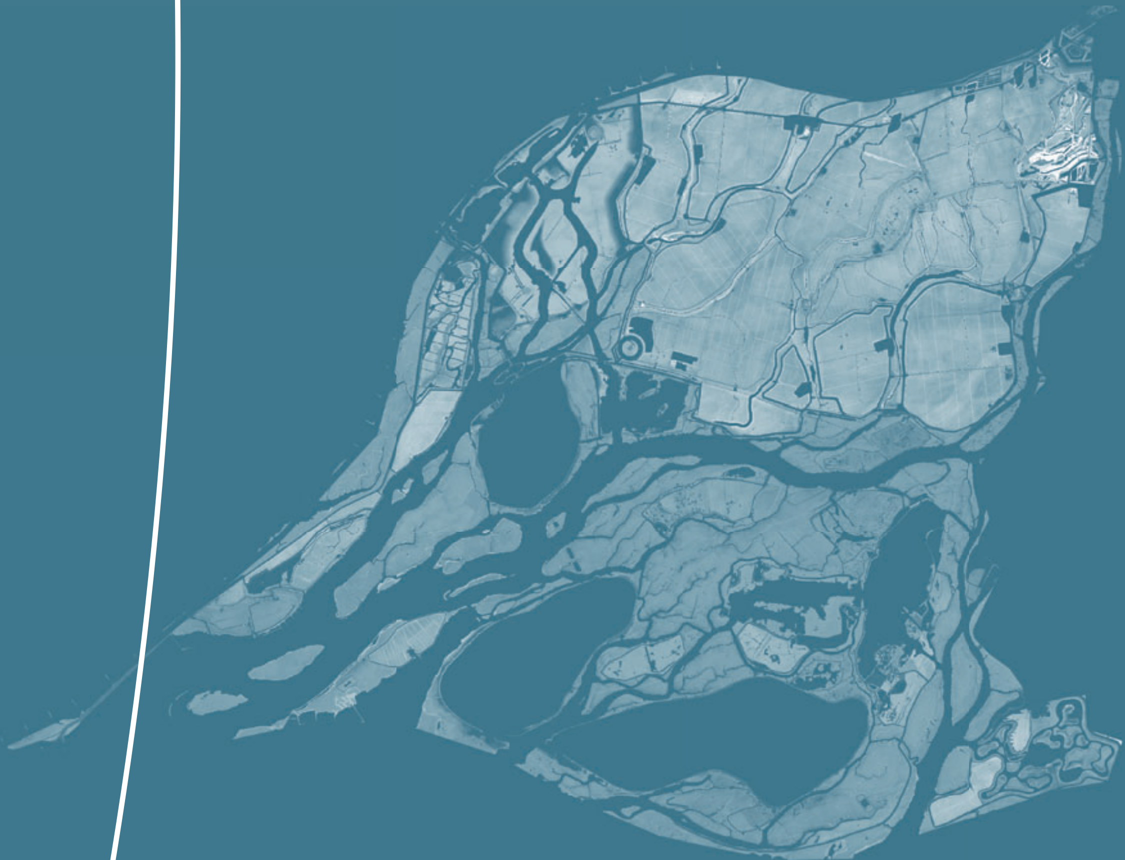
Drowning or emerging

The effect of climate change on the morphology of tidal freshwater wetlands

Eelco Verschelling



166 UTRECHT STUDIES IN EARTH SCIENCES

Drowning or emerging: the effect of climate change on the morphology of tidal freshwater wetlands

modelling sedimentation and erosion in freshwater wetlands affected by river discharge, tides and wind

Al dan niet verdrinken: het effect van klimaatverandering op de morfologie van zoetwatergetijdemoerassen

modellering van sedimentatie en erosie in zoetwatermoerassen onder invloed van rivierafvoer, getijde en wind

(met een samenvatting in het Nederlands)

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Universiteit Utrecht op gezag van de rector magnificus, prof. dr. H.R.B.M. Kummeling, ingevolge het besluit van het college voor promoties in het openbaar te verdedigen op maandag 3 december 2018 des middags te 2.30 uur

door

Eelco Verschelling

geboren op 24 oktober 1972 te Leiden

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This work was financially supported by the Dutch Technology Foundation STW (project nr. 12431).

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ISBN: 978-90-6266-518-1
Published by Faculty of Geosciences, Universiteit Utrecht, The Netherlands, in:
Utrecht Studies in Earth Sciences (USES), ISSN 2211-4335
Printing Ridderprint BV | www.ridderprint.nl
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Utrecht Studies in Earth Sciences 166

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Utrecht 2018

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"It's still magic even if you know how it's done."

Terry Pratchett, A Hat Full of Sky

Contents

Samenvatting

Draslanden (*wetlands*) zijn ecosystemen die regelmatig onder water staan. Ze zijn een essentieel onderdeel van het ecosysteem op aarde, en bieden een habitat voor allerlei soorten planten en dieren die nergens anders voorkomen. Daarnaast bieden deze gebieden een uitgebreid scala van sociale, economische en ecologische diensten die belangrijk zijn voor ons welzijn, zoals het beschermen van onze kusten tegen overstromingen, het voorzien van voedsel, en het verbeteren van de waterkwaliteit. Het is daarom van groot belang om deze gebieden te beschermen. Draslanden in de buurt van de kust (*tidal wetlands)* lopen het risico om te verdrinken onder invloed van zeespiegelstijging door klimaatverandering. Het stimuleren van sedimentatie in deze *tidal wetlands* is op dit moment een van de belangrijkste maatregelen om te voorkomen dat ze verdrinken onder invloed van zeespiegelstijging.

Vanwege het belang van zoutwater draslanden (*coastal wetlands*) als beschermer van onze kustlijn is er in het verleden al veel onderzoek uitgevoerd naar het functioneren van deze gebieden. Dit geldt echter niet voor iets verder van de kust gelegen zoetwater draslanden met een getijdecomponent (*tidal freshwater wetlands*): hoewel ook deze gebieden ecologisch belangrijk zijn, is er veel minder bekend over de risico's op verdrinking door zeespiegelstijging noch over het sedimentatieproces dat verdrinking eventueel kan voorkomen. Aangezien het transport van water en sediment in deze gebieden wordt beïnvloed door zowel het getij als door de rivierafvoer (zelf ook beïnvloed door klimaatverandering), is het aannemelijk dat overstromingsmechanismen en het effect van mitigerende maatregelen (zoals extra sedimentatie) anders zullen zijn dan in zoutwater draslanden. Dit onderzoek heeft zich daarom gericht op het kwantificeren van de factoren die erosie, sedimentatie en het percentage ingevangen sediment (*trapping efficiency*) bepalen in *tidal freshwater wetlands (hierna: TFWs)*, en hoe klimaatverandering deze factoren – en daarmee ook erosie en sedimentatie - beïnvloedt. Zowel 'externe' factoren (randvoorwaarden zoals rivierafvoeren en getijde) en 'interne' factoren (gebiedskarakteristieken zoals geometrische lengte/breedteverhouding) zijn geanalyseerd.

Om te onderzoeken hoe sedimentatie in TFWs wordt beïnvloed door het samenspel van rivierafvoer, getijde en wind, is een hydro-morfodynamisch model geconstrueerd

van de Kleine Noorwaard, een klein recentelijk ontpolderd natuurgebied dat onderdeel uitmaakt van de Brabantse Biesbosch, een groot TFW gelegen in de Rijn-Maasdelta in Nederland. Dit model is vervolgens gebruikt om voor huidige klimaatcondities te onderzoeken hoe verschillende combinaties van wind-, afvoer- en getijdegebeurtenissen de erosie en de sedimentatie in het gebied bepalen (hoofdstuk 2). Vervolgens is het model doorgerekend voor de periode 2015-2050 om het effect van veranderende randvoorwaarden (zeespiegelstijging & ander afvoerregime, beide als gevolg van klimaatverandering) op de sedimentatie en erosie te kwantificeren (hoofdstuk 3). Daarna is de focus vergroot naar de hele Brabantse Biesbosch, en is een hydrodynamisch en sediment transportmodel gebruikt om een scenarioanalyse uit te voeren naar de effecten van klimaatverandering op sedimentatiepatronen in de grote geulen (hoofdstuk 4). Tenslotte is de relatie tussen specifieke gebiedskarakteristieken en sedimentatie bestudeerd aan de hand van een hydro-morfodynamisch model van een synthetische TFW, met geïdealiseerde begincondities. Er is onderzoek gedaan naar de effecten van een groot aantal alternatieve gebied lay-outs, waaronder verschillende configuraties van het krekenpatroon, van de in- en uitlaten die het systeem verbinden met de omringende rivieren, en van geometrische gebiedseigenschappen (lengte-breedteverhouding). Hierbij is gekeken naar zowel de afzonderlijke effecten als naar de gecombineerde effecten (hoofdstuk 5).

Externe factoren (rivierafvoer, wind, getijde) beïnvloeden sedimentatie en het percentage ingevangen sediment als volgt. **Rivierafvoer** speelt een dominante rol, maar deze rol kan zowel positief zijn (meer sediment/hoger percentage) als negatief: aan de ene kant zijn TFWs afhankelijk van rivierafvoer voor de instroom van water en sediment, maar aan de andere kant leidt een grotere afvoer niet automatisch tot meer sedimentatie. In de Brabantse Biesbosch resulteren grotere afvoerpieken overwegend in een netto afname van de sedimentatie in het gebied. Dit is gedeeltelijk het gevolg van de lage sedimentconcentratie in het Rijnwater (*suspended sediment concentration*, of *SSC*), waardoor er simpelweg weinig sediment beschikbaar is dat zou kunnen sedimenteren. Daarnaast zorgen de grote stroomsnelheden van het water in de geulen van de Biesbosch tijdens piekafvoer ervoor dat relatief veel slib van de bodem weer in suspensie komt (*resuspension*) en het gebied met het doorstromende water verlaat. **Wind** heeft altijd een groot effect op de netto sedimentatie in het gebied, en dus ook op het percentage ingevangen sediment, en dit effect is altijd negatief (meer wind betekent altijd minder sedimentatie). **Getijdeamplitude** (springtij, doodtij) tenslotte heeft een relatief klein effect op de netto sedimentatie in de Brabantse Biesbosch. Dit wordt vooral veroorzaakt door de aanwezigheid van de Haringvlietsluizen in het Haringvliet estuarium benedenstrooms van de Biesbosch, waardoor de getijdeslag (en daarmee ook dood- en springtij) significant wordt gedempt. In andere gebieden is de getijdeamplitude een veel belangrijker factor. In zoutwater draslanden bijvoorbeeld wordt de water- en slibbeweging vaak uitsluitend gecontroleerd door de getijdeslag, en speelt bijvoorbeeld rivierafvoer nauwelijks een rol.

Gebiedseigenschappen bepalen het percentage ingevangen sediment als volgt. De gemiddelde waterdiepte in het gebied speelt in alle gevallen een dominante rol. Een relatief ondiep gebied met één grote inlaat en een windrichting tegenovergesteld aan de dominante stroomrichting heeft het laagste percentage ingevangen sediment. Grotere waterdieptes, een kleinere inlaat en/of een windrichting die minder tegenovergesteld is dan de dominante stroomrichting leiden allemaal tot een toename van het percentage ingevangen sediment. Naarmate de waterdiepte in een gebied toeneemt, speelt de grootte van de inlaat relatief een steeds grotere rol in de bepaling van het percentage ingevangen sediment. Tegelijkertijd neemt de rol van de oriëntatie van het gebied ten opzichte van de wind steeds verder af.

Het natuurgebied Kleine Noordwaard zal waarschijnlijk verdrinken als gevolg van klimaatverandering. Het effect van klimaatverandering op de netto sedimentatie en de morfologische ontwikkelingen in dit gebied is overigens beperkt: de morfologische stabilisatie van dit recentelijk ontpolderde gebied is veel bepalender voor de bodemveranderingen dan de gevolgen van klimaatverandering. Dit kan voor andere TFWs overigens heel anders liggen: ecomorfologische feedback loops in zoutwater draslanden zorgen er vaak voor dat de gemiddelde bodemstijging in deze gebieden pas houdt met de zeespiegelstijging door klimaatverandering. In het geval van Kleine Noordwaard zijn dergelijke feedback loops afwezig, waarschijnlijk als gevolg van ontwerpbeslissingen die zijn genomen voordat het gebied geopend werd voor het omringende water; de relatief grote gemiddelde waterdiepte in het gebied heeft ervoor gezorgd dat er nauwelijks (bodem)vegetatie kan groeien op de platen.

TFWs zijn dynamische, complexe ecosystemen waar sedimentatie en erosie worden bepaald door gebiedskarakteristieken en het samenspel tussen rivierafvoer, getijde en wind. Deze factoren beïnvloeden ook elkaar, waardoor het ingewikkeld is om van tevoren vast te stellen welke maatregelen het meest effectief zullen zijn bij het vergroten van de netto sedimentatie. Dit impliceert dat er niet zoiets is als een ‘perfecte maatregel’ die overal kan worden toegepast; de constructie van nieuwe verbindingen tussen de rivier en het drasgebied om meer sediment het gebied in te laten is bijvoorbeeld uitsluitend effectief indien de sedimentconcentratie in het rivierwater (*SSC*) zodanig hoog is dat de corresponderende toename in sedimentatie voldoende groot is om de extra resuspensie (door de eroderende kracht van de extra waterafvoer door het gebied) te compenseren. Het is daarom aan te raden om eerst te analyseren hoe de verschillende factoren precies op elkaar inwerken alvorens te kiezen voor een bepaalde maatregel. Een gedegen monitoringsplan van sleutelfactoren (sedimentconcentratie, getijdeslag, afvoeren) is van essentieel belang bij het ontwikkelen van succesvolle maatregelen.

Summary

Tidal wetlands are an essential part of the ecosystem. They provide a habitat for a wide range of vegetation communities and animal species that are found nowhere else, which makes wetland conservation important from a biodiversity conservation perspective. Wetlands also provide a wide range of social, economic and environmental services to human well-being, such as the protection of our shorelines, the provision of food, and the improvement of water quality. Tidal wetlands are under threat of drowning by sea level rise (SLR) as a result of climate change (CC). Enhancing sedimentation inside tidal wetlands is currently one of the main mitigating measures to prevent wetlands from drowning due to SLR.

Due to their importance as protector of our shorelines, drowning mechanisms in coastal wetlands have been studied extensively. In contrast, tidal freshwater wetlands (TFWs) in the transition zone between tidally-dominated and fluvially-dominated sections of a river delta have received less attention in scientific literature. Because of the larger influence of the river system, itself also affected by CC, drowning mechanisms and effects of mitigating measures such as enhanced sediment deposition will likely differ from those in coastal wetlands. Therefore, this study focused on which factors control sedimentation and erosion in tidal freshwater wetlands and how climate change affects these controls and thus sedimentation and erosion. Both external controls (boundary conditions such as riverine discharges and tides) and internal controls (wetland characteristics such as wetland length/width ratio) were analysed.

