles (Sousa et al. 2008), and increase biodeposition (Ten Brinke et al. 1995). Additionally, this zone is free of possible overestimations caused in the boundaries and it has no interaction with the fixed rock layers.

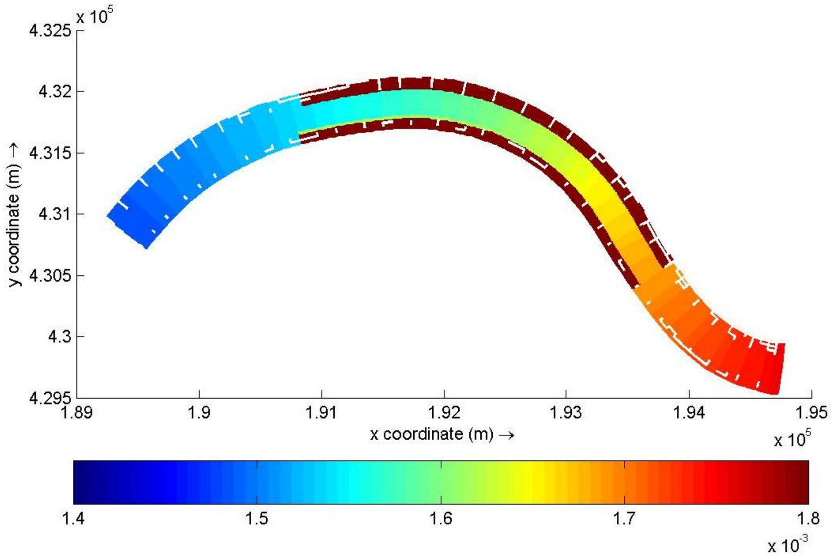


Figure 5.6 Suggested location of Corbicula fluminea in the River Waal. White lines showing the location of the groynes

Summary of Chapter 5

A Delft 3D model of the River Waal is used to investigate the impact of benthic organisms on river morphology due to the colonization of Asian clams, Zebra mussels and Quagga taking place in this river (R.S.E.W Leuven, personal communication). The model provided by Deltares consists of a 23.8 km long river branch from the Pannerdensche Kop until the outskirts of the city of Nijmegen. The model is bounded by 15 active conditions: 1) 14 upstream boundary conditions that in total make up for a constant discharge of 1640 $m^3\ s^{-1}$ and 2) a downstream boundary condition set as a water level of 6.98 m.

In order to perform the sediment transport computations, the user must define several parameters prior the modelling. The Van Rijn' 84 equation calls for the reference level $\xi_{c,}$ set at 0.3 m, and the settling velocity $w_{s,}$ set at 0.1 m s^{-1} (both values previously calibrated by Deltares). Additionally, to carry out the morphologic updates, the MorStt factor that holds the morphologic changes caused by hydrodynamics adjustments during the first time steps was set to 1600 hydrodynamic minutes (approximately two morphologic years). And the MorFac factor to scale the morphological developments of the hydrodynamics was set to 720. The model runs for 9630 (6.7 days) hydrodynamic minutes meaning that it displays the morphologic results of (6.7 days x 720) 13 years.

Initially, the study implicated the impact of the Asian clams, Zebra mussels and Quagga mussels on river morphology. However, the fact the Zebra and Quagga mussel reside primarily on the groynes is enough evidence to determine that their effect on sediment processes is irrelevant. Therefore, only the impact of the Asian clams, which are known to live in the groyne fields, is considered. For this matter, three scenarios are taken into account: 1) A stabilization scenario in which the Asian clams increases the sediment threshold of the sediment inside the groyne fields, 2) A destabilization scenario models the conditions in which the benthic activity (bioturbation) triggers erosion and 3) A maximum stabilization scenario that determines the upper boundary limit of the stabilization processes caused by the Asian clams.

6 MODEL RESULTS

6.1 Introduction

To study the biological influences on river morphology, three different cases based on the current situation of the River Waal were investigated. The results of these cases were then compared with the abiotic scenario, which accounts only for the hydraulic and morphodynamic processes within the navigation channel and groyne fields. This chapter explains the results for three specific zones, where the biological activity is expected to exert the largest influence on morphology. The model assumes constant biological activity (e.g. no density changes in time and no biofilm erosion). Figure 6.1 shows that through the alteration of the erosion threshold within the benthic bed, benthic species not only alter the physical processes inside their communities, but can also produce changes in the vicinity of the benthic bed, as well as in upstream and downstream zones of a river. Zone 2 (Figure 6.2), which comprehends the zone with the benthic accumulation, is the most relevant in this study because it allows to investigate the direct impact of benthic species on the sediment balance of a river. Therefore, the study investigates the hydrodynamic and morphologic changes in the navigation channel, as well as in the Southern and Northern bends and groyne fields. The biological effects on Zone 1 and 3 are believed to be indirectly caused by the benthic alterations in zone 2 and exaggerated by the presence of fixed rock layers in the outer bends of these zones and because of this, only the navigation channel is investigated.

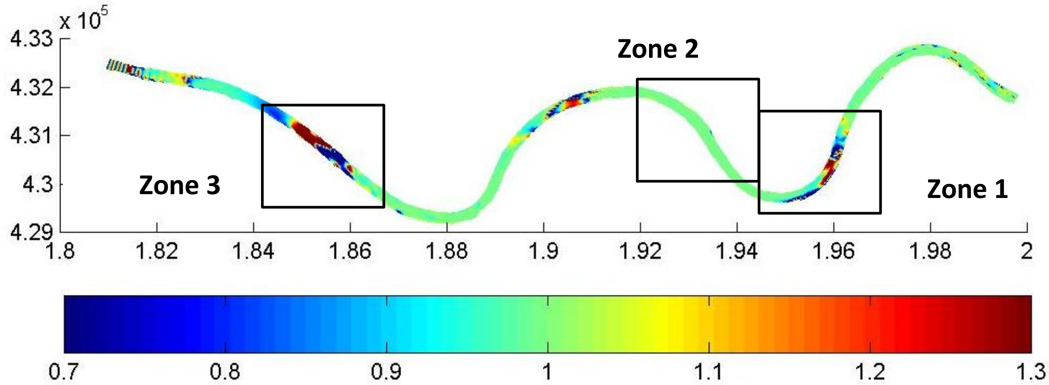


Figure 6.1 Relative cumulative erosion/deposition for the $\tau_{bio} = 2.85\tau_o$ scenario. Fixed values for visualization purposes

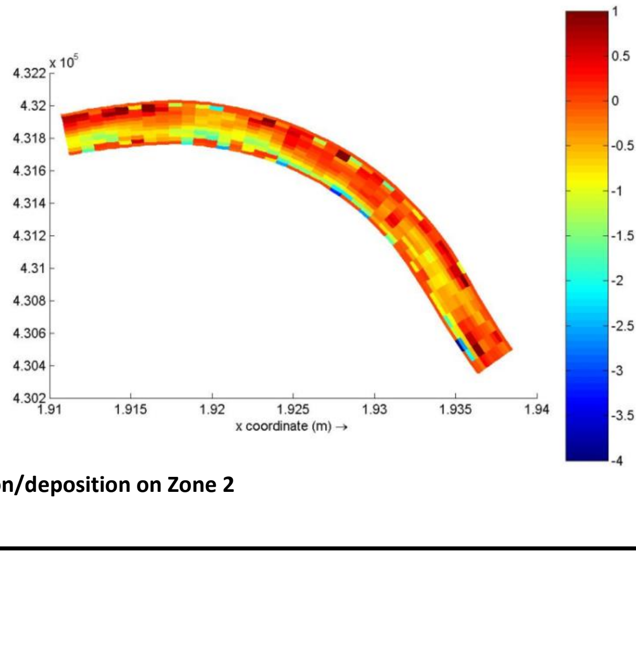


Figure 6.2 Cumulative erosion/deposition on Zone 2

6.2 Results Abiotic Scenario

The abiotic scenario accounts for the morphologic changes caused by the hydrodynamics in absence of biological activity. The model's boundaries conditions are fixed and set as mentioned in section 5.2. Figure 6.3 (top left) shows the bed level trend for the abiotic scenario. During the first 24 months, the morphologic changes are fixed by the MorStt factor (see section 4.4.3), in order to avoid the hydrodynamic "jump" provoked by the boundary conditions, therefore, the bed level does not experience any changes. However, after the morphologic changes are released, the system starts to couple hydrodynamics and morphodynamics, causing abrupt bed level changes within the zone from the 24th to 90th month. Therefore, the results of this study only focus on the last 70 months of the running period, where the system is stable and the impact of benthos is purely caused by biological factors. The section offers the outcome of this abiotic run. This time span was chosen because is believed to represent the most likely impact of the Asian clams during the biotic runs (See section 7.3.1 for further discussion)

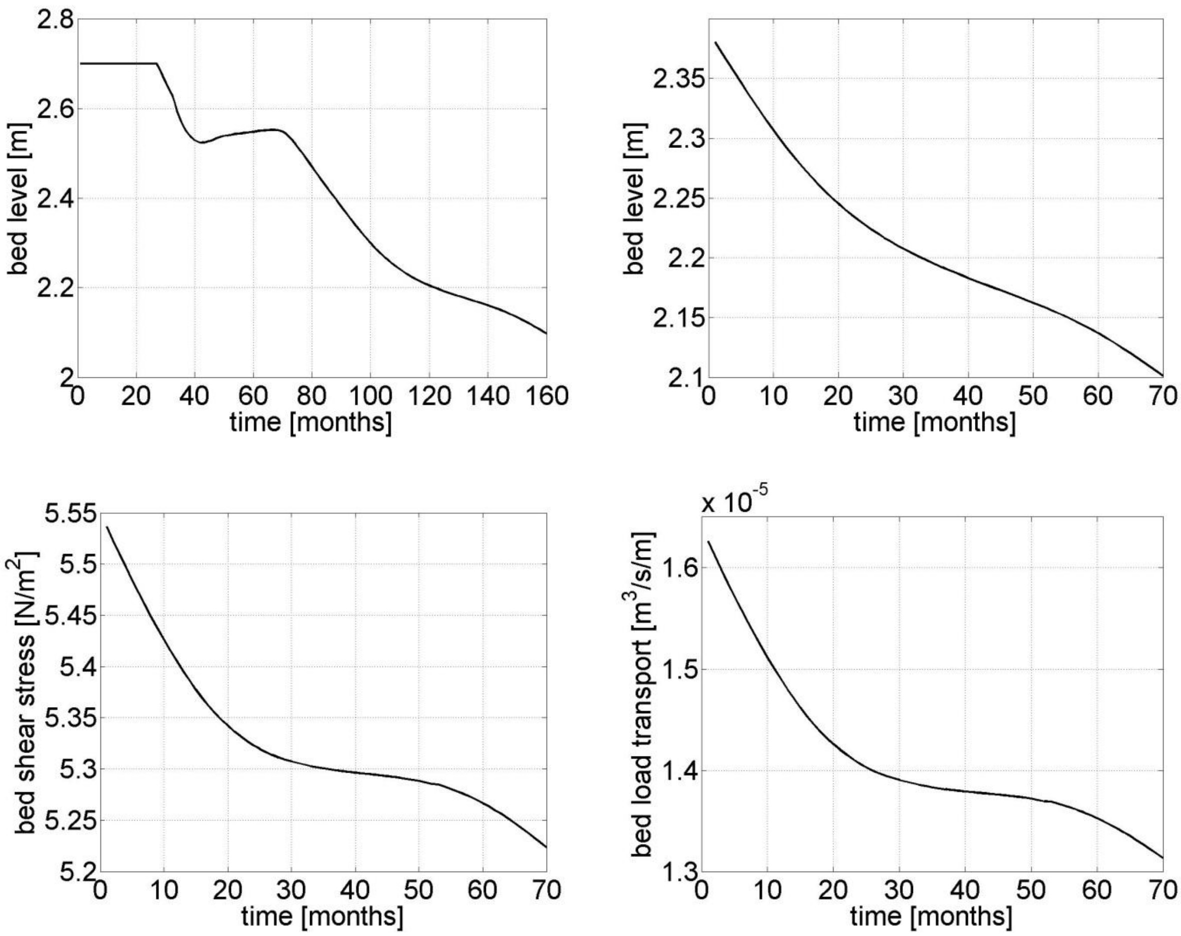


Figure 6.3 Modeled bed level changes in Zone # 2 for a running period of 13 years (top left). Bed level changes after system adjustments (top right). C) Bed Shear stress (bottom left) and the bed load Transport (bottom right)

6.2.1 Zone 2: Navigation Channel

Figure 6.3 displays the averaged bed level, bed shear stress and bed load transport of the navigation channel in Zone 2. The trends imply that for these hydrodynamic conditions, the river is subject to erosion during the complete 13-year period, possibly due to the lack of flooding that supplies sediment into the system. Figure 6.3 (top right) displays the changes in the bed level throughout the last 70-month period. The non-linear changes in the bed level indicate that 13 years of steady hydrodynamics conditions are not enough to produce a constant morphologic outcome, and hence, the model needs more time to stabilize. In zone 2, the influence of the hydrodynamics resulted in a decrease of 0.255 m on the average bed level of the section, which indicates that under steady flow conditions, the bed shear stress is high enough to provoke erosion ($\tau > \tau_{cr}$). The bottom figures in Figure 6.3 illustrate the trends for bed shear stress and bed load transport for the abiotic scenario. The results of the bed load transport are averaged over the x- and y- direction, and therefore equation 3.3 (bed level update) no longer holds, leading to a similar trend line for the bed level. The results indicate that during this time period the decrease of 0.35 N m^{-2} on the bed shear stress produce proportional effects on the sediment transport.

6.2.2 Groyne fields and tips

Groynes play an important role conserving the functions of a river. Among others, they serve to protect bank erosion, provide flood control and maintain optimal navigation conditions (Ten Brinke et al. 2004). The sand exchange between the groyne fields and the river results in two typical transport processes (Figure 6.4): 1) sediment deposition within the groyne fields and 2) a scour hole near the tip of the groynes (Yossef and de Vriend 2010). Where the first one is desired as it provides a deepening of the main channel, therefore improving the navigation purposes. Whereas the second is not desirable due to the damage that this scour has on the structure stability (Uijttewaal 2005) and because the eroded material will be deposited inside the navigation channel (Yossef and de Vriend 2010).

For an average discharge, little to zero deposition or erosion is taking place within the groyne fields in this study area. However, changes in bed level occur along the line that separates the groyne fields from the navigation channel, which in this study is assumed as the area where the scour hole is expected (Figure 6.4). Therefore the study considers the biological impact on sediment behavior along this line. Figure 6.6 shows the impact of hydrodynamics on both the Northern and Southern bend of Zone 2.

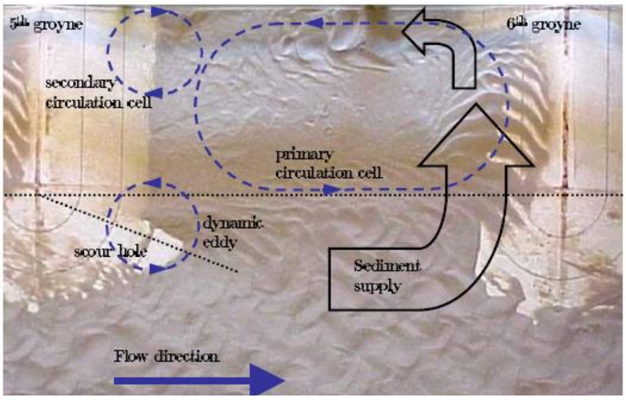


Figure 6.4 Flow and sediment processes for emerged groynes. (flume experiment) (Yossef and de Vriend 2010)

The Asian Clams were allocated inside the groyne fields, where processes diverge from those on the navigation channel (Yossef and de Vriend 2010). The sediment exchange between the groyne fields and its river depends mainly upon two factors: Sediment deposition during flooding and waves induced by navigation. In general, the deposition of groyne fields occurs during a period of high discharge, whereas the erosion is mainly provoked by waves induced by navigation (Ten Brinke et al. 2004). In this study the groynes emerge from the water, in addition, neither the waves nor high discharges were considered and therefore advection is the main transport mechanism inside the groyne fields (Yossef and de Vriend 2010). Figure 6.5 shows the bed level progression for the Northern bend of Zone 2. As predicted, the lack of waves and flooding cause in the system almost negligible effects on the sediment processes within the groyne fields, in the Southern bend there is no sediment transport taking place, whereas in the Northern bend, the transported sediment was in the order of 10^{-14} m^3 s^{-1} m^{-1}, little change that can be attribute to the hydrodynamics in the convex side of the river (Ten Brinke et al. 2004) (Figure 6.8 left). The effect of the hydrodynamics on the convex side of the river is also evident in figure 6.6, which depicts the bed level along the line where the scour hole is assumed (groyne tips). The figure clearly shows that the morphodynamics in the northern bend are not yet stable but keep having some "jumps". However, the bed level decreases more in southern bend, probably as a result of the lateral bed-load transport (Chang 1988). In curved channels the secondary flow tends to move particles away from the concave bank and toward the convex bend, which in this modeling exercise resulted in a bed level drop of 0.12 m after 70 months.

Northern bend

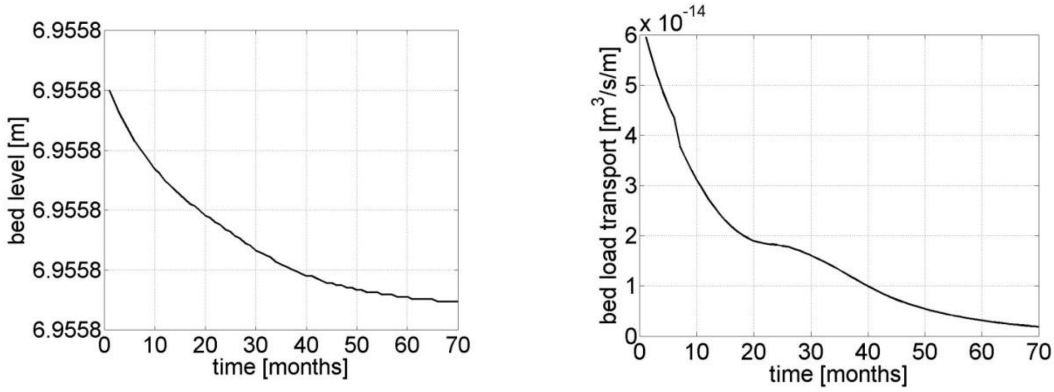


Figure 6.5 **Bed level (left) and Bed load transport (right) in the Northern bend of Zone 2**