To study how sedimentation rates and patterns in TFWs are affected by the interplay of river discharge, wind waves and tide, a hydro-morphodynamic model was

constructed of Kleine Noordwaard, a small de-embanked polder that is part of the Brabantse Biesbosch TFW in the Rhine-Meuse delta in the Netherlands. This model was used to carry out an event analysis to examine how different combinations of hydro-meteorological boundary conditions control sedimentation and erosion under current climate conditions (chapter 2). Next, the model was applied to different climate scenarios by carrying out transient scenario runs for the period 2015-2050 with gradually changing boundary conditions in order to assess current and future net sedimentation rates, patterns and trapping efficiencies, and compare predicted rates of bed level change to predicted rates of SLR (chapter 3). After that, the focus broadened to the entire Brabantse Biesbosch wetland, and a scenario analysis was carried out to evaluate the effect of climate change on sedimentation patterns, rates and trapping efficiencies, using a model of hydrodynamics and sediment transport of the main wetland channels as well as the surrounding river system (chapter 4). Finally, the relation between wetland characteristics and sedimentation rates and trapping efficiencies was studied with a model describing morphodynamics in a schematic TFW with idealized initial conditions. The effects of a large number of alternative wetland layouts were analysed, including different creek systems, in- and outlets, and wetland aspects (length-width ratio), both separately (main effects) and in combination (interaction effects)(chapter 5).

External controls (boundary conditions) affect sedimentation rates and trapping efficiencies as follows. Discharge always has a major effect, positive or negative. TFWs depend on riverine discharges for inflow of water & sediment, but more discharge does not automatically mean more sedimentation: in the Brabantse Biesbosch, larger discharge events generally lead to a net loss of sediment due to resuspension and outflow of previously settled material. This is partly caused by the low suspended sediment concentration (SSC) in the surrounding rivers. Wind as a boundary condition has a major effect on sedimentation rates and trapping efficiencies, and only negative. The effect of tidal range on sedimentation rates is more limited than the effect of wind and discharges; however this strongly depends on the location of the wetland in the delta. Morphodynamics in wetlands further away from the coastline, such as the Brabantse Biesbosch, is strongly controlled by riverine discharges, especially during discharge waves. In these cases, a larger tidal range would have little effect. Coastal wetlands however are almost completely controlled by tidal levels and range. For those systems, riverine discharge is a less important control of sedimentation rates than tidal dynamics.

Wetland characteristics control trapping efficiencies as follows. A main factor determining the trapping efficiency is the average water depth within the wetland. A relatively shallow TFW with one large inlet and a main flow direction opposite to the predominant wind direction has the lowest trapping efficiency. Deeper TFWs with a small inlet and a flow direction more or less the same as the dominant wind direction trap relatively more sediment. As the depth increases, the inlet size starts to become a more important control in the trapping efficiency, while the role of wetland orientation with respect to the predominant wind direction diminishes.

The *Kleine Noordwaard* TFW is likely to drown due to CC. The effect of CC on sedimentation rates and morphological developments is limited: morphological stabilization of this newly developed area is a far more important driver of bed level changes than CC. For other TFWs, the effect of CC on sedimentation rates may be very different: coastal wetlands often gain elevation at speeds similar to SLR due to ecogeomorphic feedback loops. For *Kleine Noordwaard*, we speculate that design decisions made prior to the de-embankment have prevented such feedback loops that may have promoted accretion, but instead have led to large scale vegetation die-off.

TFWs are dynamic, complex systems in which the sedimentation rates are controlled by the interplay between river discharges, tides, wind and wetland characteristics. These controls also affect each other, making it difficult to predict beforehand which measures will be most effective in enhancing sedimentation rates. This implies that there is not a single 'perfect measure' that can be applied everywhere to enhance sedimentation rates. For example, the construction of river diversions towards wetlands is only effective in case the SSC of the feeding river is sufficiently high to counteract the eroding effect of the incoming current. It is therefore advisable to thoroughly analyse the relative importance of the different hydro-meteorological controls and layout of the wetland before deciding on restoration measures. Monitoring of key parameters (SSC, tidal range, discharges) over a sufficiently long period is an essential step in gaining the knowledge needed to develop successful restoration strategies.

1 Introduction

Tidal wetlands provide a habitat for a wide range of vegetation communities and animal species that are found nowhere else, which makes wetland conservation important from a biodiversity conservation perspective. Wetlands also provide a wide range of social, economic and environmental services to human well-being, such as the protection of our shorelines, the provision of food, and the improvement of water quality (Millennium Ecosystem Assessment, 2005). Wetland degradation leads to a reduction of these benefits. It is often caused by anthropogenic activities or disturbances that occur too rapidly for the wetland to adapt to (Alexander and McInnes, 2012). Tidal wetlands are under threat of drowning by sea level rise (SLR) as a result of climate change (CC), sediment starvation due to modifications to the river system such as construction of levees or dams, and subsidence (e.g. Delgado et al., 2013; Kirwan and Megonigal, 2013; Beckett et al., 2016; Belliard et al., 2016). Drowning of a tidal wetland due to SLR occurs when the wetland platform is not able to gain elevation at least at the same pace as the rate of SLR. Wetland elevation gain can be expressed as the sum of sedimentation, erosion, subsidence, and compaction (Figure 1.1). Enhancing sedimentation inside tidal wetlands is currently one of the main mitigating measures to prevent wetlands from drowning due to SLR (Darke and Megonigal, 2003; Paola et al., 2011; Kirwan and Megonigal, 2013).

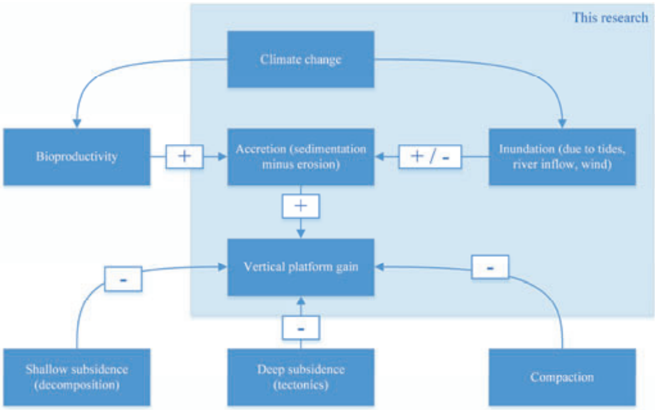

Figure 1.1: Factors affecting vertical elevation gain of the wetland platform (after FitzGerald et al., 2008).

Due to their importance as protector of our shorelines, drowning mechanisms in coastal wetlands have been studied extensively, often focusing on understanding historical and present-day sedimentation rates and patterns and comparing these with SLR. Coastal wetlands often gain elevation at rates similar to SLR due to ecogeomorphic feedback loops that cause increased deposition of both mineral sediment and organic material as the water depth increases (French, 2006; Kirwan and Megonigal, 2013). However, these feedback loops only occur until a certain flooding threshold, beyond which the vegetation dies off and the feedbacks are stopped, causing wetlands to drown (Kirwan and Megonigal, 2013). For coastal wetlands, this threshold can be reached in case of very high rates of local SLR, in some cases causing wetland submergence (Cahoon et al., 1995; Kirwan et al., 2010).

In contrast to the coastal wetlands, tidal freshwater wetlands (TFWs) in the transition zone between tidally-dominated and fluvially-dominated sections of a river delta have received less attention in scientific literature. Because of the larger influence of the river system, itself also affected by CC, drowning mechanisms and effects of mitigating measures (such as enhanced sediment deposition) will likely differ from those in coastal wetlands. To understand the impacts of CC on TFWs, research is required on the sedimentation processes and drowning mechanisms of these wetlands.

1.1 Factors governing sedimentation in tidal freshwater wetlands

Sedimentation and erosion are controlled by a wide range of factors pertaining to the wetlands, the surrounding river and downstream coastal system, and climate conditions. Research on coastal wetlands showed that net deposition inside wetlands is affected by the supply of sediments (Siobhan Fennessy et al., 1994; Neubauer et al., 2002), tidal range (Allen, 2000), wind (Orson et al., 1990; Delgado et al., 2013), vegetation density (Brueske and Barrett, 1994; Pasternack and Brush, 2001; Darke and Megonigal, 2003; Nardin and Edmonds, 2014; Nardin et al., 2016), wetland shape properties such as average depth/wetland elevation, distance to tidal creeks, and wind fetch lengths (Hupp and Bazemore, 1993; Temmerman et al., 2003a; Hupp et al., 2008; Mitsch et al., 2014). Water and sediment supply, currents, and waves together control bed shear stresses, sediment particle fall velocity and suspended sediment concentrations (SSC) inside the wetland. Together with the critical shear stresses for erosion and deposition, these factors control sedimentation and erosion (Partheniades, 1965). Although these previous studies yielded relevant insight in these controls and their effects, it is difficult to compare results or to generalise the findings due to the large diversity in study areas and methods. Furthermore, most of the previous studies focused only on one specific control. For example they studied the relation between a) stationary water discharges and sediment deposition in a synthetic TFW (Nardin and Edmonds, 2014), b) tidal ranges, sediment concentrations and bed level changes in a TFW in the Scheldt estuary, Belgium/Netherlands (Temmerman et al., 2003b), or c) wind waves and resuspension on a tidal mudflat in Willipa Bay, USA (Mariotti and Fagherazzi, 2013). However, effects of changes in these controlling factors may sometimes be interrelated, for example in the case of water discharge and wind and their effect on sediment resuspension: more water discharge usually leads to larger water depths, which in turn may reduce the impact of wind on resuspension. Therefore, to develop successful sedimentological restoration strategies in TFWs in the transition zone of a delta, a more thorough understanding of the separate and combined impact of these factors is essential.

1.2 Research aim and objectives

The general aim of this research is to quantify the factors that control sedimentation and erosion in tidal freshwater wetlands, and gain a better understanding of how climate change affects these controls and thus sedimentation and erosion. For this purpose, the factors affecting sedimentation and erosion can be classified according to their origin: external factors (boundary conditions) (related to the surrounding river system, downstream (sea) water level and tide, SSC in the feeding river, and hydro-meteorological conditions), which are all directly impacted by climate change, and internal factors (wetland characteristics such as internal connectivity, wetland elevation, and the length/width ratio). To analyse the effect of climate change on the morphology of TFWs, this research has the following objectives:

1. Assess how different configurations of boundary conditions together control sedimentation rates, patterns and trapping efficiencies in a tidal freshwater wetland affected by river discharge, tides and wind.
2. Evaluate the effect of climate change (CC) on morphological developments and sedimentation rates in a tidal freshwater wetland.
3. Assess how different configurations of wetland characteristics together control sedimentation rates, patterns and trapping efficiencies a generalised tidal freshwater wetland affected by riverine discharges, tides and wind.

1.3 Study area

The research in this thesis focuses on the Brabantse Biesbosch National park, a 9000 ha tidal freshwater wetland located in the lower Rhine and Meuse delta in the Netherlands (Figure 1.2). Located at some 55 km from the coast, the water levels and currents inside the area are governed by a combination of river discharge, tides, and wind. Because the area is affected by tides, it is potentially threatened by SLR, making the Brabantse Biesbosch a perfect study area for this PhD research.

The area has a long history, in which the year 1421 stands out. In this year, the area was hit by two storm surges and two river floods, together commonly known as St. Elisabeth flood. The flood destroyed most of the small embankments that had been built by then by local settlers to protect their lands from inundation from the surrounding river system. Over the years after, the area turned into an inland sea, that slowly filled up with sediments from the rivers, thus creating an inland delta system (Zonneveld, 1999). Over the centuries, the slowly rising land inside the delta enabled the local population to once again reclaim small areas of land. From the mid-twentieth century onwards, some of the reclaimed areas were purposefully abandoned in the interest of nature conservation (van Staveren et al., 2014). The year 1970 marks another landmark year for the Biesbosch wetland, because in this year the construction of the Haringvliet storm surge barrier was finished. It is located some 50 km downstream at the mouth of the Haringvliet estuary, and contains tidal gates that effectively reduced the tidal range inside the Biesbosch area from around 1.9 m to 0.2 m – 0.4 m (de Boois, 1982). The reduction in tidal range led to the formation of shallow lagoons, the filling in of deeper channels, a large decrease in intertidal area, and erosion of levees and banks. As a result, channel banks are now often steep and - especially along the larger northeast-southwest oriented channels - have been armoured by riprap to prevent further erosion.

In 2007, an area called *Kleine Noordwaard*, located at the Northern side of the Biesbosch (figure 1B) was de-poldered, in the interest of both nature conservation and flood prevention. By opening the embankment at a few discrete locations, a new semi-isolated flow-through wetland was created that supplies Brabantse Biesbosch with extra water and sediment from Nieuwe Merwede. The limited number of connections facilitates the construction of sediment and water balances, making this part of the Brabantse Biesbosch an ideal area to study in more detail.

In 2015, *Grote Noordwaard*, a large agricultural area on the northern border of the national park, was reconnected to the Nieuwe Merwede and the rest of the wetland as part of the Room for the Rivers programme. This project carried out by Dutch National Water Authority (*Rijkswaterstaat*) aimed at flood protection and improving environmental quality and nature restoration of the riverine landscape (Rijkswaterstaat, 2000). These new flow diversions supply the Biesbosch area with extra water and sediment, making it a perfect site to study wetland sediment dynamics.

Nowadays, the wetland consists of a network of rivers and creeks, flowing through a landscape that is characterised mostly by willow forests, reed lands, islands, mudflats and de-embanked polder areas. The area is wedged in between its two feeding rivers: to the north and west the river Nieuwe Merwede (a Rhine branch) and to the south river Amer (a Meuse branch) (Figure 1.2B, Figure 1.3). The majority of the area acts like a tidal basin, receiving water and sediment from the rivers to the south-west only during rising tide, while the rest of the area receives water and sediment from the feeding rivers through recently constructed river diversions, but only during floods.

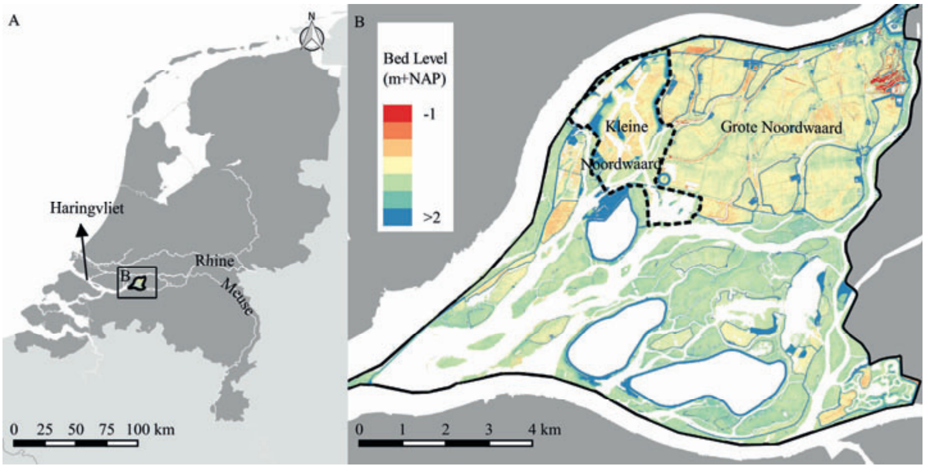

Figure 1.2: Location of the Biesbosch study area

Figure 1.3: Overview of project area. Image from September 8, 2016. Map data: Google, DigitalGlobe.