Northern bend **Southern bend**

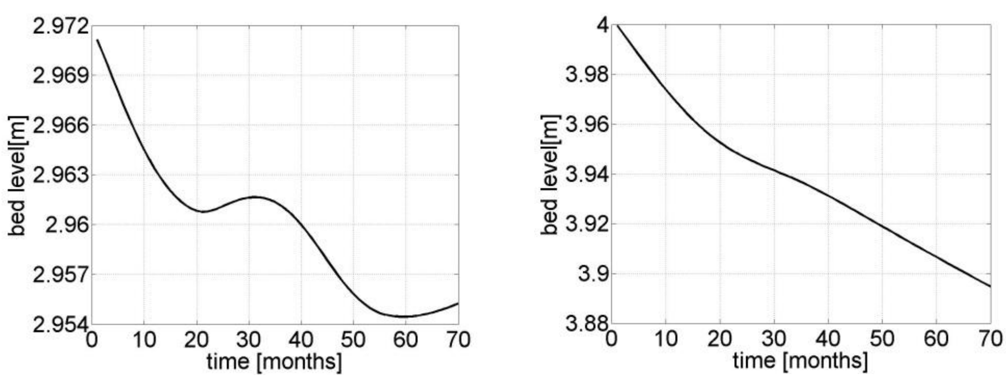


Figure 6.6 **Bed level [m] along the groyne tip line**

6.3 Biotic Scenario Zone 2

6.3.1 Average bed level

As mentioned in section 3.3 the bed evolution in time depends upon the sediment exchange gradient in the x- and y- direction (eq. 3.8). Table 6-1 displays the navigation channel bed level averaged during the last 70 months of the run for the abiotic and biotic scenarios. The results are obtained along the navigation channel, and neglect the deposition inside the groyne fields due to its minor morphological consequences for these hydrodynamic conditions. The bed level correlates with the bed load transport in the navigation channel increasing along the river reach causing erosion and a lower bed elevation (see Figure 6.8 right).

Table 6-1 Average bed level changes [m] and benthic impact on the navigation channel

	Zone 1		Zone 2		Zone 3	
	Bed level	Impact	Bed level	Impact	Bed level	Impact
Abiotic scenario	2.6810		2.2663		1.3136	
Biostabilization	2.6838	-3.414E-04	2.2659	-4.122E-04	1.3131	-4.961E-04
Max. biostabilization	2.6838	-3.425E-04	2.2659	-4.068E-04	1.3131	-4.916E-04
Biodestabilization	2.6838	-3.458E-04	2.2659	-4.149E-04	1.3131	-4.950E-04

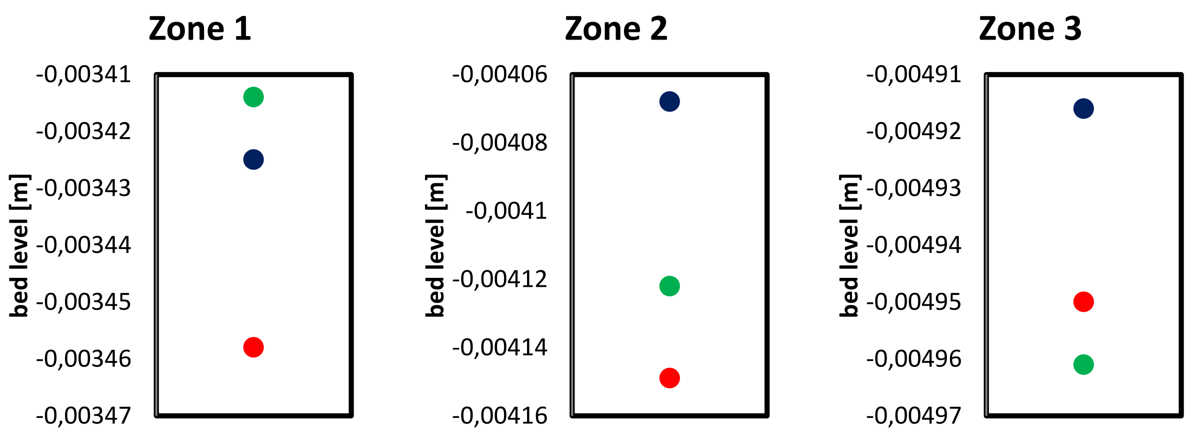


Figure 6.7 Schematization of the impact of benthic species on the navigation channel on the difference zones τ_{bio} = 15.9 τ_o , τ_{bio} = 2.85 τ_o , τ_{bio} = .8 τ_o

Figure 6.7 reflects the average impact that the Asian Clams localized in the groyne fields have on the navigation channel. Regardless the coverage percentage and the impact of the biofilms, the results show that the benthic activity inside the groyne fields will generate erosion along the channel. In Figure 6.7 (zone 2) it can be seen that the biological impact on sediment dynamics follows the expected sediment pattern: higher erosion for the biodestabilization scenario and lower erosion for the scenario with maximum biostabilization. In Zone 1 and 3 this is not the case, presumably because the impact on these zones is not merely caused by benthic interaction, but as a product of a backwater curve initiated in Zone 2 (Figure 6.14). In any way, erosion caused by the benthic activity is extremely small in comparison with the erosion caused by hydrodynamics.

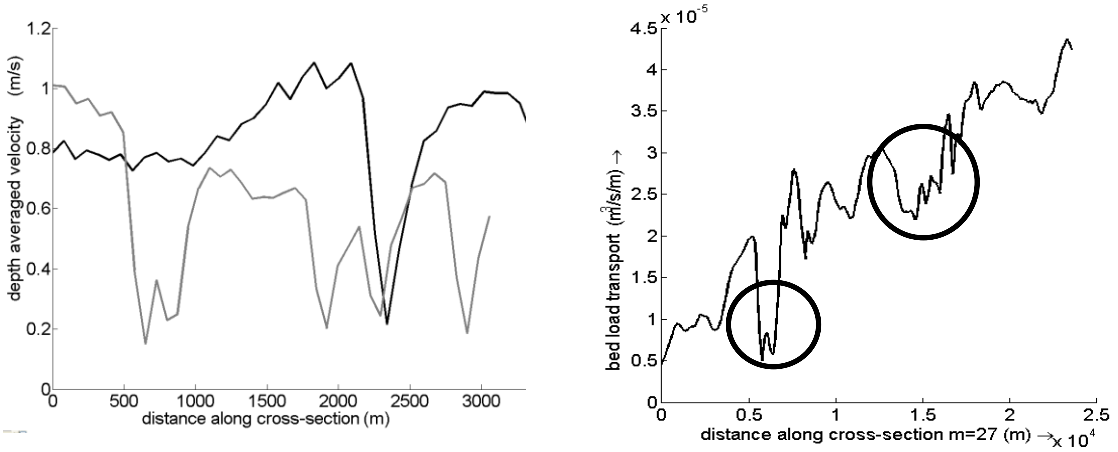


Figure 6.8 Depth averaged velocity (left) in the northern and southern bend (black line Northern, gray line Southern). Bed load transport (right) along a central line in the navigation channel (t=70th month). Fixed rock layers are enclosed.

6.3.2 Navigation Channel

The effects of the boundary condition imposed in the abiotic scenario result in a global erosion of 0.27 m in the Navigation Channel inside Zone 2 (Figure 6.3 top right). For the biotic scenarios, the model predicted similar trends, with slight modifications produced by the benthic organisms. Figure 6.9 displays the changes in bed level, bed shear stress and bed load transport caused by the alteration of the erosion threshold of the sediment inside the groyne fields. Note how the destabilization (τ_{bio}=0.8τ_o) and stabilization scenarios (τ_{bio}=2.85τ_o, τ_{bio}=15.9τ_o) generate similar developments during this period of time, even occasioning the same results during the last 12 months, possibly caused by the assumed constant hydrodynamic and biological conditions seeking for a new equilibrium.

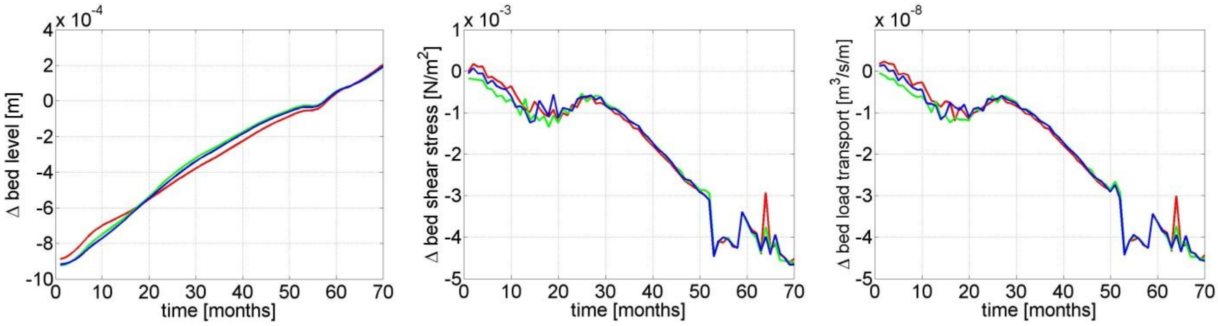


Figure 6.9 Navigation channel changes in bed level (left), bed shear stress (middle) and bed load transport (right) caused by increase/decrease of the erosion threshold (biotic – abiotic). τ_{bio} = 15.9 τ_o , τ_{bio} = 2.85 τ_o , τ_{bio} = 0.8 τ_o

In Figure 6.9 (left) it can be seen how the biological activity indirectly influences the bed level in the River Waal, where in general it produces a reduction of the bed level. Apparently the changes of the erosion threshold inside the groyne fields of this zone causes higher erosion during the first time steps of the run, in addition, the lower bed shear stress causes lower sediment supply (Figure 6.9 middle and right) in the navigation channel, thus impeding the system to recuperate from the morphologic changes of the first time steps. During the complete time period, the biotic scenarios developed less bed shear stress and therefore lower sediment transportation (erosion), leading to a progressive increase of the bed level. Through the first 20 months, the destabilization scenario has the highest bed load transport, nevertheless, it seems that the sediment is being deposited within the same zone leading to an average increase of the bed level. From the 20th to 60th month the three biotic scenarios have the same bed load transport, however, with a higher bed level in the stabilization scenarios (without dramatic changes between the both) and finally, the bed level of the three biotic scenarios converge after the 60th month.