1.4 General approach and thesis outline

In the first phase of this PhD research, I focused on gaining more understanding of how sedimentation rates and patterns in TFWs are affected by the interplay of river discharge, wind waves, and tide. The study area for this phase was the former polder area *Kleine Noordwaard* (Figure 1.2B). This particular area was chosen because it is a flow-through wetland, making it representative for a large number of riverine wetlands with a tidal component, and because of a number of practical reasons, including the relatively easy accessibility, the small area and limited number of connections with the surrounding river system. Therefore, the collection of data and the construction of water and sediment balances is relativity easy for this area. A number of measurement campaigns were carried out in cooperation with a parallel PhD research project by Van der Deijl (2018) to collect data on bathymetry, bed material, flow velocities, water levels, suspended sediment concentrations, and particle fall velocity. I used these data to construct and calibrate a detailed depth-averaged Delft3D model of hydrodynamics - including short waves to account for the effect of wind -, sediment transport and morphology. With this model, I carried out an event analysis to examine how different combinations of hydro-meteorological boundary conditions control sedimentation and erosion under current climate conditions (chapter 2).

In the second phase of this research, I updated the previously constructed model of the Kleine Noordwaard to include the effect of vegetation on hydraulic resistance and wave energy using the methods of Baptist et al. (2007) and Suzuki et al. (2012), respectively. Next, I applied the model to different climate scenarios by carrying out transient scenario runs for the period 2015-2050 with gradually changing boundary conditions, using a novel statistical method to combine correlated 40-year time series of wind, water discharge and water levels into a consistent synthetic one-year time series with the same statistical properties. This allowed assessment of current and future net sedimentation rates, patterns and trapping efficiencies, and comparison of bed level change to predicted rates of SLR (chapter 3).

In the third phase of this research, I considered the entire Brabantse Biesbosch wetland and extended an existing one-dimensional hydrodynamic model of the study area and the surrounding river system with a one-dimensional sediment transport model. I applied this combined model in a climate scenario analysis, in which I assessed changes in sedimentation patterns, rates and trapping efficiencies due to CC (chapter 4).

In the fourth and final phase of this research, I constructed a depth-averaged Delft3D model that describes morphodynamics of a schematic TFW with idealized initial conditions that capture the most prominent topographic wetland features. The boundary conditions and general area characteristics were loosely inspired by the detailed Delft3D model of the Kleine Noordwaard. I applied this model to study the effects on net sedimentation of a large number of alternative wetland layouts, including different creek systems, in- and outlets, and wetland aspects (length-width ratio), both separately (main effects) and in combination (interaction effects). This allowed to understand and quantify relations between the initial conditions on the one hand and sedimentation rates and trapping efficiencies on the other hand in generic TFWs (chapter 5).

This thesis concludes in chapter 6 with the main findings of this research, applicability of the research findings to other wetlands, challenges for future research, and recommendations for wetland management.

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2 Effects of discharge, wind and tide on sedimentation in a recently restored tidal freshwater wetland

Abstract

Sediment deposition is one of the key mechanisms to counteract the impact of Sea Level Rise in Tidal Freshwater Wetlands (TFWs). However, information about sediment deposition rates in TFWs is limited, especially for those located in the transition zone between the fluvially-dominated and tidally-dominated sections of a river delta where sedimentation rates are affected by the combined impact of river discharge, wind and tides. Using a combined hydrodynamic-morphological model, we examined how hydro-meteorological boundary conditions control sedimentation rates and patterns in a TFW located in the Rhine-Meuse estuary in the Netherlands. The modelling results show that net sedimentation rate increases with the magnitude of the river discharge, while stronger wind increasingly prevents sedimentation. Sediment trapping efficiency decreases for both increasing river discharge and wind magnitude. The impact of wind storms on the trapping efficiency becomes smaller for higher water discharge. The spatial sedimentation patterns are affected by all controls. Our study illustrates the importance of evaluating both the separate and the joint impact of discharge, wind and tides when estimating sedimentation rates in a TFW affected by these controls. Such insights are relevant to design measures to reactivate the sedimentation process in these areas.

Published as: Verschelling E, van der Deijl E, van der Perk M, Sloff K, Middelkoop H. Effects of discharge, wind, and tide on sedimentation in a recently restored tidal freshwater wetland. Hydrological Processes. 2017;31:2827–2841. https://doi.org/10.1002/hyp.11217

2.1 Introduction

Tidal freshwater wetlands (TFWs) are home to characteristic and diverse vegetation communities and animal species, and their protection is thus important from a biodiversity conservation perspective. Wetlands also provide various ecosystem services to human well-being, for example the provision of food (e.g. fish) and recreational opportunities, and regulating water quality (Millennium Ecosystem Assessment, 2005). TFWs are vulnerable to sea level rise (SLR) through both increased risk of inundation and possible salt water intrusion (e.g. Burkett and Kusler, 2000; Anderson and Lockaby, 2012).

Enhanced sedimentation is considered an effective strategy to prevent further wetland loss in case horizontal wetland migration to higher zones is not possible (Darke and Megonigal, 2003; Paola et al., 2011; Kirwan and Megonigal, 2013). Previous research has indicated that sedimentation rates of wetlands may in general be controlled by factors such as the supply of fluvial sediments (Siobhan Fennessy et al., 1994; Neubauer et al., 2002), tide, wind (Orson et al., 1990; Delgado et al., 2013), vegetation cover (Brueske and Barrett, 1994; Pasternack and Brush, 2001; Darke and Megonigal, 2003; Nardin and Edmonds, 2014; Nardin et al., 2016), wetland shape properties such as average depth/wetland elevation, distance to tidal creeks, and wind fetch lengths (Hupp and Bazemore, 1993; Temmerman et al., 2003b; Hupp et al., 2008; Mitsch et al., 2014).

Yet, little research has focused on TFWs located in the transition zone between the *fluvially-dominated* and *tidally-dominated* sections of a river delta (terms in italic as defined by Leonardi et al., 2015), where sedimentation rates are controlled by the combined impact of discharge, wind and tide. The majority of previous studies has focused on cases where only one or two of these controls are relevant, for example to study the relation between a) stationary water discharges and sediment deposition in a synthetic TFW (Nardin and Edmonds, 2014), b) tidal ranges, sediment concentrations and bed level changes in a TFW in the Scheldt estuary, Belgium/Netherlands (Temmerman et al., 2003a), and c) wind waves and resuspension on a tidal mudflat in Willipa Bay, USA (Mariotti and Fagherazzi, 2013). However, a more thorough understanding of the combined impact of these hydro-meteorological controls is essential to develop successful sedimentological restoration strategies in TFWs in the transition zone of a delta.

The objective of this study was to quantify and understand how sedimentation rates and patterns of mud and sand in TFW are affected by the interplay of river discharge, wind waves and tide. To this end, we carried out numerical experiments using a hydrodynamic and sediment transport model of a recently restored, sparsely vegetated TFW in the south-western part of the Netherlands. We conducted 14 simulations with varying discharge, wind magnitude, and tidal conditions, and compared average surface accretion, trapping efficiency (defined as the proportion of the incoming sediment that is deposited or trapped in the area), and sedimentation patterns. This study concentrates on the first stage of renewed sedimentation of the TFW after the opening of the levees. Therefore, the effect of vegetation on the vertical mass balance (through increased sedimentation of suspended material and possible accretion due to production of organic material) is not considered.

This study took place within the framework of a larger project on the effects of restoring sedimentation in a former polder area, in which field measurements were carried out (water levels, flow velocities, turbidity, sediment concentrations, settling velocities, sediment thickness). These measurements were used for the model setup and calibration. The measurement program and results will be described in a separate paper in preparation.

2.2 Study area

The study area is located in the eastern section of *De Biesbosch* National Park, a 9000 ha tidal freshwater wetland in the lower part of the Rhine-Meuse delta in the Netherlands. The study area comprises three former polders (*Spiering, Kleine Noordwaard*, and *Maltha*) and has a total surface area of around 700 ha. It was de-poldered in 2008 by the park authority (State Forestry Service, or *Staatsbosbeheer* in Dutch) as part of an on-going programme to reduce flood water levels by enlarging inundation areas and to restore former wetland areas. Not only is this area itself potentially threatened by future sea level rise and, as such, a relevant case, the de-poldering also created an excellent research environment to study sedimentation processes due to the size of the area and the limited number of in- and outlets, which facilitated the establishment of water and sediment balances.

The embankment around the polder was opened at two locations: on the northern side along the river *Nieuwe Merwede* (a major Rhine branch) close to location g1 in Figure 2.1, and on the southern side along the *Gat van de Noorderklip* (location g4), a smaller branch that connects with the *Hollands Diep* estuary. The dominant flow direction through the study area is from North to South. The area consists of inundated flats (former grassland and arable fields), a man-made channel system connecting the northern and southern in- and outlets, and a vegetated island in the centre of *Kleine Noordwaard,* which was constructed using the material dug from the channels. The substrate in the study area consists of a clay layer on top of a thick layer of fluvial-tidal splay sands (Kleinhans et al., 2010). Artificial channels were dug through this clay layer into the sandy layer underneath.

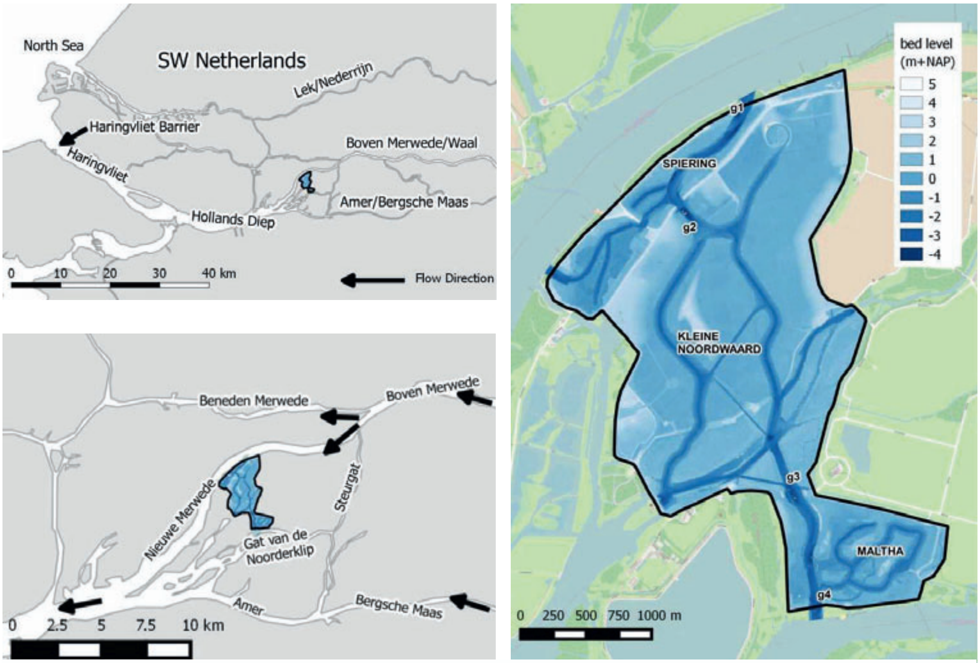

Figure 2.1: Study area. Locations g1 to g4 refer to the locations of the gauging stations in the area.

The hydraulic regime in the study area is semidiurnal microtidal with an average tidal range of 0.2 to 0.4 m. Because the TFW is located in the backwater of the North Sea, water levels in the TFW are influenced by storm surges as a result of heavy westerly wind storms at sea and the operation settings of the Haringvliet barrier (between Hollands Diep and the North Sea). The water levels are also affected by the discharge of the Rivers Rhine and Meuse. Most of the time, the tidal flats are inundated with depths ranging from 0 to 50 cm. Complete exposure of the flats only occurs in summer (when river discharge is low) at low tide or during strong easterly winds. The wave climate within the area is characterised by local short waves generated by winds mainly coming from the West-South-West. The significant wave height during windstorm events was observed to grow up to 0.2 m, as a result of the relatively long fetch lengths across the inundated flats and the distinct lack of vegetation, especially in winter. However, the development of the waves is hampered by the low water depths that occur during low tides or low river discharge.

The suspended sediment concentration (SSC) in the Nieuwe Merwede typically varies from 10 to 40 mg/l during average flow conditions with estimated peak values of up to 140 mg/l during periods of high discharge in the River Rhine (Asselman, 2000; Asselman et al., 2003).

Bed load transport of coarser material dominates the changes in the channels' bed, especially close to the in- and outlets of the system where the flow velocities can reach values of up to 2 m/s. The flats have remained relatively unchanged due to the high erosion resistance of the thick clay layer of this former polder and the low flow velocities here (0 to 0.2 m/s). Since the opening of the area in 2008, the flats have become gradually covered by a layer of mud of around 2 to 5 cm thick.

Dominant vegetation types in the study area include bulrush vegetation with *Schoenoplectus triqueter* and *Bolboschoenus maritimus* on the shoreline, pioneer species such as *Limosella aquatica*, *Veronica anagallis-aquatica* and *Pulicaria vulgaris* on the mud flats, and locally some *Myriophyllum spicatum* in open water. The vegetation on the flats is regularly cut in order to keep the hydraulic roughness low, thereby maintaining the flood-conveying capacity of the area. The area has become an important habitat for many bird species. Large flocks of geese frequently spend time in the Biesbosch area to feed on the vegetation, effectively removing most of it.

2.3 Methods

2.3.1 Model setup

We used Delft3D (Lesser et al., 2004) to model hydrodynamics, sediment transport and bed level changes in the study area. The following sections describe the setup of the model domain and the modules for hydrodynamics, sediment transport and morphology.

Model domain and bathymetry

The computational grid covers the polders Spiering, Kleine Noordwaard and Maltha (Figure 1). The land boundary largely follows the highest point of the original embankment around the polders. The upstream and downstream boundaries were chosen to coincide with the locations of fixed monitoring stations. The resolution and grid orientation were defined to account for dominant flow directions and important features in bathymetry (e.g. channels, island, in- and outlets). This resulted in a curvilinear grid of 144 x 145 cells, with cell sizes varying from 5 to 30 m (Figure 2.2).

The initial bathymetry of the model area was constructed using the 2003 version of the official Dutch DEM 'AHN1' with a horizontal resolution of 5×5 m^2 (Van der Zon, 2013), supplemented by a local LIDAR DEM with a horizontal resolution of 1×1 m^2 from 2010 for the central island and other artificially elevated areas, and a 2011 multibeam echo-sounder dataset covering the channel system. All bathymetric data sets were provided by the National Water Authority (*Rijkswaterstaat*).

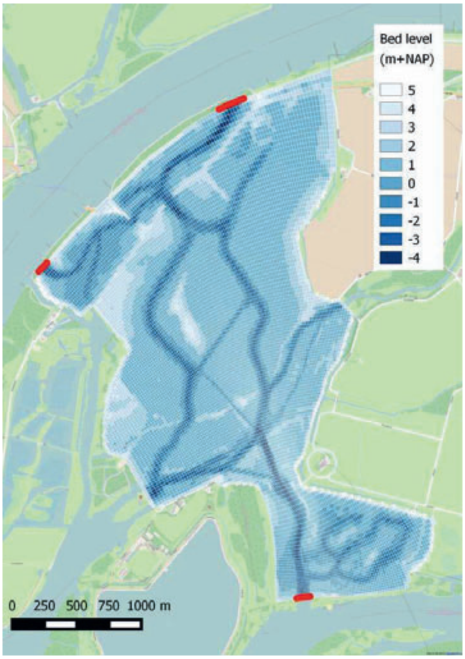

Figure 2.2: Model grid (in white), bathymetry, and open boundaries (in red)

Hydrodynamics

Delft3D-FLOW calculates water levels and water flow velocities for every computational time step on spherical or orthogonal curvilinear coordinates by solving the unsteady shallow water equations in two or three dimensions. For this study, we used a curvilinear grid and a computational time step of 30 seconds. Given the explorative character of this study, the small gradient over observed vertical sediment concentration profiles and the focus on large scale horizontal sediment gradients, we decided to use depth-averaged simulations (2DH) to speed up the simulations.

We used the third-generation short wave model SWAN (Booij et al., 1999) to simulate the effect of wind-driven short waves on hydrodynamics, morphology and transport of sand and mud through increase in bed shear stress and wave-induced momentum. This model is available within Delft3D as Delft3D-WAVE, and calculates a wave field based on hydrodynamic conditions and wind data. Delft3D-WAVE was coupled dynamically to Delft3D-FLOW, with the wave field being updated every hour. The effect of bottom friction in the energy balance equation in SWAN was included using the JONSWAP method described by Hasselmann et al. (1973), and the wave-induced bed shear stress in FLOW was included using the method described by Fredsøe (1984).

Discharge time series were imposed at the two upstream (northern) open boundaries between Nieuwe Merwede and polder Spiering, and a water level time series was imposed at the downstream (southern) open boundary, discharging into Gat van de Noorderklip.

The hydrodynamic roughness was defined using Manning's friction coefficient, which was set as a uniform value for the entire area after an a-priori sensitivity analysis that showed that simulated levels and flows were relatively insensitive to different patterns of distributed friction definitions due to the low flow velocities and limited amount of aquatic vegetation in this recently restored wetland. Default settings were used for all other Delft3D parameters (Deltares, 2014), except for the parameters listed in Table 2.1; the values for these parameters were defined based on field observations and expert judgement.

Table 2.1: Settings FLOW and SWAN models

FLOW Parameter	Unit	Value
Horizontal eddy viscosity	m^2/s	0.5
Horizontal eddy diffusivity	m^2/s	2
Computational time step FLOW model	min	0.5
WAVE Parameter	Unit	Value
Computational time step WAVE model	min	60
JONSWAP coefficient	m^2/s^3	0.038

Sediment transport

Delft3D simulates suspended load transport of cohesive sediment fractions, suspended and bed-load transport of non-cohesive sediment fractions, and the morphological changes that result from these processes. We defined one cohesive mud fraction and one non-cohesive sand fraction. Transport of the non-cohesive sediment fraction was modelled with the Van Rijn equation (Van Rijn, 1984). Uptake and settling of suspended sediment of the cohesive fraction was modelled with the Krone and Ariathurai–Partheniades formulations (Partheniades, 1965). The implementation of both transport formulae in the Delft3D framework is described by Lesser et al. (2004).

To obtain input SSC at the upstream boundary of the model, we used a sediment rating curve that was constructed following a procedure described by Asselman (2000), using discharges and SSCs from station Vuren, which is the closest river gauging station along the River Waal, located 31 km upstream of the study area. The SSC values estimated with the rating curve range from 20 mg/L for average river discharge (1500 m^3/s) to 140 mg/L for extreme river discharge (6800 m^3/s). The estimated SSC values for corresponding wetland inlet discharges (between 20 and 100 m3/s) agree well with SSCs at the inlet of the model area, which were measured using a calibrated turbidity sensor between July 2014 and April 2015.

The sediment densities of both fractions were left at default values (specific density of both mud and sand: 2650 kg/m^3, dry bed density mud: 500 kg/m^3, dry bed density sand 1600 kg/m^3) as defined in Deltares (2013). Based on field observations, the effective settling velocity W_s of the mud fraction was set at 0.04 mm/s, and the D_{50} of the sand fraction at 200 µm.

The initial channel bed composition was modelled as one uniformly mixed layer with a spatially varying composition based on field observations and geological maps of the area: 100% mud on the flats with a layer thickness of 2 cm, and 100% sand on the island and in the artificial channel system with a layer thickness of 3 m. The stiff polder clay layer underneath the mud layer was assumed to be non-erodible.

2.3.2 Model calibration & validation

Model calibration and validation were carried out using a stepwise approach. The hydrodynamic model (including the SWAN wave module) was calibrated and validated first; subsequently the bed load transport of the coarse fraction, and finally the suspended load transport and deposition. Because of limitations in data availability, different calibration periods were chosen for hydrodynamics and morphology.

Hydrodynamic model

The hydrodynamic model was calibrated against observed water levels at three gauging stations in the case study area (points g2, g3 and g4 in Figure 2.1), using the root mean square error (RMSE) as optimisation criterion. The Manning's roughness coefficient was used as calibration parameter with an *a priori* range of 0.01 to 0.05 $s/m^{1/3}$.

We selected the period between 1 August 2014 to 1 December 2014 as calibration period. August and September 2014 were relatively dry, apart from a few small discharge peaks in August. In late October 2014, there was a heavy windstorm event in combination with a small discharge peak. The calibration period ended with relatively dry and calm conditions. Discharge and water level series were derived from ADCP and diver measurements taken at the locations of the gauging stations. For more information on these time series, we refer to Van der Deijl (2015). Wind conditions (hourly values of average wind speed and direction during the last 10 minutes of every hour) for four surrounding stations during the calibration period were obtained from the Royal Dutch Meteorological Institute KNMI (www.KNMI.nl).

The hydrodynamic model was validated against observed water levels at the same locations for the period between 1 December 2014 and 1 April 2015. December was relatively dry and calm except for a minor discharge peak around 23-24 December 2014. Between 10 and 17 January 2015, there was a minor combined discharge-windstorm event. The rest of the validation period was relatively dry with below-average discharges and no significant discharge peaks.

The SWAN model was not calibrated separately due to lack of quantitative data on wave characteristics. Instead, the performance was checked by comparing the significant wave heights for the calibration period with qualitative visual observations during field visits.

Sediment transport model

Calibration of the sediment transport models was done at the level of 20 subareas (10 sections, see Figure 2.3, each further subdivided into a *channel* and a *flat* subsection), comprising the *polder Kleine Noordwaard* and *polder Maltha*. Table 2.2 lists the calibration parameters and their a-priori value range. The specified ranges were based on a combination of available literature, expert judgement and a-priori sensitivity analysis. Calibration was carried out manually with the RMSE between measured and simulated accretion volumes (i.e. area-weighted accretion rates) in the 20 subareas over the entire calibration period as evaluation criterion.

The calibrated sediment transport model was evaluated using the Brier Skill Score (BSS) (Sutherland et al. (2004), which is commonly used to evaluate the performance of a morphological model. We redefined the BSS in terms of bed volume changes rather than bed level changes:

$$BSS = 1 - \frac{\left\langle \left(\Delta V_{i,meas} - \Delta V_{i,sim} \right)^2 \right\rangle}{\left\langle \left(\Delta V_{i,sim} \right)^2 \right\rangle} \tag{1}$$

In this equation, "$\langle .... \rangle$" denotes the arithmetic mean, in this case over the 10 * 2 subsections.

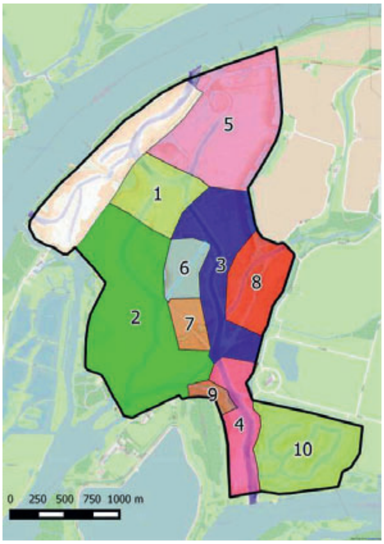

Figure 2.3: Calibration sections

Table 2.2: Sediment transport model calibration parameters and their minimum and maximum values

Sand transport model parameter	Unit	min	max
Van Rijn calibration coefficient	-	0.1	2
Roughness height	m	0.01	2
Silt transport model parameter	**Unit**	**min**	**max**
Critical shear stress for sedimentation	N/m^2	0.1	2
Critical shear stress for erosion	N/m^2	0.1	2
Erosion parameter	$kg/m^2/s$	0.00001	0.1

The sediment transport model was calibrated for the period between two most recent channel bathymetry surveys (1 March, 2011 to 1 March, 2012). The time series of the boundary conditions for that period are shown in Figure 2.4. The upstream river discharge was schematised as a step-wise wave, with step values based on a cumulative frequency distribution curve for the calculated discharges (using measured water levels and flow velocities at the upstream gauging station) during the calibration period.

We used a morphological scale factor of 20 to compress the upstream discharge time series, resulting in a simulation time of almost 20 days for a one-year period. For each computational time step, the scale factor is applied to both the erosion and deposition fluxes, thereby accelerating the bed-level changes. The use of the morphological scale factor requires that the effect of bed-level changes on hydrodynamics during one calculation time step is negligible, which can be considered valid in our study (cf. Roelvink (2006); van der Wegen and Jaffe (2013)).

The water level series at the downstream model boundary was schematised as a harmonic wave representing the dominant wave condition (M2 tide), superimposed on a step-wise wave with values based on a cumulative frequency distribution curve of the measured levels at the downstream gauging station. This method assumes a strong correlation between upstream discharge and downstream water level. For higher discharges at the inlet of the study area this is indeed the case. However, such a strong correlation does not exist between upstream discharges and wind conditions. Therefore, we focused on wind coming from the prevailing wind direction only (SW quadrant) and constructed 10 alternative semi-random wind speed events, all of which conformed to the cumulative frequency curve for measured wind speeds. We then calculated the average morphological changes during these events, and used the wind event that came closest to the average morphological changes for the calibration. We used wind data from the closest surrounding stations (hourly values, stations Cabauw, Gilze-Rijen, Herwijen, Rotterdam) from the Dutch Meteorological Institute KNMI (www.knmi.nl) for the calibration of the sediment transport model.

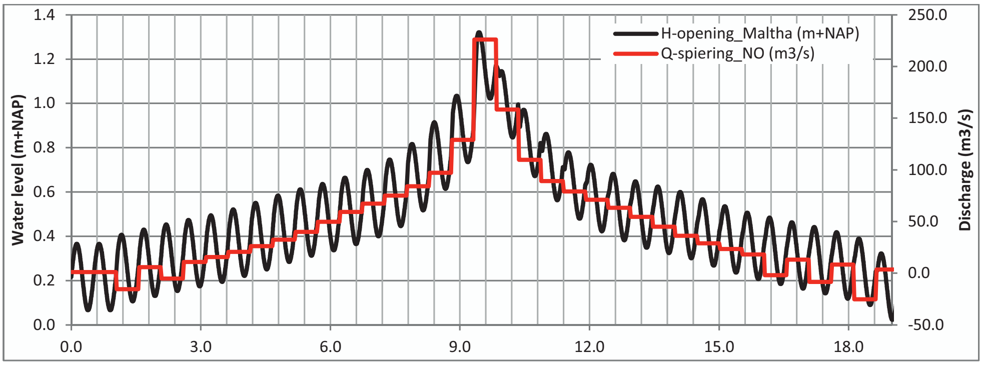

Figure 2.4: Boundary conditions for the calibration of the sediment transport model: discharge & water level. Q = incoming discharge, H = water level at the outlet

2.3.3 Sensitivity analysis

To analyse the impact of different types of hydro-meteorological controls on net sedimentation quantities and patterns, a sensitivity analysis was carried out (Table 2.3). The analysis was carried out for the following boundary conditions:

- Discharge events of different duration and magnitudes. DISCH1 has a discharge peak with a return period of 1 year (T1) and DISCH2 a peak with a return period of 50 years (T50). Average tidal conditions (M2) apply in both cases and there is no wind. DISCH0 is the reference scenario: a stationary discharge event without any wind and with average tidal conditions.
- Windstorm events from four different wind directions (SW, NW, NE, SE) with a return period of 1 year, with corresponding windstorm surge at sea (WIND1 through WIND4). Also one windstorm event with a return period of 50 years and SW wind direction, with corresponding windstorm surge at sea (WIND5). Average discharge conditions apply for all these events, and DISCH0 is again the reference case.
- Alternative tidal ranges: neap tide and spring tide during average discharge conditions and during a windstorm event (TIDE1 through TIDE4). WIND1 and DISCH1 are reference cases for analysing this tidal effect.
- Combinations of discharge and windstorm events: DISCH1 with WIND1 (COMB1), and DISCH1 with a smaller windstorm (with a return period of 1/25 years), both with corresponding surges at sea. WIND1 and DISCH1 are reference cases.

Table 2.3: Overview of event runs. Q_lobith and sea water level refer to the upstream discharge and downstream water level boundary of the 1D model of the Dutch part of the Rhine delta. T1, T50 and T(1/25) refer to the return periods of the events (1, 50 and 0.04 years, respectively). Note that the magnitude of the T1 wind speed is different for every direction, and that SW winds are most common.