These results suggest that the benthic impact may be enlarged by hydro and morphodynamic changes. Thus, since in reality the discharge is variable, the continuous update of the morphologic changes in conjunction with the biological impact will cause higher erosion within the navigation channel. However, in case of a constant boundary conditions, the system is permitted to reach a new bed level equilibrium (biota included), that according to the last months in Figure 6.9 (left) is higher than the bed level for abiotic conditions and identical amongst biotic scenarios.

6.3.1 Groyne fields

Figure 6.10 displays the direct effect of the Asian clam benthic activity on the sediment and morphologic processes inside the groyne fields. The figure only displays the results on the northern groyne fields because in the southern bend no changes were observed, suggesting that the changes within the zone are merely a product of the benthic impact on the Northern bend. Both the stabilization and destabilization effects are visible in this figure, with different patterns in the bed load transport and bed level amongst the biotic scenarios. Once again, the sudden morphologic changes during the first time step (Figure 6.10 left) seems to cause the highest variations at the commencement of the 70 month-period. Figure 6.10 (middle) represents the biological alteration of the bed shear stress inside the Northern groyne fields, tough the results shows variation with the abiotic scenario, similar stresses and different sediment transportation are recorded amongst the biotic scenarios, expected behavior as the erosion threshold differs from one scenario to another. In the destabilization scenario, the sediment is more erodible due to the benthic activity of the Asian clams, such as pedal feeding and higher roughness, and therefore higher erosion is triggered under similar bed shear stresses. However, the changes in bed level product of the sediment destabilization and stabilization by benthic interaction are in the order of 10^{-7} m (Figure 6.10 left), suggesting that there is a minor sediment exchange between the groynes fields and the navigation channel and therefore irrelevant for the river morphology and its functions.

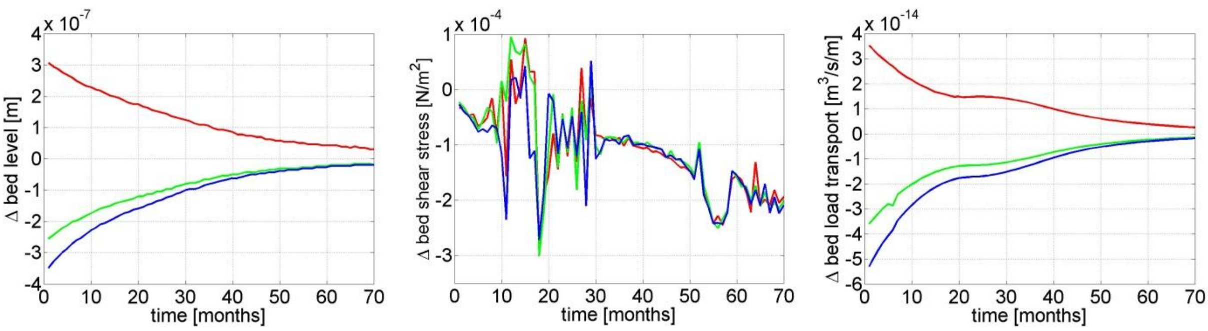


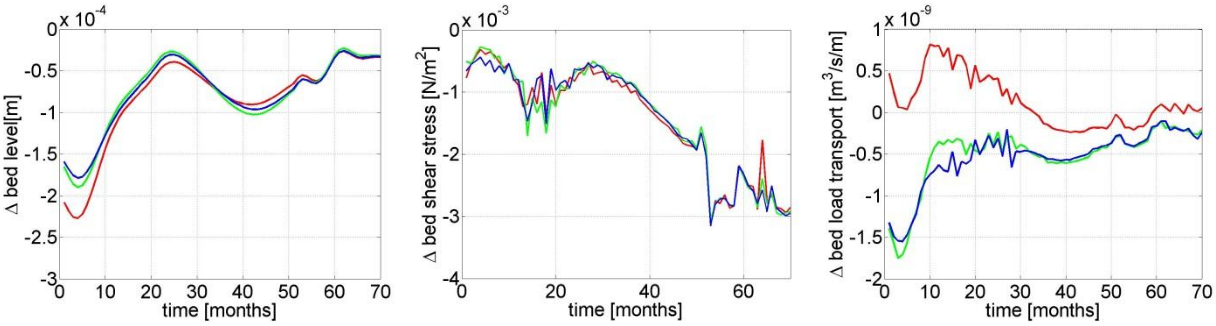
Figure 6.10 Changes in bed level (left), bed shear stress (middle) and bed load transport (right) caused by increase of the erosion threshold (biotic – abiotic). τ_{bio} = 15.9 τ_o, τ_{bio} = 2.85 τ_o, τ_{bio} = .8 τ_o

6.3.2 Groyne tips

In the Northern Bend of Zone 2 (abiotic scenario), the bed level after 70 months was reduced by 0.017 m (Figure 6.6 left). Seemingly, the running time is not enough to stabilize the processes within this line and abrupt morphologic changes continue during this period (see discussion 7.3.1). As a result, the impact of the benthic bed is stimulated during the first months (5^{th}-25^{th}), leading to higher erosion. Figure 6.11 (Above-right) depicts the difference in the amount of sediment being transported in relation with the abiotic scenario. As expected the lower erosion threshold in the destabilization scenario (τ_{bio}= 0.8τ_o) intensifies the bed load transport and causes more erosion (Figure 6.11 top right-middle), while the stabilization scenarios (τ_{bio}= 2.85τ_o and 15.9τ_o) decrease the sediment transport and erosion around the groyne's tips. These results suggest that under the current and extreme conditions, biological activity in the Northern Bend will lower the scour around the groyne's tips, decreasing therefore the deposition inside the main channel. Conversely, in case the densities reach approximately 650 Ind m^{-2} (biodestabilization scenario, τ_{bio} = 0.8 τ_o) and only 25% of the material is being deposition, the impact of biological species will increase the sediment erosion around the groyne tips.

In the southern bend the biological effects are less abrupt (Figure 6.11 bottom) (see Figure 6.8 left). The bed load transport in this line is lower in the biotic scenarios regardless the densities and biofilms, and the bed level stabilizes gradually and in the same rate for the three biotic scenarios. As expected, the bed level is further decreased in the Southern bend as a result of the benthic interaction coupled with the lateral bed-load transport (see section 6.2.2).

Northern bend



Southern bend

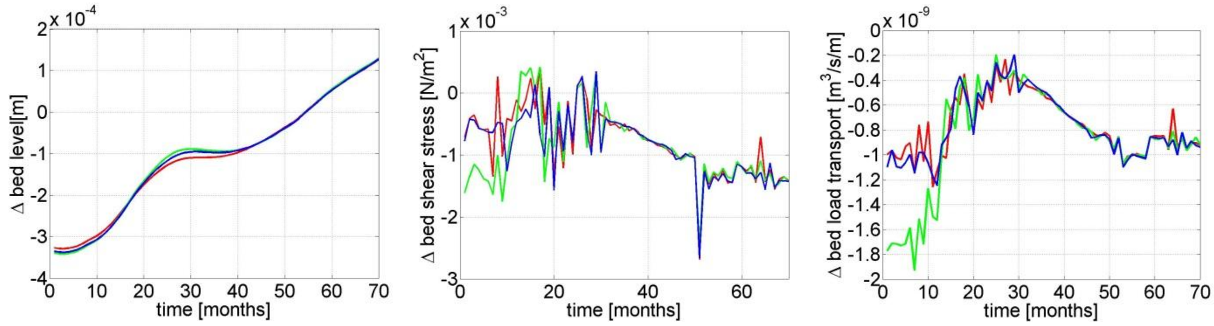


Figure 6.11 **Average morphologic effects on groyne's tip of the Northern (top) and Southern bend (bottom) (biotic – abiotic). τ_{bio} = 15.9τ_o, τ_{bio} = 2.85τ_o , τ_{bio} = .8τ_o**

6.4 Indirect Benthic Effect: Zone 1 and Zone 3

As mentioned in the introduction of this chapter, the little impact of benthic activity on river morphology is not limited to the zones infested by the Asian clams. Variations on the physical processes were registered both in the downstream and upstream direction (Figure 6.1), where the upstream alterations were possibly caused by a backwater curve originated in Zone 2 (Hager 2010) (see Figure 6.14), resulting in an water level and flow velocity increase of the complete river branch. Zone 1 and 3 are located in the vicinity of the fixed rock layers installed to protect the concave bends within this river reach. Figure 6.12 (right) shows the flow velocity throughout the river reach for the last time step of the 13-years period. The circles enclose the peak velocities of the system, which are reached in the vicinity of the fixed rock layers as a result of the smaller transverse area. This increase of flow velocity, leads to a higher bed load transport on the abiotic and biotic scenarios. Figure 6.12 (left) displays the difference between the bed load transport of the biotic scenarios with respect the abiotic scenario. Clearly the biggest alterations result just before the fixed rock layer (3500 km), suggesting that not only a sudden change in hydrodynamics increases the benthic impact but also the hydraulic structures.