	Q_lobith (m3/s)	wind dir	wind speed (m/s)	sea water level
CALIBR	N/A	meas	meas	N/A
DISCH0	Average (2300)	-	-	astr
DISCH1	T1 wave (5893 max)	-	-	astr
DISCH2	T50 wave (11762 max)	-	-	astr
WIND1	Average (2300)	SW	T1 (17.9)	astr + surge
WIND2	Average (2300)	NW	T1 (14.4)	astr + surge
WIND3	Average (2300)	NE	T1 (11.8)	astr + surge
WIND4	Average (2300)	SE	T1 (9.3)	astr + surge
TIDE1	Average (2300)	SW	T1 (17.9)	astr + surge + NT
TIDE2	Average (2300)	SW	T1 (17.9)	astr + surge + ST
TIDE3	T1 wave (5893 max)	-	-	astr + NT
TIDE4	T1 wave (5893 max)	-	-	astr + ST
COMB1	T1 wave (5893 max)	SW	T1 (17.9)	astr + surge
COMB2	T1 wave (5893 max)	SW	T(1/25) (6.4)	astr + surge
WIND5	Average (2300)	SW	T50 (24.3)	astr + surge

The event analysis was carried out as follows. First, boundary conditions for all 2D model runs were derived by using a calibrated 1D hydrodynamic model (SOBEK v.3.3) of main river channels in the entire Dutch part of the Rhine and Meuse delta (which includes a coarse model of the study area) described by De Waal (2007). For every hydro-meteorological event, a coherent set of boundary conditions was constructed for the 1D model, based on Geerse (2003) and Chbab (2012), who describe extreme value statistics of river discharge, wind conditions, and sea levels in the Rhine delta. Figure 2.5 shows two examples of 1D boundary conditions that were constructed based on these statistics. Next, using the 1D model output as boundary conditions, every event was simulated with the 2D model to simulate corresponding water flow, sedimentation quantities and patterns within the study area. All events had the same simulation period of 26 days (even though windstorm events only last 48 hours) in order to make the results comparable.

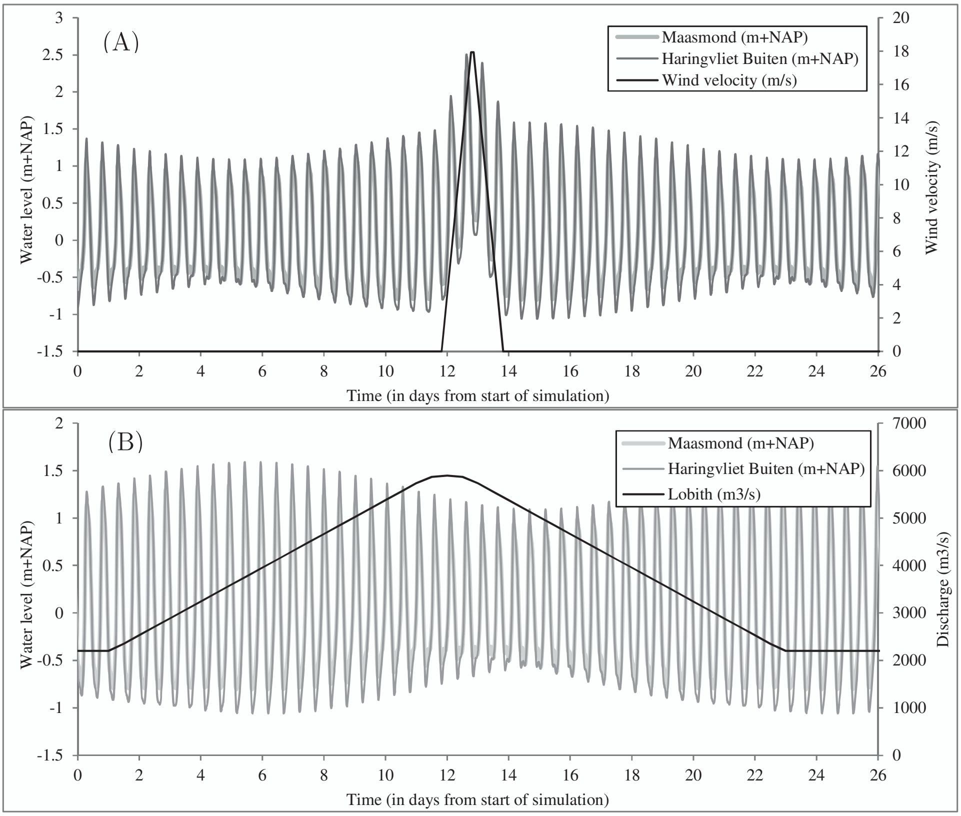

Figure 2.5: 1D model boundary conditions for runs TIDE2 (A) and TIDE3 (B). *Lobith* refers to the location of the upstream boundary, and *Maasmond* and *Haringvliet Buiten* are the locations of the downstream boundaries of the 1D model. In (A), the discharge boundary Q (location Lobith) has a constant value of 2300 m^3/s and is purposefully omitted. In (B), the wind velocity has a constant value of 0 m/s for this run and is purposefully omitted.

2.4 Results

2.4.1 Calibration and validation

Hydrodynamic model

The calibration of the hydrodynamic model yielded a best fit when Manning's roughness coefficient was set at 0.025 $s/m^{1/3}$. Figure 6 shows the observed and simulated water levels using the calibrated model for the inlet of the Kleine Noordwaard (measurement location G2). Table 4 summarises the model performance criteria for the three measurement locations. It can be concluded that the calibration of the hydrodynamic model resulted in a good agreement between the observed and simulated water levels for both the calibration and validation period.

Table 2.4: Model performance indicators for the calibrated model. ME = mean error (cm); RMSE = root mean square error (cm); NSE = Nash-Sutcliffe efficiency index (-)

	Calibration period			Validation period		
Location	ME (cm)	RMSE (cm)	NSE (-)	ME (cm)	RMSE (cm)	NSE (-)
(G1) Opening Spiering	-0.19	1.80	0.99	-1.25	2.91	0.99
(G2) Brug Bandijk	-1.97	2.41	0.98	-2.47	3.24	0.99
(G3) Brug Maltha	-0.09	0.46	1.00	0.71	0.88	1.00

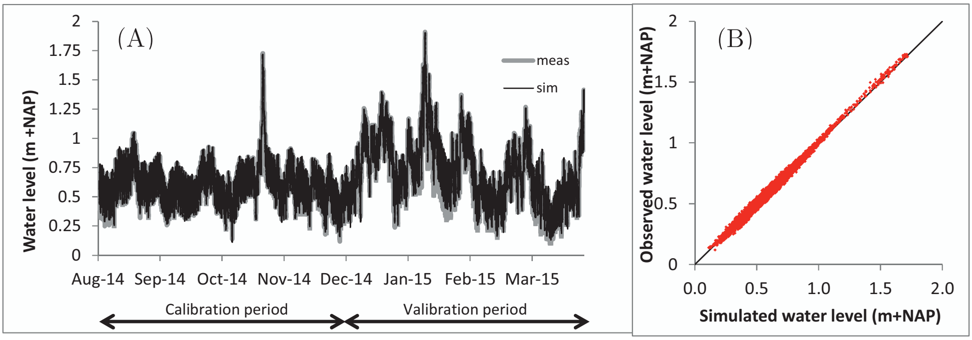

Figure 2.6: (A) simulated and observed water levels for entire calibration-validation period at station G2. (B) scatter plot of observed water levels against simulated water levels at station G2 for the calibration period.

Sediment transport model

The results of the manual calibration of the sediment transport model are summarized in Figure 2.7. This chart shows the measured and simulated cumulative sedimentation and erosion volumes in the model area during the calibration period. The associated (lowest) RMSE is 1.3×10^3 m^3. The results in most sections agree reasonably well with the measurements except for section 10 (Figure 2.3), for which the model overestimated erosion in the channels and underestimated sedimentation on the flats.

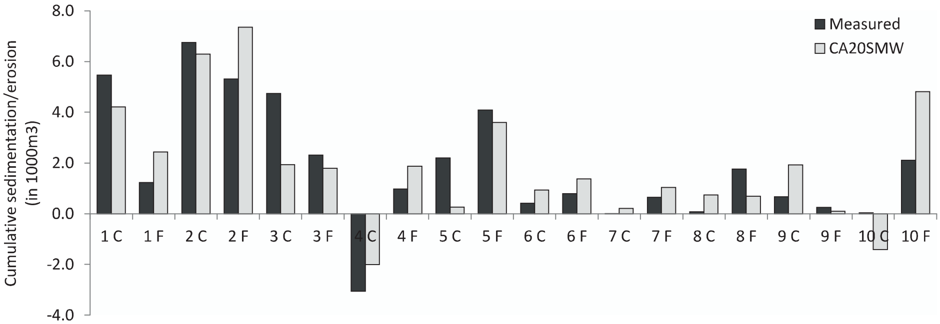

Figure 2.7: Cumulative sedimentation/erosion (in 1000 m^3) per subsection (numbered 1 to 10) over the calibration period. 'C' stands for 'Channel', 'F' for 'Flat'. Note that the measured values for the flats are based on the estimation of a uniform accretion rate of 0.5 cm per year.

The resulting set of calibrated parameter values is listed in Table 2.5. The evaluation criterion BSS equals 0.81, which means that the performance of the morphological model can be classified as 'good' according to the Sutherland's proposed classification table (Sutherland et al., 2004).

Table 2.5: Parameter settings of calibrated sediment transport model

Sand transport model parameter	Unit	Value
Van Rijn calibration coefficient	-	1.5
roughness height (m)	m	0.4
Silt transport model parameter	Unit	Value
critical shear stress for sedimentation	N/m2	0.1
critical shear stress for erosion	N/m2	0.3
erosion parameter	kg/m2/s	0.001

2.4.2 Sensitivity to varying boundary conditions

Discharge events

High shear stresses occurring at the inflow point in the northern part of the study area (Polder Spiering) cause sand on the channel bed to move in downstream direction, towards the major bifurcation in Polder Noordwaard, where the sand is deposited on the bar in-between the bifurcating channels (Figure 2.8). Close to the outlet of the system (between g3 and g4 in Figure 2.1), the high shear stresses in the converging water flow cause the channel bed material to become mobilized and to leave the area both through bed load and suspended transport. Thus, close to the inlet mostly an internal redistribution of sand occurs, while close to the outlet there is a net loss of sand from the area. In the channel system further away from the in- and outlet shear stresses are too low for mobilizing or transporting sand, leading to stable channels. Overall, bed level changes in the channel system are dominated by deposition and erosion of sand, and exhibit a strong correlation with the magnitude of the discharge event (Figure 2.9).

Sedimentation of mud on the flats mostly takes place close to the channels due the large gradient in flow velocity there (Figure 2.8). However, higher discharges deposit the material farther away from the channels due to the larger water depth and consequent smaller gradient in flow velocities. Local topographic irregularities in the bottom surface also affect the deposition patterns: the former drainage ditches prove to be very good sediment traps, and former roads or small dikes may prevent sediment loaded water from flowing back to the channels after the highest water levels have passed. This is especially notable for the heaviest discharge event, which inundates the entire system. Gradual sediment depletion causes a small gradient in sediment deposition from the inlet (more sedimentation) to the outlet (less sedimentation). Deposition of the mud inside the channels occurs only to a very small extent: mainly in the dead-end channels on the eastern side of the system.

Larger discharges cause both more erosion of mud in the channels and more sedimentation on the flats (Figure 2.9). There is no direct relation between these two effects: the bed level of the flats increases mostly because of sedimentation of silts coming from the upstream boundary, while the sand that erodes from the channels stays in suspension and leaves the area through the downstream boundary. Sedimentation of suspended sand occurs only on a specific part of the flats close to the post-confluence channel section.

The total amount of mud retained in the study area increases with the magnitude of the discharge peak and corresponding increased influx of sediment, whereas the mud trapping efficiency decreases (Figure 2.10). The reduced trapping efficiency is caused by the increased shear stresses during the high discharge events, which also causes most of the fines to stay in suspension during their transport through the channels in the area.

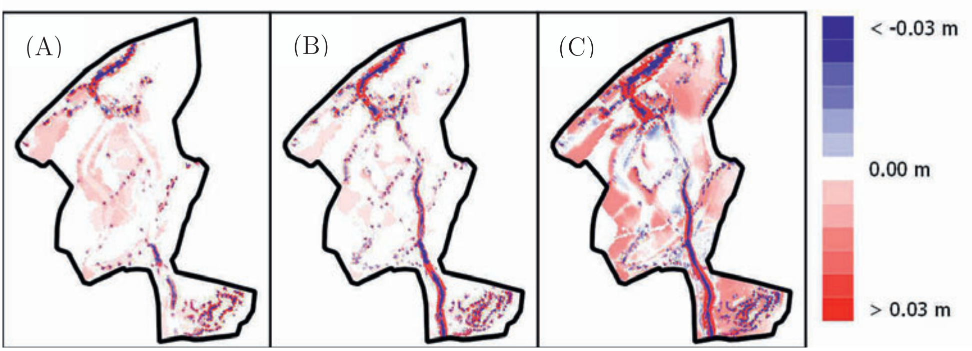

Figure 2.8: Impact of discharge events on erosion/sedimentation patterns compared to the reference case. (A) sedimentation/erosion pattern of the reference case DISCH0, (B) and (C) sedimentation/erosion pattern of DISCH1 and DISCH2 minus the sedimentation/erosion pattern of DISCH0, respectively.

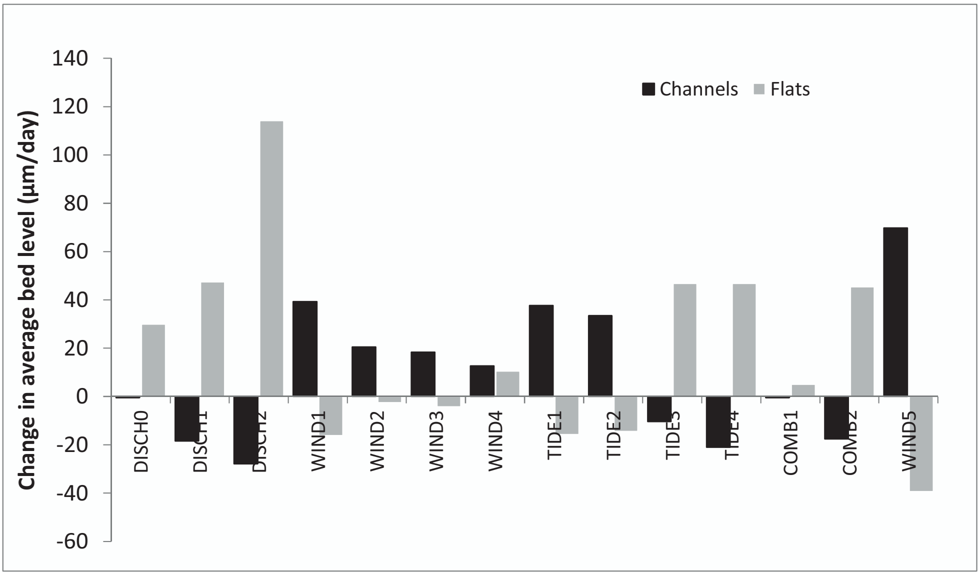

Figure 2.9: Change in average bed level of the channels and flats for all event runs

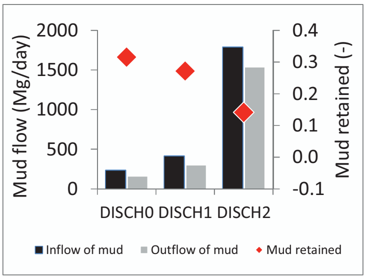

Figure 2.10: Average daily inflow and outflow of mud, and the fraction of mud retained in the study area (trapping efficiency) for increasing discharge magnitudes (DISCH1 and DISCH2). DISCH0 is the case with a (yearly average) stationary discharge and is included for reference.

Windstorm events

The analysed windstorms have a large impact on the net sedimentation/erosion patterns compared to the reference case: all storm scenarios lead to less sedimentation on the flats (Figure 2.11) through resuspension of fine sediment. This is the result of a combination of a relatively shallow water depth and large fetch length, which leads to the development of wind waves that can reach the bed level and hence cause bed shear stresses to increase. Part of the resuspended sediment settles in the deeper channel system due to the low shear stresses resulting from the stable, stationary discharge conditions. This causes correlation between the decrease of the average bed level of the flats and the increase of average bed level inside the channel (Figure 2.9).

Another part of the mobilised mud is redistributed over the flats, with sedimentation/erosion patterns largely governed by the wind direction: most of the sedimentation occurs on the lee side of the island, and erosion takes place especially in those areas where the waves are most developed (Figure 2.11). In WIND1 for example, the relatively long fetches in the NE part of the system caused most of the erosion to take place in that particular area. In WIND2 on the other hand, the geometry of the SE part of the area (Polder Maltha) restricted the build-up of significant waves during the event, leading to less erosion.

The rest of the resuspended mud stays mobile and leaves the study area through the downstream outlet with the stationary water discharge. This leads to a net reduction in mud trapping efficiency for all windstorm events, regardless magnitude and direction, when compared to the reference case DISCH0 without wind (Figure 2.12 and 12Figure 2.12Figure 2.10). The only exception is WIND4. This event has the lowest wind speed of all T1 windstorm events as well as a wind direction that is opposite to the flow direction, which causes it to have a less pronounced impact on the mud trapping efficiency than the other T1 windstorm events (Figure 2.11).

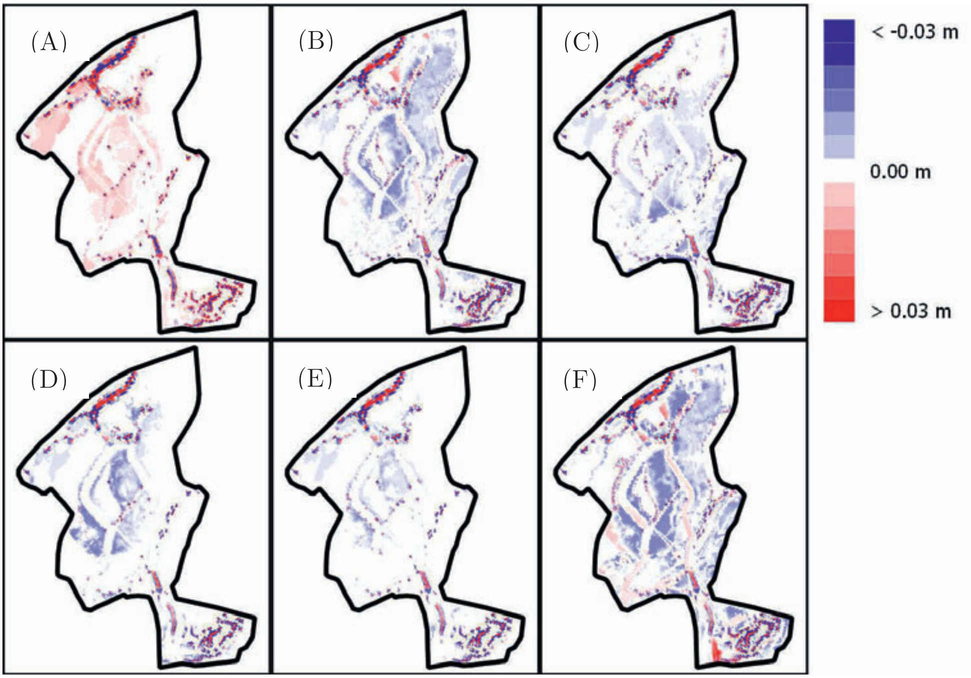

Figure 2.11: Impact of windstorm events on erosion/sedimentation patterns compared to the reference case. (A) sedimentation/erosion pattern of the reference case DISCH0. (B) sedimentation/erosion pattern of WIND1 minus the sedimentation/erosion pattern of DISCH0. (C) through (F) corresponding differences with the reference case of WIND2 through WIND5.

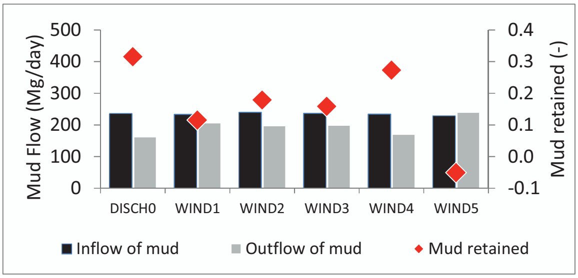

Figure 2.12: Average daily inflow and outflow of mud, and the fraction of mud retained in the study area (trapping efficiency) for alternative wind directions (WIND1 to WIND4) and magnitude (WIND5) DISCH0 is included for reference.

WIND5 is the only event that leads to an outflow of sediment that is larger than the sediment inflow, and hence results in a negative trapping efficiency (Figure 2.12). The T50 SW storm causes wave heights on the flats of up to 25 cm, preventing new sediment from settling and bringing most of the previously settled sediment into suspension. This also results in this event having the largest decrease in bed levels of the flats of all events (Figure 2.9). Furthermore, WIND5 is the only event that leads to a net accumulation of sand in the study area. This is caused by the strong SW wind during the periods of reversed flow direction in the southern part of the study area, which fills an area close to the outlet (Polder Maltha) with sand in suspension from the northern section of the study area, where the flow direction is not reversed. Although this process may indeed occur in reality, we did not have sufficient data to verify this model outcome. Finally, WIND5 also causes the largest increase in bed level in the channels of all events (Figure 2.9). Most of this increase can however be attributed to the deposition of sand in polder Maltha.

Tidal range

Varying the tidal range from average to neap or spring tide has little effect on the sedimentation/erosion patterns compared to both reference cases (Figure 2.13), even though these patterns seem to be strongly affected by tidal water level fluctuations. The net retention rates of mud compared to both reference cases remain also relatively unaffected (Figure 2.14). Still, the net outflow of sand from the study area during the discharge event depends slightly on the tidal amplitude, with a decrease during neap tide (TIDE3) and an increase during spring tide (TIDE4). The average channel bed level changes accordingly (Figure 2.9).

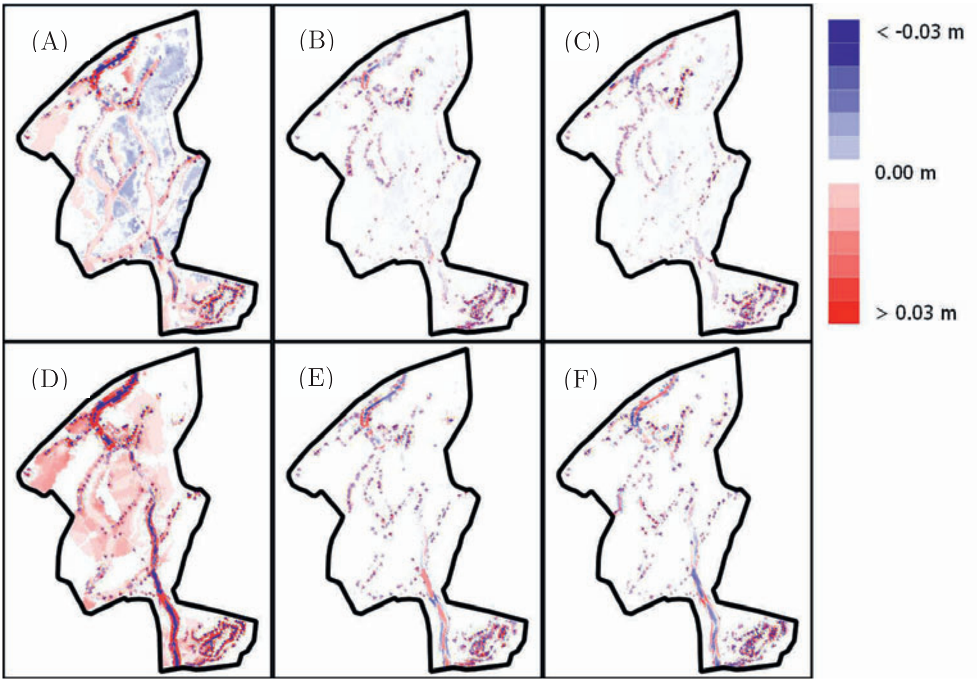

Figure 2.13: Impact of tidal range on erosion/sedimentation patterns compared to two reference cases. (A) shows the sedimentation/erosion pattern of reference case WIND1. (B) and (C) sedimentation/erosion pattern of TIDE1 and TIDE2 minus the sedimentation/erosion pattern of

(A), respectively. (D) sedimentation/erosion pattern of reference case DISCH1. (E) and (F) sedimentation/erosion pattern of TIDE3 resp TIDE4 minus the sedimentation/erosion pattern of (D), respectively.

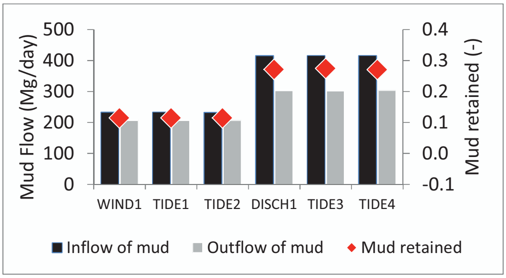

Figure 2.14: Average daily inflow and outflow of mud, and the fraction of mud retained in the study area (trapping efficiency) for cases with alternative tidal range (neap, spring) during a windstorm event (TIDE1 and TIDE2) and during a discharge event (TIDE3 and TIDE4). WIND1 and DISCH1 are included for reference.

Combined discharge – windstorm events

A T1 windstorm coinciding with a discharge event (COMB1) mobilises the initial mud layer on the flats in a similar fashion as during average discharge conditions (e.g. WIND1), albeit to a slightly lesser extent. This is the result of the increased water depth in the system due to the discharge event, which makes it more difficult for the wind waves to reach the bed. The wind also hinders the settling on the flats of 'new' sediment entering the system with the discharge wave, which results in a negligible increase of average bed level of the flats (Figure 2.9). Part of the resuspended sediment settles in the deeper parts of the channel system which, in combination with the bed erosion occurring in other parts during the passing of the discharge event, leads to an almost neutral channel bed level change (Figure 2.9).

Another part of the mobilised mud is redistributed over the flats. The sedimentation/erosion pattern of COMB1 strongly resembles WIND1 (Figure 2.15), although the total amount of sedimentation on the flats is slightly higher in the combined case because of the passing of a discharge wave.

The rest of the resuspended mud remains mobile and leaves the study area through the downstream outlet, together with the sediment that originates from the upstream boundary and that was unable to settle on the flats due to the wind conditions. This leads to a large reduction in mud trapping efficiency when compared to reference case DISCH1 (Figure 2.16). A much smaller windstorm (COMB2) still leads to a reduction of sediment trapping efficiency compared to the base case DISCH1, albeit very small.

Trapping efficiencies of combined discharge-windstorm events depend on both parameters as follows: Given an average discharge regime, switching from a T1 windstorm to a T50 windstorm leads to a large reduction in trapping efficiency (Figure 2.17). Given a T50 discharge event however, the trapping efficiency is reduced by only a small amount when switching from a T1 to T50 windstorm. We hypothesize that the larger water depths during the T50 discharge event reduce the impact of the waves on the bed shear stresses, thereby effectively reducing the resuspension of mud. Furthermore, increased sedimentation occurs in those areas that are less affected by wind, such as the deep dead-end channel sections and parts on the lee side of the island.

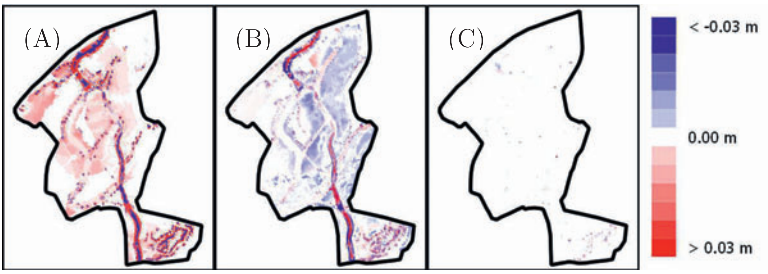

Figure 2.15: Impact of combined discharge-windstorm events on erosion/sedimentation patterns compared to the reference case. (A) sedimentation/erosion pattern of the reference case DISCH1. (B) and (C) sedimentation/erosion pattern of COMB1 resp COMB2 minus the sedimentation/erosion pattern of DISCH1.

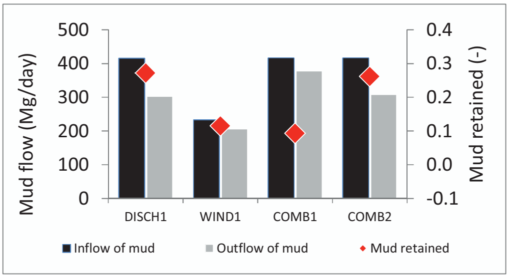

Figure 2.16: Average daily inflow and outflow of mud, and the fraction of mud retained in the study area (trapping efficiency) for combined discharge-windstorm events COMB1 and COMB2. DISCH1 and WIND1 are included for reference.

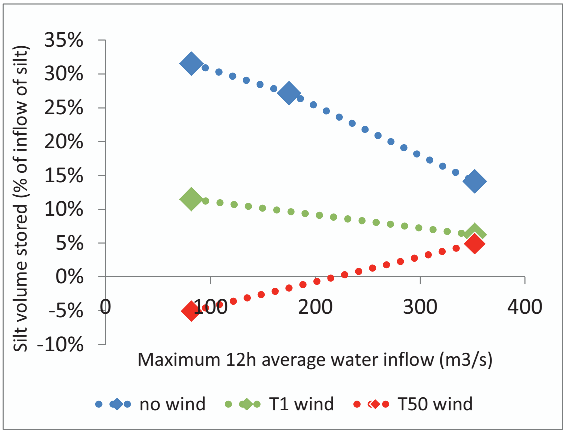

Figure 2.17: Relation between discharge magnitude (defined by the maximum 12-hour moving average water inflow from the upstream boundary) and sediment trapping efficiency for three different windstorm scenarios (all from SW). The discharge values of 82 m3/s, 175 m3/s and 352 m3/s correspond to average, T1 and T50 discharge, respectively.