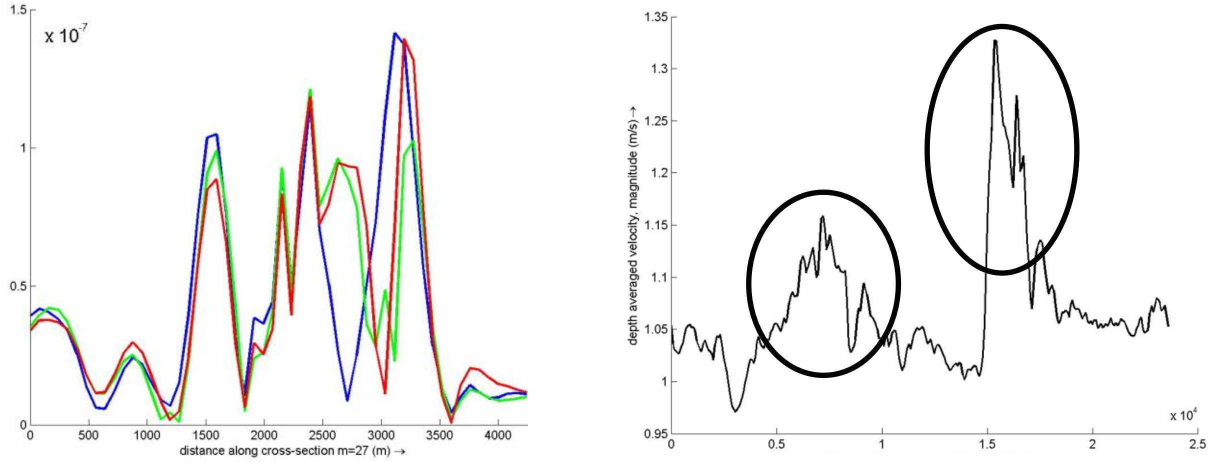


Figure 6.12 Difference in bed load transport [$m^3/s/m$] after 13 years, with respect the abiotic scenario (left). Depth averaged flow velocity for a center line of the navigation channel (right). $\tau_{bio} = 15.9\ \tau_o$, $\tau_{bio} = 2.85\ \tau_o$, $\tau_{bio} = .8\ \tau_o$

Figure 6.13 (top and bottom left) displays the bed level changes through time in zone 1 and 3. In Zone 1 the bed level decreases progressively, while zone 3 is not completely stable yet and suffers a sudden "jump" at the 20th month as a result of morphologic adjustments (Figure 6.13 bottom left). Figure 6.13 displays the bed level and bed load transport change as an indirect effect of the benthic activity localized in Zone 2. As a general trend for both zones, the bed load transport decreases during the complete 70 months, decreasing erosion and allowing the system to recuperate from the morphologic changes of the first time steps. However, it will take 70 and 50 months respectively of constant discharge for Zone 1 and 3 to change from a destabilization to stabilization trend. As previously discussed, these results suggest that variable discharge of the River Waal in conjunction with its benthic activity will contribute to erode the navigation channel of the complete river reach. Nevertheless, the benthic contribution is too small to be considered either as positive or negative for the river functions.

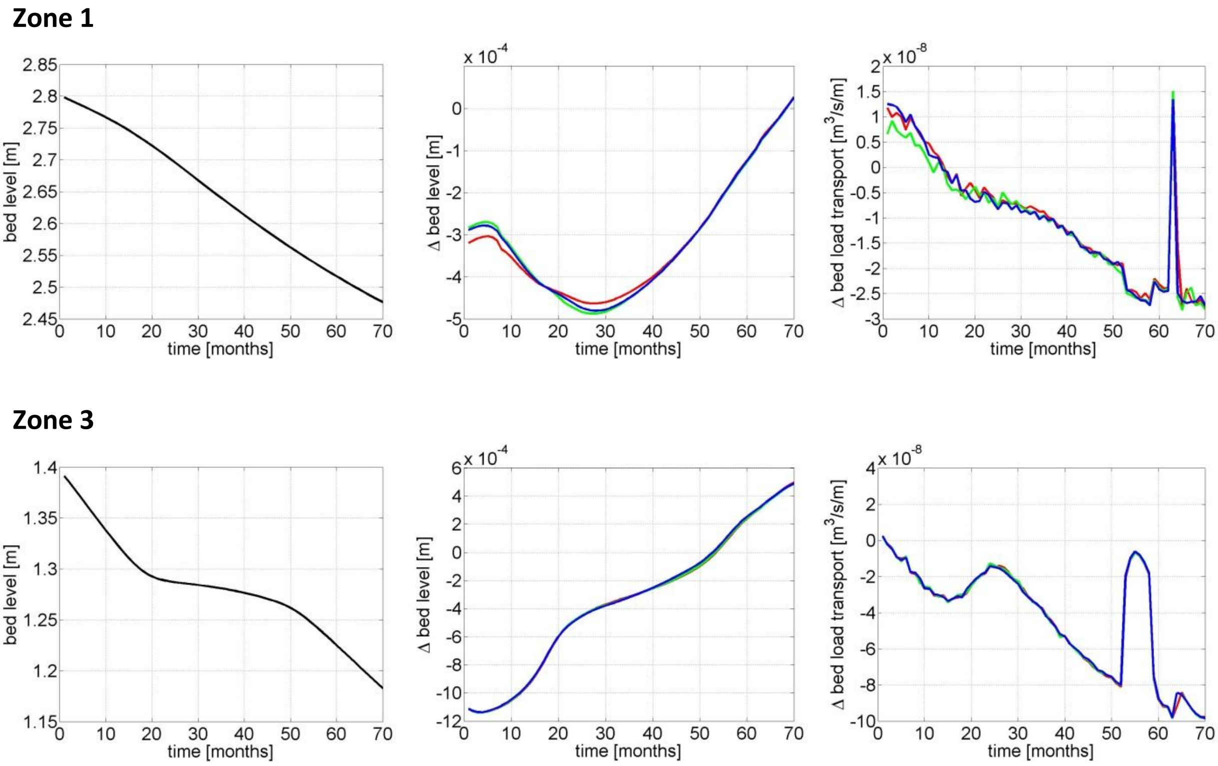


Figure 6.13 **Changes in bed level (left), bed shear stress (middle) and bed load transport (right) caused by increase of the erosion threshold in Zone 1 and 3.** **τ_{bio} = 15.9 τ_o , τ_{bio} = 2.85 τ_o , τ_{bio} = .8 τ_o**

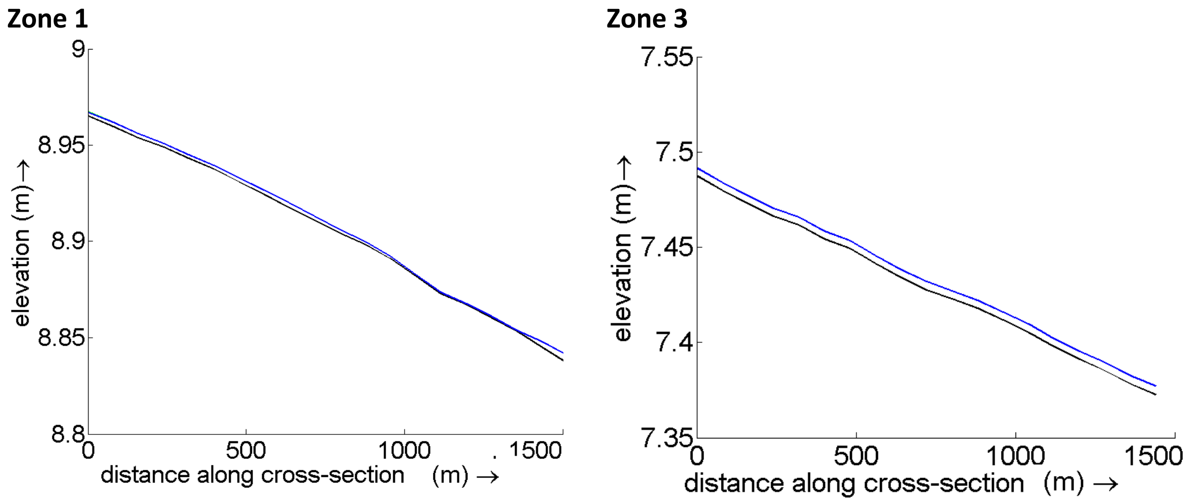


Figure 6.14 **Water levels in zones 1 and 3. Backwater curve caused by the benthic activity in Zone 2 (left), changes in upstream water level (right). The figure only shows the results of the τ_{bio} = 15.9 τ_o scenario because the similarity with other scenarios.**

Conclusion of Results

This Chapter describes the results of the modeling exercise executed to investigate the impact that the benthic activity of the Asian Clams could have on the River Waal. The simulation time extends for 13 years to avoid the sudden morphologic changes caused by the hydrodynamics and to allow the morphodynamics updates during the firsts time steps. However, the results only considerer the last 70 months of this period, because during these last months the modeling results are more stable and solely reflect the biological impact. Further results are not illustrated because were not believed as probable scenarios and because the largest benthic impact took place in the course of the first time steps (see discussion 7.3.1). The results suggest that under these hydrodynamic conditions the benthic alteration of the sediment erosion threshold inside the groyne fields does not have a relevant effect on river morphology.

The minor effect of the benthic activity result in a deepening of the navigation channel for all biotic scenarios, therefore, with no effect on the navigation functions of the river. Three specific locations experience the largest alteration on morphology. Zone 2 where the Asian Clams directly impact the sediment processes within the groyne fields. And Zone 1 and 3, where the changes provoked in Zone 2 indirectly impact the upstream and downstream sections of this river reach as a product of a backwater curve. Changes in Zone 1 and 3 were probably augmented by the hydrodynamic conditions in the vicinities of the fixed rock layer, which increases the bed load transport. This conduct, coupled by the fact that abrupt hydrodynamics changes during the first time steps produced higher erosion for the biotic scenarios, suggest that the erosion caused by the benthic species is closely related to the hydro and morphodynamic processes of the river, and therefore changes in the river's cross section and non-steady conditions are believe to increase the erosion of the navigation channel.

Groynes serve to preserve the river functions, among others they protect the river banks against erosion and conserve optimal navigation conditions. Under constant hydrodynamic conditions, the current colonization of the river system benefits from the benthic activity, especially by the biofilms for which the erosion threshold is more sensitive than the coverage percentage. Overall the Asian clam is expected to reduce the erosion taking place inside the groyne fields and around the groyne's tip, therefore decreasing the amount of sediment being deposited inside the navigation channel. In conclusion, no negative impact for the river functions are expected under steady and non-steady hydrodynamics conditions.

7 DISCUSSION

When modelling physical processes, it is common that there are so many variables related to the study that the researcher has to take the decision to neglect processes, looking for a better understanding of the parameters subjected to the investigation. This is also the case in this study, which tries to couple the effects of biological activity and physical processes within a river system. Trying to implement the biological and physical processes accurately can be time consuming, impossible due to the restrictions of the computer program knowledge or might results in high uncertainties. Therefore, several assumptions have been made throughout this investigation. In this section, these assumptions are discussed.

7.1 Biological Activity

7.1.1 Effect of temperature and flow velocity

The temperature and discharge in this study were considered constant and inoffensive for the benthic species, however in reality these factors play an important role in the habitat conditions of these species. For instance, although the filtration rate appeared not relevant for this study, it can be lower during low temperatures (MacIsaac 1996), in addition, the low temperatures in the Waal during the winter season (Figure 7.1) are close to the lower permissible limit of the Asian Clam of 2 ^{o}C (Werner and Rothhaupt 2008) and can impede further colonization of the species. Similar to the water temperature, the discharge (and therefore flow velocity) is in constant change throughout the year, which could prevent the settlement of juveniles (Morales et al. 2006) and detach the adults from the sediment (MacIsaac 1996). In conclusion, if these factors were to be considered, the expected effects on river morphology would be lower than the obtained in this study.

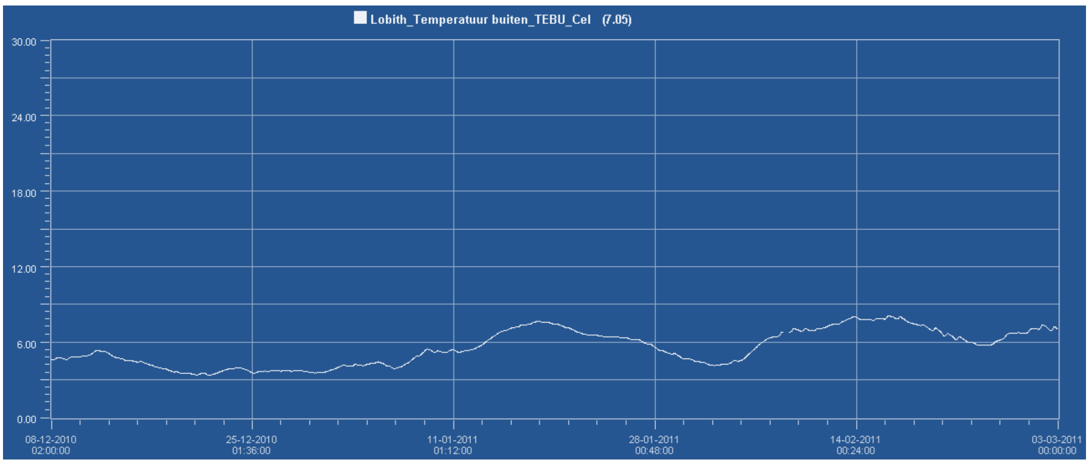


Figure 7.1 Temperature of the Rhine at the Lobith Station. Obtained data from: Ministerie en Verkeer en Waterstaat. Retrieved 26/06/2011 from : http://www.aqualarm.nl/

7.1.2 Bioturbation by Asian clam

In this study is assumed that the Asian Clams are the only bivalves living in the groyne fields, even though the literature study indicated that the Zebra and Quagga Mussel are also capable to live in sediment (Mackie and Schloesser 1996). Therefore, the Asian Clam is the only species that through its benthic activity causes direct sediment stabilization or destabilization. The Asian Clam can bioturbate the sediment around itself in different ways: 1) redirecting the flow around shells (Neumeier et al. 2006; Miyawaki et al. 2008), 2) destabilizing the sediment trough pedal feeding (Mackie 1991), 3) crawling through the bed searching for food and 4) burrowing into the sediment. However in this study, the impact of the crawling, which can be up to 1.5 m d^{-1} is neglected by suggestion of Dr. R.S.E.W Leuven (personal communication, 2011). In conclusion only the overall impact of the coverage percentage on sediment is taken into consideration. This measure is adequate as the non-cohesive sediments in the River Waal lack the physico-chemical interaction of the cohesive sediment (Brown et al. 1999). Erodability of non-cohesive sediment depends upon the mean grain size D_{50} and flow conditions, therefore the benthic movements of the Asian clams are not breaking any physico-chemical binds nor increase erodability.

7.2 Parameterization

7.2.1 Biodeposition effect on sediment

When combining the effects of coverage and biofilms, it is clear that the effect of the biofilm on the erosion threshold is considerably higher. In Section 2.2.4 was mentioned that the sediment erosion threshold can increase by a factor of 10 in the marine environment (Neumeier et al. 2006; Le Hir et al. 2007) and therefore two assumption were made: 1) The erosion threshold inside the groyne field can increase by a factor of ten and 2) The impact of the biofilm in the erosion threshold increases linearly (e.g. 30 % biofilm development = $3\tau_o$). The former can lead to an overestimation of the erosion threshold because in a marine environment the sediment consists of cohesive particles (Widdows et al. 2002; Paarlberg et al. 2005) which will be easy for the biofilm to glue due to its natural physico-chemical characteristics (Brown et al. 1999) (see Recommendations). The latter is assumed due to the lack of research in this topic, however, the relationship between biofilm and sediment erodability is unknown and worthwhile to study due to the possible impact in other aquatic systems and for different densities.

7.2.2 Densities

The densities in this study were assumed constant, however, in reality densities may vary along the river. The settlement of benthic species is highly influenced by the flow and sediment stability and therefore some locations are more suitable than others for benthic accumulation (Morales et al. 2006; Sousa et al. 2008). This is also the situation for the river Waal, which presents highly populated areas in addition to areas with low densities, a situation that may lead to areas in which the benthic activity triggers erosion and other areas in which the sediment is being stabilized, thus creating a different exchange pattern within the groyne fields and the navigation channel.

7.2.3 Algae interaction with the erosion threshold

Different researchers have found and use the correlation between the Chlorophyll *a* content and sediment stability to model the biological effects on different aquatic systems (Widdows et al. 2002; Paarlberg et al. 2005; Borsje 2006). In this study, this relation was not utilized because the direct impact of the coverage and biofilm was assumed to be more relevant. Nevertheless, the reduction of Chlorophyll *a* by the filter mechanisms of the Asian clams, Zebra and Quagga mussels, could have an impact on the erosion threshold of the navigation channel, meaning that not only the Asian clam will play a role in sediment dynamics but also the other two species, and that the impact on sediment dynamics will not be restricted to the groyne fields.

7.3 Model

7.3.1 Steady vs non-steady flow conditions and time span (13-years period)

Scientific research often uses constant boundary conditions to simplify the physical processes within models in order to have a better understanding of the processes under investigation (see Paarlberg et al. 2005; Uijttewaal 2005). This is also the case of this study, which assumed constant hydrodynamic conditions (average discharge) in order to have a better visualization of the biological impact within the model. Naturally, this condition does not equal reality, but it was a valuable assumption in order to subtract the impact of non-steady hydrodynamics and merely quantify the benthic intervention. Even though the model was bounded by a constant condition (discharge), during the first time steps the model needed time to couple the hydrodynamics with the morphology, leading to non-steady flow conditions. These non-steady flow conditions resulted in a relatively large erosion of the River Waal during the first time steps (Figure 6.3) and produce the largest benthic impact (Figure 6.9). These results suggest that under the real dynamic changes, the biological interaction will always reduce the bed level in the navigation channel, contrary to the obtained results in figure 6.9, where during the last months, the benthic impact produce an elevation of the bed level. The change from an overall reduction to an increase of the bed level by the benthic activity is not reached until the model is running for 12 years of steady conditions, situation that will never happen in reality. Therefore, it was decided not to take into account the results of further years.

7.3.2 Flow velocity and temperature

Definitely the largest effect of constant flow velocity and temperature will not be the one related with the biological activity, but with the hydrodynamics and morphology. The temperature affects sediment transport trough two mechanisms. The first is the viscosity, which decreases at higher water temperature and therefore increasing the settling velocity (Chang 1988). The second one is that related with flow resistance. At lower temperatures the flow discharge becomes steadier and dunes can gradually wash out, thus flattening the bed and dropping the friction factor. Additionally, the flow velocity varies throughout the year (Shabalova et al. 2003) thus continuously changing the transport processes and bed forms in the navigation channel (Chang 1988).