2.5 Discussion

Our site-specific results show the sedimentation patterns and rates inside a flow-through TFW, and how these change in response to various combinations of hydro-meteorological controls. Until now, most research focused on a single control on sedimentation processes in a wetland (e.g. Temmerman et al., 2003b; Mariotti and Fagherazzi, 2013), however our results demonstrate that there are cases in which there is important interaction among the three controls (discharge, wind and tide). In this section we discuss the role of both separate and combined controls, first on the sediment balance and trapping efficiency, and then on sedimentation patterns.

For our study area, the role of the separate controls on the *sediment balance terms* and the *sediment trapping efficiency* is as follows: river input is the major source of sediment of this flow-through wetland, and the discharge through the inlet determines net sediment deposition rates (positive correlation, due to increased amounts of sediment conveyed into the area) and trapping efficiency (negative correlation due to increased bed shear stresses at higher flow velocities). Similar relations were reported by for example Yang et al. (2005), who linked reduction in vertical growth rate of intertidal wetlands in the Yangtze delta to decreased riverine sediment supply caused by the construction of a large number of dams. Wind causes resuspension of fine sediments, similar to the processes taking place in shallow lakes such as Lake Markermeer, the Netherlands (Kelderman et al., 2011). A large part of the resuspended material immediately leaves the area along with the continuous water flow through the wetland. This causes the trapping efficiency to decrease for increasing wind speeds. Varying tidal range (neap, spring) has surprisingly little effect on the sediment balance, although the wetland is located in the backwater of the sea. This low impact is largely caused by the presence of a saltwater barrier (Haringvliet sluices) downstream of the wetland, which severely dampens the tidal signal. In other TFWs tidal range was shown to be a major control of sedimentation (e.g. Kirwan and Guntenspergen, 2010; Vandenbruwaene et al., 2011), and should therefore normally not be neglected.

The combined impact of discharge and wind on the sediment balance and trapping efficiency is as follows: with increasing discharge, the impact of wind through resuspension decreases due to the increased water depths caused by higher discharges along with wind setup on the Haringvliet estuary (for westerly wind). Net loss of sediment from the area only occurs during extreme windstorms in combination with low flow-through discharges – all other combinations lead to a positive trapping efficiency, albeit very small for cases with wind and low discharges.

With respect to *sedimentation patterns* in the study area, our results generally agree with previous research in similar areas (e.g. Temmerman et al., 2003b; Hupp et al., 2008; Delgado et al., 2013; Mitsch et al., 2014): the highest sedimentation rates are found close to the inlet of the wetland and close to the internal channel network. Topographic irregularities in the submerged terrain - particularly former polder drainage ditches and old embankments - also influence local sedimentation patterns. Larger discharge events cause a larger portion of the sediment to settle farther away from the inlet and the channels. Wind influences sedimentation patterns by resuspension and internal redistribution, usually resulting in a net transport of sediment from the flats towards the channels.

The impact of wind on bed shear stresses is caused especially by locally-generated wind waves, and not by wind-driven currents. This is also observed in tidal mudflats, for example along the Westerscheldt estuary (Callaghan et al., 2010). Interestingly, we find an almost linear (negative) correlation between wind speed and mud retention, for all wind directions (Figure 2.18), even though fetch lengths for the various wind directions show large differences due to the distinctly elongated shape of the study area along the NW-SE axis. As Mariotti and Fagherazzi (2013) pointed out for the case of a tidal mud flat in Willapa Bay, USA, different fetches only start to impact bed shear stress above a certain critical water depth. We hypothesise that water depths in our study area (generally between 0.1 and 1 m) are below this critical value. The determination of this critical depth is an interesting topic for further research.

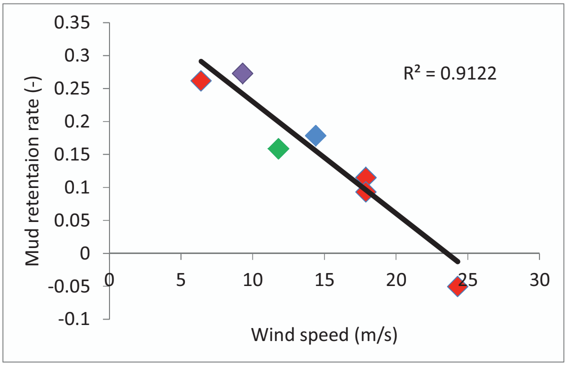

Figure 2.18: Relation between wind speed and mud retention rate. Red points indicate wind from SW, blue from NW, green from NE, and purple from SE.

To answer the question whether this TFW will survive the impact of SLR, the next step will be to analyse long-term effects for different climate scenarios in which the frequency and duration of these and other events are incorporated in longer time series, and are adapted in accordance with future climate scenarios. This step also requires that the effect of vegetation and possibly subsidence be accounted for in the models. Application to other TFWs in the world requires further extension of the analysis by evaluating the effects on sedimentation rates and patterns of for example wetland size, shape, position within the delta (distance to turbidity maximum), and vegetation.

2.6 Conclusions

To gain insight in both the average wetland surface accretion rates and the spatial sediment distribution in a Tidal Freshwater Wetland (TFW) and the role of various different controls, we developed a combined hydrodynamic, morphological and wave model of a TFW in the Netherlands and applied it to analyse sediment rates and patterns for various windstorm and discharge events under different tidal conditions. The main conclusions for this area are:

- The net sediment deposition rate inside the TFW increases with water discharge magnitude and associated increases in SSC of the inflowing water, decreases with windstorm magnitude, and is relatively unaffected by changes in tidal conditions (neap, spring).
- The trapping efficiency decreases with water discharge magnitude as a result of increased bed shear stresses. Windstorms during any discharge event reduce the

trapping efficiency compared to the same discharge event without any wind. The actual reduction increases with wind velocity, depends on wind direction (highest for SW winds), and decreases for higher water inflow from the river.
- Sedimentation rates are highest close to the inlet of the wetland, and the channel system within the wetland. Local sedimentation patterns are affected by irregularities in the topography, particularly former polder drainage channels and old embankments.
- Regardless of wind direction, windstorms lead to a) a net transport of sediment from the flats towards the channels, b) a net transport from the downwind sections of the flats to other sections and c) an increased outflow of sediment from the study area.
- TFWs have the potential to trap large amounts of sediment, yet the actual deposition rate shows large variations depending on the interplay between discharge conditions, windstorms and tidal conditions. This interplay should be taken into account when predicting long-term sedimentation rates.

Results are found to be in line with findings from previous studies. However, the specific location of this wetland in between tidally and fluvially dominated areas makes it particularly important to consider the various controls or boundary conditions in combination. Follow-up research will focus on a) the identification of critical thresholds of combined boundary conditions for sedimentation and erosion in TFWs and b) the application of the model to quantify the long-term response of the TFW to SLR.

2.7 Acknowledgements

This study was financed by the Dutch Technology Foundation STW (project no. 12431). We thank everybody who assisted us with the data collection, especially Dr. H. de Boois. We thank the people of Staatsbosbeheer and Rijkwaterstaat-WNZ for the provided data, logistic support and assistance. We also thank two anonymous referees for their careful reviews and constructive comments.

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3 The impact of climate change on the morphology of a tidal freshwater wetland affected by tides, discharge and wind

Abstract

Tidal freshwater wetlands are threatened by climate change, especially by rising sea levels. Until now, research in these wetlands has focused mostly on determining historical and present-day accretion rates without analysing the influence of climate change on future developments. We study a recently constructed freshwater wetland under influence of tides, wind and riverine discharges, and carry out a scenario analysis to evaluate the impact of climate change on morphodynamics. We use a numerical model that describes the hydrodynamics and morphology in the study area and includes the impact of vegetation, and carry out transient scenario runs for the period 2015-2050 with gradually changing boundary conditions. We conclude that the simulated accretion rates are significantly lower than the rate of sea level rise, meaning that the wetland will gradually convert to open water. We also find that the morphological changes can largely be attributed to morphological stabilization of the constructed wetland and not to climate change. Wind plays an important role through resuspension and redistribution of fine sediment, and neglecting it would lead to a significant overestimation of accretion rates on the flats.

Published as: Verschelling E, van der Perk M, Middelkoop H. The impact of climate change on the morphology of a tidal freshwater wetland affected by tides, discharge, and wind. River Res Applic. 2018;34:516–525. https://doi.org/10.1002/rra.3282

3.1 Introduction

Tidal wetlands are threatened by a combination of sea level rise, sediment starvation, and subsidence (e.g. Delgado et al., 2013; Kirwan and Megonigal, 2013; Beckett et al., 2016; Belliard et al., 2016). Survivability of coastal wetlands in the face of relative sea level rise (RSLR: SLR and subsidence combined) has been studied extensively, and depends on factors such as the availability of sediment (Neubauer et al., 2002), wetland elevation (Temmerman et al., 2003), vegetation cover (Gedan et al., 2010; Belliard et al., 2016), subsidence (Beckett et al., 2016), and the ability of the wetland to move in landward direction (Fagherazzi et al., 2013; Kirwan and Megonigal, 2013). Tidal freshwater wetlands (TFWs) in the transition zone between *tidally-dominated* and *fluvially-dominated* sections of a river delta have received less attention in scientific literature.

Depending on wetland location and properties, flooding and sedimentation in TFWs are governed by the combined influence of tides, riverine discharges, and wind (Verschelling et al., 2017). Drowning mechanisms and measures that mitigate the impact of climate change (CC) in these areas, therefore, differ significantly from those in coastal areas, especially if CC also impacts river discharges and wind. Most research in TFWs has focused on understanding historical and present-day sedimentation rates and patterns, and has shown that sedimentation rates depend on factors such as supply of sediment (Neubauer et al., 2002), impact of tides and wind (Orson et al., 1990; Vandenbruwaene et al., 2011; Verschelling et al., 2017) and wetland parameters such as average water depth, wind fetch lengths and distance to creeks (Hupp and Bazemore, 1993; Temmerman et al., 2003; Delgado et al., 2013).

This paper focuses on the long-term effects of CC on the morphology of freshwater wetlands. More specifically, our objective is to understand and quantify the effects of climate change on the morphology of a freshwater wetland affected by discharges, tides, and wind. To this end, we use a small microtidal flow-through wetland, located in the Biesbosch National park in the Rhine-Meuse delta in the Netherlands, as a case study and compared net sediment deposition rates and sedimentation patterns of two distinct climate change scenarios to present-day climate conditions. For this analysis, we deployed a numerical model that accounts for the interactions between hydrodynamics, morphology, and vegetation. We carried out transient scenario runs for the period 2015-2050, in which the boundary conditions changed on a yearly basis, using synthetic yearly time series of discharge, water level, and wind with similar statistical properties (auto and cross correlations) as the original measured time series. The simulation results were then post processed to net sedimentation/erosion patterns over the years, bed levels and the evolution of average and flat levels over time. Finally, we tested the sensitivity of the accretion rates to an alternative vegetation scenario and to the impact of wind.

3.2 Study area

The study area consists of a number of former polders in the Biesbosch National park, a 9000 ha tidal freshwater wetland in the lower Rhine and Meuse delta in the Netherlands (Figure 1). During 2007-2008, a channel network was constructed through the polders and the embankments were opened at the northern and southern sides of the area, connecting the newly created wetland to the River Nieuwe Merwede and Gat van de Noorderklip, respectively. The objective of this opening was to lower upstream flood levels by enlarging local conveyance capacity of the River Rhine. Due to the location of the newly created wetland in the backwater of the North Sea (Kleinhans et al., 2010), it is potentially threatened by SLR, making it a relevant study area. It has a limited number of connections to the surrounding water system, which facilitates the construction of sediment and water balances.

The flow-through wetland has a surface area of about 700 ha and has a dominant flow direction from north to south. The sandy material that was dug from the channels was used to create an artificial island in the centre of the area. The rest of the area has an average surface level of NAP +0.3m and consists of mud flats still covered by the original layer of polder clay. The channels occupy around 25% of the surface area of the study area. Tides in the region are semidiurnal with a typical range between 0.2 to 0.4m. Average depth on the tidal flats ranges from 0 to 0.5m. Occasional exposure of the flats occurs at low tide or during easterly winds in the summer. Water levels in the area are strongly affected by Rhine discharge and tides. Storm surges from westerly winds at sea occasionally cause large setup in the wetland. Winds play an important role in shaping the morphodynamics of the system. Locally-generated wind waves cause a substantial amount of resuspension due to the long fetch lengths across the inundated flats (Verschelling et al., 2017).

Suspended sediment concentrations (SSC) at the inlet of the system typically vary from 10 to 40 mg/l during average flow conditions. During peak discharges, SSC in the upstream Rhine River can reach up to 140 mg/l (Asselman, 2000). Since the de-embankment of the area in 2008, sedimentation has taken place in the central section of the channel system with values up to 14.3 mm year^{-1}, whereas channel sections close to the inlet and outlet have experienced significant erosion (van der Deijl et al., 2017). The flats have remained relatively intact due to the erosion resistance of the layer of polder clay in combination with low flow velocities. Since 2008, most of the flats have been covered by a layer of mud 2 to 5 cm thick, with most of the aggradation occurring close to the channels (Verschelling et al., 2017). We refer to van der Deijl et al. (2017) and Verschelling et al. (2017) for more details on the morphological evolution in the study site.

Vegetation in the study area is sparse. It consists mostly of shrublands and softwood riparian forests on the higher grounds, reed fields, pioneer herbs and multiple types of grassland on the banks along the island and the flats, and multiple species of mudwort and macrofytes on the flats (Van der Werf, 2016). Currently, vegetation is kept short by grazing (cows and geese) as well as by mowing. This effectively removes most of the vegetation from the mudflats and the island, and also conserves the grassland.

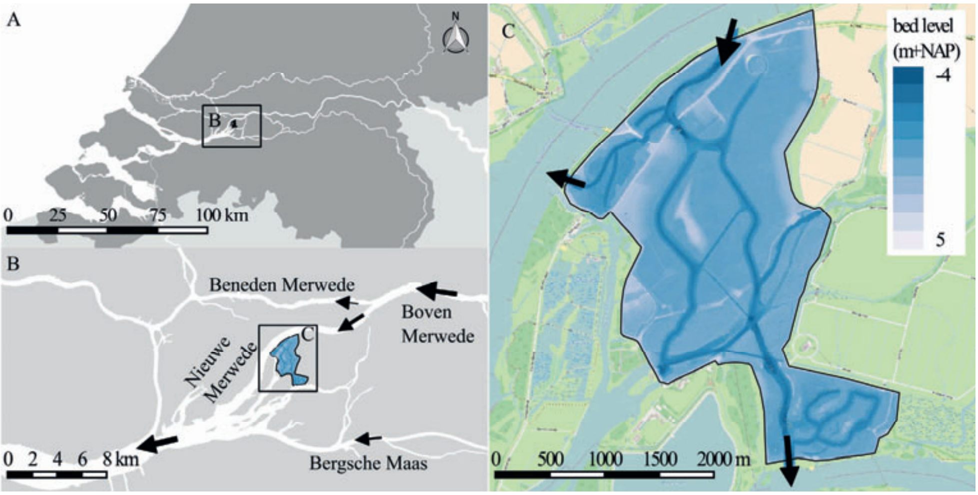

Figure 3.1: Study area. The arrows indicate the main flow directions.