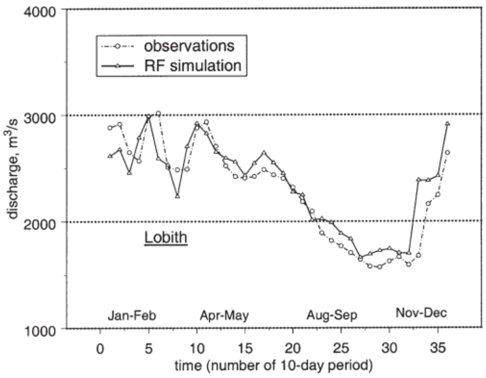


Figure 7.2 **Observed discharge of the Rhine at Lobith compared with a simulation (Shabalova et al. 2003)**

7.3.3 Groynes

As commented in the results, groynes are essential to control the river functions. In this study the boundary conditions were fixed and therefore the study only accounted for the situation with emerged groynes. However, the processes for when the groynes emerged from the water level diverge from when they are submerged. In the former the sediment is advected to the groyne fields following the path of the primary circulation cell (see figure 5.6), whereas in the submerged case the sediment is transport across the whole length of the normal line (Yossef and de Vriend 2010). Additionally, Ten Brinke et al. (2004) state that erosion inside the groyne fields is mainly produced by waves induced by the navigation.

If the effects of high discharges and navigation were considered, the model should display higher deposition inside the groyne fields during high discharges (submerged groynes) and higher erosion in situations with emerged groynes (waves). During high discharges (assuming low washing off of benthic species) the Asian clam will benefit from the deposition of nutrients taking place inside the groyne fields, it may also lower the deposition of material as the species will bioturbate the sediment by crawling to the top of the sediment layer (Karatayev et al. 2010), the effect of this upward migration on sediment stability is not well-documented, however, is not expected to cause major changes in the net deposition inside the groyne fields.

On the other hand, benthic species may play an important role in sediment stability during periods of lower discharges in which the navigation waves provoke erosion. Figure 7.3 displays the bed shear stress on a south bank of the River Waal (Ten Brinke et al. 2004). The black line represents the abiotic critical bed shear stress inside the groyne fields of the model provided by Deltares. Clearly, the waves induced by navigation exceed the abiotic critical bed shear. However, the alteration of the erosion threshold inside the groyne fields could dramatically change the sediment exchange between groyne fields and the navigation channel. The green and blue lines in Figure 7.3 represent the stabilization scenarios in this study. The bed shear stress increment product of an extreme colonization (blue line) could almost stop the erosion within the groyne fields. This situation is unlikely to happen because it assumes that the biofilm is not being eroded and that the density is reaching the maximum ever recorded (3200 Ind m^{-2}) (Karatayev et al. 2010).

However, if the current situation in the River Waal is considered, the scenario may also contribute to the reduction of erosion inside the groyne fields (Figure 7.3 green line). An increase of a factor of 2.85 (from .036 N m^{-2} to 1.03 N m^{-2}) of the erosion threshold, due to a density of 130 Ind m^{-2} and a biofilm development of 30% is the closest scenario to reality and it may enhance the function of the groynes. According to Uijttewaal (2005), the deepening of the channel is a wanted effect of the groynes in a river. Apparently, the current situation in the River Waal may decrease the sediment exchange from the groyne fields into the navigation channel and thus the unwanted deposition inside the navigation channel could be lowered by benthic interaction. Conversely, the destabilization scenario will increase the sediment exchange into the main channel, but as in the maximum stabilization scenario, the densities of the Asian Clams are too extreme in comparison with the current situation to determine that this is what is happening in reality. In conclusion, groyne field erosion may be diminished by the Asian Clams, especially in the straight stretches, where navigation waves play an important role generating erosion (Ten Brinke et al. 2004).

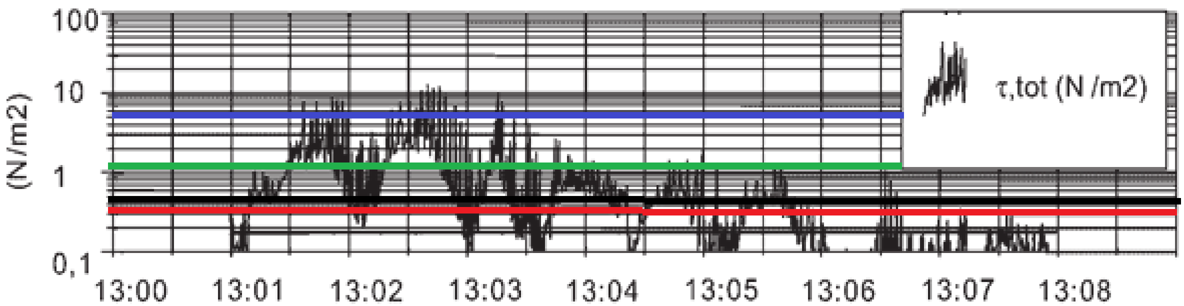


Figure 7.3 Bed shear stress on the south bank, of a straight stretch of a the River Waal, during the passage of a fully loaded motorized vessel (Ten Brinke et al. 2004). Lines: τ_0, τ_{bio}=.8 τ_0, τ_{bio}=2.85 τ_0, τ_{bio}=15.9τ_0

8 CONCLUSION AND RECOMMENDATIONS

The aim of this research was *to investigate, by using a Delft 3D model, the influence of benthic species on water and sediment dynamics, and the possible changes on river bed morphology due to the presence of benthic species.* Based on this aim, four main questions were proposed. The conclusions of this study are done by addressing these questions:

8.1 Answers to Research Questions

How do benthic organisms influence sediment dynamics in river systems?

Benthic organisms influence the sediment dynamics of aquatic systems through four main processes: coverage of sediment, bioturbation, creation of biofilms (EPS, extracellular polymeric substances) and filtration feeding. The benthic coverage may stabilize or destabilize the sediment by redirecting the flow between the shells of the organism (Miyawaki et al. 2008). Bioturbation of sediment, defined as "all the processes implying sediment particle displacements generated by benthic organism in order to satisfy their vital needs (motion, protection from predators, feeding and excretion)" (Le Hir et al. 2007). These include, the pedal activity of the Asian clam, which uses a foot to collect buried nutrients from the substrate (Mackie 1991), the crawling along the river bed and the burring activity which can be as much as two centimetres (Karatayev et al. 2010). The creation of biofilms (EPS) increases the erosion threshold and decreases the erosion rate. The sediment stability caused by this substance occurs by two mechanisms. 1) The EPS binds the surface of the sediment particles by increasing the interparticle attractive forces and 2) form strands that connect sediment particles, increasing stability by physical binding (Tolhurst et al. 2002). Finally, the filtration rate of benthic species may increase sediment deposition within the benthic communities, however, in section 4.1.3 was determined that due to the higher settling velocity this activity does not provoke relevant changes in river sedimentation.

How can the biological processes be parameterized in order to be recognized by the transport equations in Delft 3D?

Delft 3D is able to calculate the transport of non-cohesive sediment by different transport formulas (Van Rijn (1993), Engelund-Hansen (1967), Bijker (1971), etcetera). All these formulas depend on the median grain size D_{50}, which can be altered per grid cell to locally incorporate the changes in sediment erodability (See Deltares 2009). This study uses the Van Rijn' 84 equation to model the bed load transport. The formula calculates the bed load transport rate in accordance with the Shields parameter (3.16), which is a function of the median grain size $D_{50.}$ Therefore, altering the grain size of the sediment inside the groyne fields will automatically change the erosion threshold, modelling in the exact location the expected changes as a result of the coverage percentage and biofilms (see section 4.2). In order to avoid modification of the transport rate by the alteration of the roughness product of the different grain size, the trachytopes files can be utilised. These files allow the user to specify the roughness on a sub-grid level, thus preventing the possible over (under-) estimation due to different grain sizes.

To which biological parameters are the sediment processes more sensitive?

The overall effect of coverage and biofilms will results in a rise/decline of the abiotic erosion threshold depending on the biodeposition and densities (see Chapter 4). The bioturbation of species, caused in this study by the Asian clam coverage of the area, can contribute to both stabilization and destabilization of sediment (see Figure 4.1). For coverage percentages of 27 %, the destabilization caused by this species reaches its maximum, decreasing the abiotic erosion threshold to 20% and for maximum coverage percentages increasing it by 60%. For the current situation in the River Waal (130 Ind m^{-2}), the cover percentage (no biodeposition) of 4 % was calculated to reduce the abiotic erosion threshold by 5 %.

In contrast with the coverage percentage, biofilms will only increase the erosion threshold of aquatic systems (Tolhurst et al. 2002; De Brouwer et al. 2005). Until what extend the biofilm will increase the erosion threshold of river sediments is still unknown, but the ranges for marine systems hover between 1 and 10 times (see section 2.3.2) and therefore this values were assumed in this study. When combining both effects on sediment during the parameterization (Figure 4.2) it can be seen that sediment dynamics in river systems are more sensitive to the alteration of the erosion threshold by the biofilms for coverage percentages between 0-20 % and 55 – 100 %, whereas the bioturbation caused during coverage percentages between 20-55 % will govern the erosion threshold of the groyne fields. At the moment, biofilms seems to produce the larger alterations inside the groyne fields, however still considerably small to account on morphology.

What is the impact of each species on bed and suspended sediment transport, bed roughness, flow velocity, erosion/deposition, water level?

For the current situation of the River Waal, in which the Zebra and Quagga mussels live on groynes and the Asian clam habitats the groyne fields. Literature study and data from the River Waal (R.S.E.W Leuven, personal communication) suggest that only the Asian clams are expected to produce changes river morphology. Table 8-1 gives a summary of that these species have on the modelling exercise.

Table 8-1 Impact of benthic species on the modeling exercises

Processes	Benthic impact
Bed transport: (erosion)	It can be increased and decreased depending on the impact of the processes within the benthic bed (coverage percentage and biofilm). If there is an accumulation of biodeposition, the sediment will be harder to erode and the bed transport will decrease. In contrast, the different benthic densities can either stabilize or destabilize the sediment. For the current situation in the Waal, the results show that the density of the Asian clams is triggering erosion, however it is expected that the biofilm will play a major role reducing sediment transport.
Suspended transport: (deposition)	This is the only process on which all the three species have an effect. Through their filtration feeding activity, the Asian Clam, Zebra and Quagga mussel will decrease the suspended sediment concentration of the River Waal. However, the settling velocity of the particles travelling in suspension is considerably higher than the additional settlement cause by the filtration rate.
Bed roughness:	Due to the small alteration of sediment dynamics in the modelling exercise, the bed roughness changes produced by benthic activity are too small to be considered. On the other hand, flume experiments have demonstrated that the additional roughness increase turbulence and thus erosion.
Flow velocity:	The shell roughness which according to the literature review alters the flow direction and velocity was not included physically in the model, the overall effect was included within the parameterization of the coverage factor and therefore the benthic impact on the flow velocity cannot be investigated quantitatively. The changes in flow velocity between scenarios were product of a higher water level in the complete river reach.
Water level	The negligible changes in sediment dynamics leaded for all biotic scenarios to an increase of the water level of the complete reach and therefore changes in the upstream and downstream direction. This increase of the water level is merely related to differences in sediment dynamics between the abiotic and biotic scenarios and must not be confused by the water level increase that the presence of a benthic bed could cause.

8.2 Do We Have to Account for Benthos?

This study addresses the impact of benthic species (*Corbicula fluminea, Dreissena polymorpha and Dreissena bugensis)* on river morphology. The Delft 3D model has been set-up according to the real conditions of the River Waal (e.g. bathymetry, groynes) and the parameters (e.g. MorFac, discharge) were previously calibrated by Deltares in order to deliver an accurate simulation of reality. It is important to bear in mind that the outcomes of this modelling exercise are a product of the biologic, hydrodynamic and morphologic interaction under the defined conditions. Different conditions (e.g. densities, discharge and depth) will obviously change the results of this analysis. Furthermore, it must be remarked that the study only reflects the physical and direct impact that benthic organisms have on sediment dynamics, other processes caused by their benthic activity such as the reduction of chlorophyll *a* (Schöl et al. 2002) or penetration of oxygen into the sediment (Jones and Lawton 1994) may play a role in sediment dynamics (Paarlberg et al. 2005) but were not included due to lack of documentation and in order to bound the modelling exercise to merely morphologic effects.

To analyse the benthic influences on the morphological changes in the River Waal, the study performs the parameterization of the two main processes affecting sediment erodability: the erosion caused by the coverage percentage and biostabilization caused by the creation of biofilms of pseudofaeces and faecal pellets. For the colonization reached in the River Waal, sediment stability seems to be more sensitive to biofilms than to the erosion caused by the Asian clam communities. Literature study and current data of the River Waal (R.S.E.W Leuven, personal communication) suggest that only the Asian clams are expected to produce changes in the sediment erodability and morphology. Apparently, the Zebra and Quagga mussels have not yet migrated onto the sediment and the colonization remains on the groynes, therefore, only the Asian Clams living in the groyne fields are exerting a direct change on sediment stability.

In average hydrodynamics conditions and no navigation activity, the impact of the Asian clams inside the navigation channel seems to have negligible effect on the river morphology, in general they tend to produce a deepening of the navigation channel, which may enhance navigation, but the changes are too small to be considered. The highest sediment alterations are product of their direct benthic activity (bioturbation and biofilms) and should be expected within the groyne fields. The current colonization in the River Waal suggests that the Asian Clams biostabilizes the sediment, reducing the bed load transport in groynes and the sediment exchange into the navigation channel, however, with low impact on morphology due to the lower flow velocity in these zones. Benthic organism may enhance the groyne functions by preventing groyne field erosion due to navigation waves during low discharges. Nevertheless, this supposition is yet to be investigated.

In conclusion, under steady conditions and no erosion induced by navigation waves, the exotic benthic species in the River Waal do not play an important role on river morphology and if any tendency is to be expected it would have a positive effect on navigation. Therefore, the hypothesis that benthic activities in river systems may affect the morphologic processes of rivers as in marine and estuarine systems is rejected. Apparently the conditions in those aquatic systems, such as cohesive sediment and lower flow velocities, are more sensitive to benthic interaction.

8.3 Recommendations for Future Research

Regarding the effect of biofilms on sediment erodability.

Efforts have been made in literature to understand the impact of biofilms (EPS) on sediment erodability (Widdows et al. 2002; De Brouwer et al. 2005; Neumeier et al. 2006). Until now, the research has lead only to approximations, with interesting correlation between chlorophyll *a* concentration and the erosion threshold (Paarlberg et al. 2005; Borsje 2006). Nevertheless, most of these studies have been performed in marine and estuarine systems and for a limited number of species (e.g. *Macoma balthica* and *Myilus edulis*). No investigation has been made in relation with the impact of biofilms in river system and for river species.

A complete study of the effect of benthic species present in the Dutch rivers would be very helpful to investigate correctly the impact of benthic organism on river morphology. From this study it can be concluded that benthic organisms can impact sediment dynamics in three ways: 1) bioturbation, 2) changing sediment erodability (biofilms) and 3) increasing deposition of material through filtration rate. The correct understanding of the role of biofilms in sediment dynamics will help to obtain more reliable results.

Regarding grid size and local impact on sediment (groynes)

In the current model, the grid cells inside the navigation channel are too big to include the impact of the benthic species locally, and therefore it was assumed the same impact for the complete area. However, in reality benthic accumulation and biofilms development occur in patches rather than complete areas (Neumeier et al. 2006; Van Leeuwen et al. 2010). A smaller grid could facilitate the modelling and visualization of these patchy areas. In this research, the objective was to determine the impact of benthic activity on the complete river branch. Partly because of the limitation within the model grid, the study did not take into account the local effect that the benthic organism may have inside the groyne field. The study of this is highly recommended due to the possible effects of benthic organisms on the sediment exchange between the groyne fields and the river and the importance of this exchange for navigation purposes. In order to carry out this study a variable discharge, a finer grid, the implementation of suspended sediment, the introduction of several layers within the water column and the presence of waves are recommended.

Regarding the possible routes of invasion.

In this study the effects on sediment dynamics caused by the three species is discussed. However, as mentioned in the introduction and in chapter 2, the invasion of these exotic species are known to cause large economic losses due to the ecologic changes they produce in the aquatic systems (Thorp et al. 1998; Schöl et al. 2002), and principally, for the high density biofouling on water pipes of industries and power plants (MacIsaac 1996). Connelly et al. (2007) estimated the total economic impact caused by the Zebra mussel on drinking water plants and electric power facilities throughout United States, comprising a period from 1989 to 2004, the economic losses rose up to $267 million dollars.

Clearly, the most straight forward economic impact is that related with the biofouling of the Zebra and Quagga mussels on industrial pipes. This major concern calls for an investigation of the possible routes of invasion of these species, in order to predict the highly prone zones for invasion. Similar studies have been performed by Murray et al. (1993), based on water chemistry data, however only for the conditions of the United States, nothing has been done to understand the potential invasion of these species in the Netherlands or Europe. A correct forecast of the invasion routes will prevent the authorities, giving them time to control the invasion, reducing thus the risk of a non-expected rise in maintenance cost.

Regarding Impact on other aquatic system (e.g. canals)

Invasion of the Asian clam, Zebra and Quagga mussel have been reported in rivers as well as in other freshwater aquatic systems such as lakes, reservoirs, streams and canals. In all these other systems the water and sediment processes differ from each other (e.g. flow velocity and deposition), which can ease the invasion of some species over the others. For instances, higher densities of Zebra mussel should be expected in lakes because Zebra mussel can be easily swept downstream, whereas the population of Asiatic Clam is not highly impacted due to the crawling activity of the species, which allows them to move freely upstream and downstream (Karatayev et al. 2005).

However, both species can be abundant in canals, where the conditions for the invasion are favourable. In canals the current maintains an appropriate level of nutrients and oxygen, in addition the lower flow velocity stabilizes the sediment and the suspended concentration is much lower. Records of extremely high densities have been found in canals. Karatayev et al. (2005) reported densities between 40000-61000 Ind m^{-2} for the Zebra mussel and 2255-16688 Ind m^{-2} for the Asian clams, which suggest than in canals, the impact of these exotic species on morphology could be expected larger than in rivers.

Regarding the navigation and variable discharge

As previously mentioned, in order to highlight the benthic impact, several assumptions were made. These include the absence of the role that navigation and a variable discharge play on the sediment exchange between the river and its groynes. Ten Brinke et al. (2004) state that deposition within the groyne fields takes place within high discharges, when the groyne are submerged, whereas erosion from the groyne fields is mainly influenced by navigation waves. Therefore, the introduction of these two processes is suggested in a further research of the impact of benthic species on river morphology. From the results of this modelling exercise and the literature study of the species, it can be hypothesized (assuming no benthic wash-off) that sediment will be deposited within the groyne fields during the flooding, and the Asian clam will always migrate to the top of the sediment, thus creating biofilms and increasing the erosion threshold of material just being deposited. Therefore, after the flooding period is passed the erosion of the groyne fields caused by the navigation waves will be reduced, decreasing thus the exchange of sediment from the groyne fields into the navigation channel. If this hypothesis is proven, it could be concluded that the impact of benthic species on rivers is beneficial for navigation purposes.

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