3.3 Methods

3.3.1 Model setup & calibration

We used the depth-averaged version of the Delft3D modelling framework (Lesser et al., 2004) to simulate water flow, sediment transport, and bed level changes in the study area. Here we provide a short overview of the model setup and calibration, both of which are described in more detail by Verschelling et al. (2017).

Bed level changes are simulated based on differences in sediment transport rates of cohesive and non-cohesive sediment fractions, calculated with the Krone and Ariathurai-Partheniades equations (Partheniades, 1965) and the Van Rijn equation (Van Rijn, 1984), respectively. The SWAN short wave model (available in Delft3D as Delft3D WAVE) was used to account for the impact of wind-generated waves on hydromorphodynamics. The computational grid covers the study area as highlighted in Figure 1C. It is a curvilinear grid with 144 x 145 cells, and has cell sizes ranging from 5 to 30 m. The initial bathymetry was constructed by combining a 2011 dataset describing the channel bathymetry, the 2003 version of the official Dutch DEM ('AHN1'), and a local 2010 LIDAR DEM of the higher grounds in the system (Verschelling et al., 2017). These datasets were provided by the Dutch National Water Authority (*Rijkswaterstaat*). Initial bed composition consisted of one uniformly mixed layer of two sediment fractions (one cohesive mud fraction, one non-cohesive sand fraction) with 100% mud on the flats and 100% sand in the rest of the system (channels and island). The hydrodynamic and sediment transport models were calibrated and validated for periods in 2011, 2014, and 2015. The hydrodynamic model calibration was carried out for measured water level series at three gauging stations and resulted in RMSE values ranging from 0.46 to 1.80 cm. The calibration of the sediment transport model yielded a Brier skill score of 0.81, which means that the model performance can be classified as "good" (Verschelling et al., 2017).

3.3.2 Scenario calculations

We used the so-called *2050GL* and *2050WH* climate change scenarios developed for the Netherlands by the Dutch meteorological institute KNMI (Van den Hurk et al., 2014). The 2050GL scenario expects low changes in air circulation patterns combined with moderate rise of global temperature, which translates into a 4% increase in precipitation and 0.15 to 0.3 m increase in mean sea level at the North Sea coast compared to the reference climatic period, 1981-2010 (Van den Hurk et al., 2014). The 2050WH scenario combines a relatively large rise of global temperature with changes in atmospheric circulation patterns, leading to 5% more precipitation and an increase in mean sea level of 0.2 to 0.4 m. For the purpose of this scenario analysis, we chose to use the most extreme values of expected SLR (0.3 m for 2050GL and 0.4 m for 2050WH). For reference, we also included a 2050 scenario without any climate change (*2050REF*). We chose 2015-2050 as scenario period, because 2050 is a horizon year that fits well with the KNMI scenarios and is commonly used in climate scenario research projects (e.g. IPCC, 2007).

Model boundary conditions for the 2015-2050 simulations consisted of one-year synthetic time series of discharges at the upstream boundary (river Nieuwe Merwede), water levels at the downstream boundary (creek Gat van de Noorderklip) and WNW winds over the entire model domain (Table 3.2). These time series were constructed through linear interpolation between 2015 and the two scenario 2050 time series.

The 2015, 2050GL, and 2050WH time series were constructed as follows. First, we used scenario-specific time series for the period 1-1-1967 to 1-1-2007 of the daily discharge at Lobith (location A in Figure 3.2) developed by Sperna Weiland et al. (2015), 2-hourly tidal water levels at Hoek van Holland (location B) and Haringvliet-buiten (location C) provided by the Dutch department of waterways and public works (Rijkswaterstaat, 2016), and the 2-hourly wind speed and velocity at four surrounding stations provided by KNMI (KNMI, 2016) . Second, we routed those signals to the boundary locations of our Delft3D model using a 1D model of the Dutch river network, described in Chbab (2012).

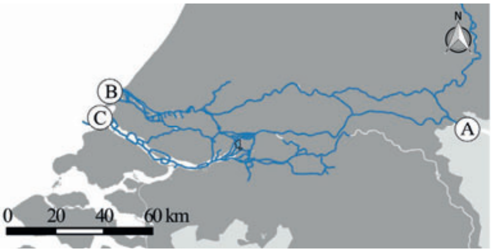

Figure 3.2: Extent of the 1D model (in blue) and locations of 1D model boundary conditions: Lobith (A), Hoek van Holland (B), and Haringvliet-buiten (C)

Third, we constructed synthetic time series of 2-hourly discharges, water level, and wind speed (assuming dominant wind direction of WNW) with a duration of one year using an approach described in detail in Van den Boogaard et al. (2003). This approach consists of an iterative optimization algorithm that uses random seeds to construct synthetic time series that satisfy several *a-priori* defined statistical properties. In this case, those properties are the marginal probability density distribution and auto-covariance function of the routed signals at the locations of the Delft3D boundaries. For the water level, a distinction was made between a so-called carrier signal (setup) and a residual signal (tide). Although the algorithm was originally developed for univariate distributions only, we manually checked for cross correlations between the discharge, water level and wind speed. This is important because in our case these variables are correlated due to the location of our study area at the transition point between the discharge dominated and tidally dominated parts of the river system. We therefore constructed six alternative sets of time series and then selected the sets of time series that best satisfied the cross-correlations of the original dataset. A comparison between statistical properties of the original time series and the synthetic versions is given in Table 3.1, and Figure 3.3 shows the synthetic time series.

Table 3.1: Statistical properties of the original time series for the present-day (2015) climate and the synthetic version of these series. AvG = average, SD = standard deviation, Sk = skewness, Tac = autocorrelation time. CmxQ, CmxH and CmxU are the maximum correlations with discharge upstream, water level downstream and WNW wind velocity, respectively. A similar comparison for the other two sets of time series (2050wh and 2050gl) gave similar differences and is therefore omitted from this table.

		Original time series 2015						
Parameter		Avg	SD	Sk (-)	T_{ac} (d)	$C_{mx}Q$ (-)	$C_{mx}H$ (-)	$C_{mx}U$ (-)
Discharge upstream	m3/s	71.5	60.5	0.9	20.0	-	0.45	0.18
Water level downstream	m+NAP	0.49	0.27	0.79	4.0	0.45	-	0.55
WNW wind velocity	m/s	0.88	3.51	0.46	1.0	0.18	0.55	-
		Synthetic time series 2015						
		Avg	SD	Sk (-)	T_{ac} (d)	$C_{mx}Q$ (-)	$C_{mx}H$ (-)	$C_{mx}U$ (-)
Discharge upstream	m3/s	71.5	48.5	2.2	20.0	-	0.67	0.41
Water level downstream	m+NAP	0.49	0.23	1.07	4.0	0.67	-	0.73
WNW wind velocity	m/s	0.92	3.51	0.46	1.0	0.41	0.73	-

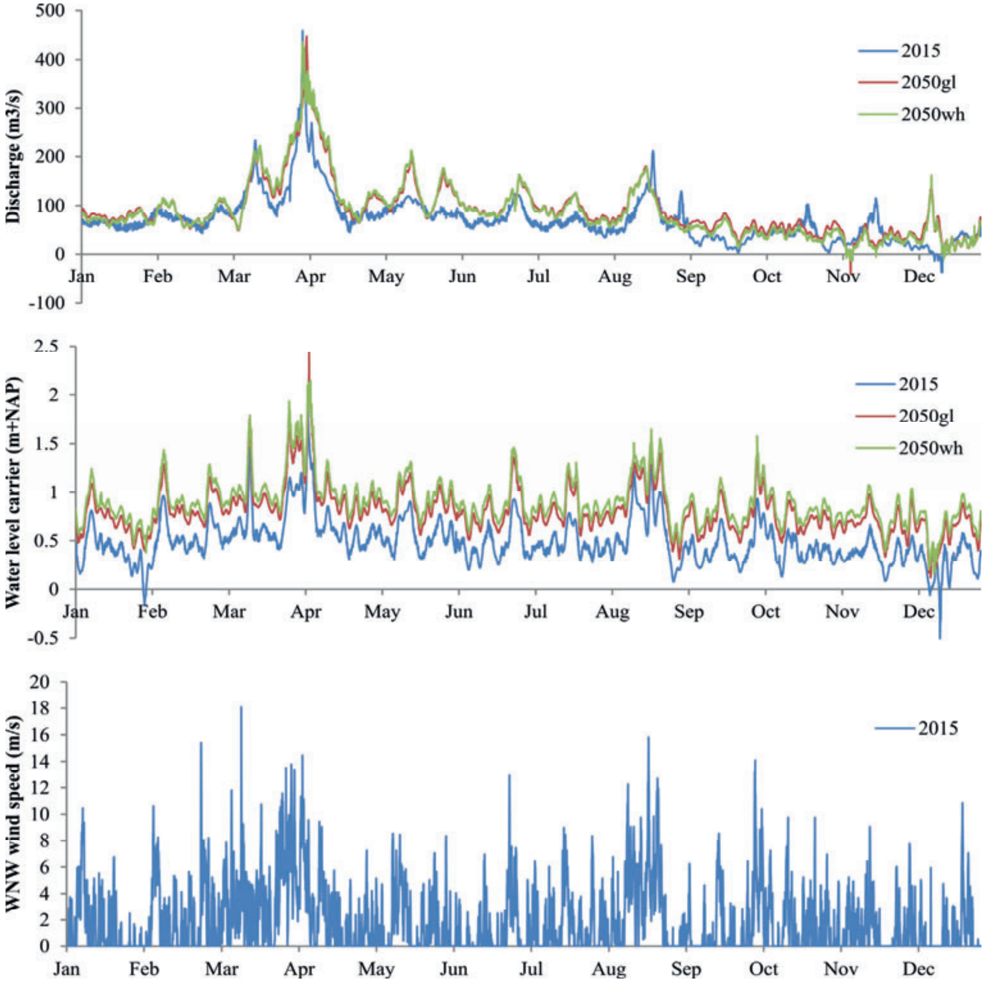

Figure 3.3: Yearly synthetic time series of discharge, water level (carrier) and wind velocity for 2015, 2050gl and 2050wh.

Fourth, we split each of these time series into a summer season (May-October) and a winter season (November-April). Although we could have used these time series to carry out the scenario analysis, this would have been very impractical due to the long calculation times. As a fifth step, we therefore applied a compression technique to the time series using a variable morphological multiplication factor in the range from 1 to 50 with a yearly average value of 21, leading to stepwise compressed time series of discharge, water level carrier and wind speed (Figure 3.4). Finally, a harmonic tidal signal was superimposed on the water level carrier time series, similar to the approach described by Verschelling et al. (2017). This resulted in compressed time series for both seasons for all scenarios. Boundary conditions for individual simulations in 2015-2050 were derived from these time series by linear interpolation.

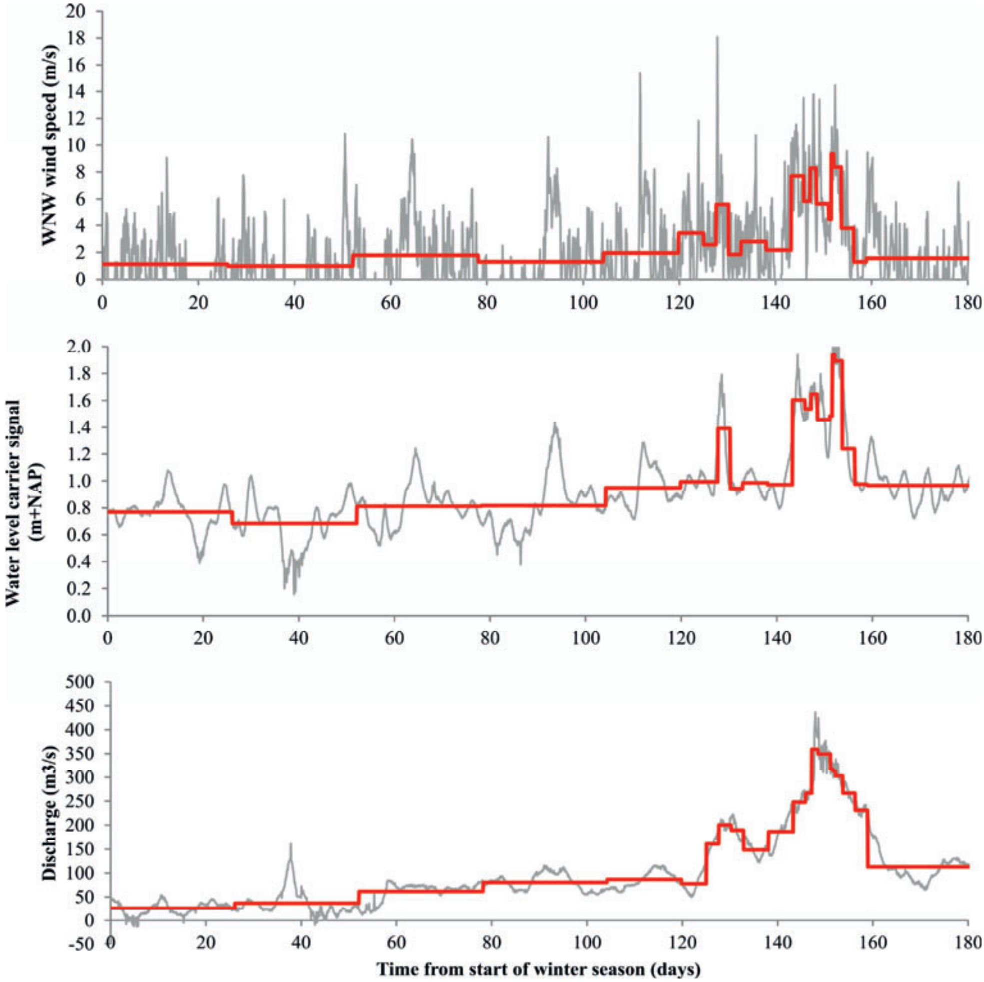

Figure 3.4: Synthetic time series (in grey) and stepwise compressed series (in red) of wind speed, water level (carrier) and discharge for the 2050WH/winter scenario. Every step of the compressed series represents 12h25m (one tidal cycle) simulation time with a corresponding value of the morphological factor: the longer the step, the larger the morphological factor. Note that the compressed series consist of 21 steps, which means that the simulation time of a winter season is almost 11 days with an average morphological factor of 17.

The suspended sediment concentrations at the upper model boundary locations were defined using the sediment rating curves constructed previously by Verschelling et al. (2017).

Table 3.2: Overview of scenarios and their boundary conditions. Scenarios 2050NOWIND and 2050GRAZING are described in the discussion section and included here for completeness.

	2015 boundaries		2050 boundaries		
Scenario	Q & h	wind	Q & h	wind	vegetation
2050REF	2015	2015	2015	2015	2015
2050GL	2015	2015	2050gl	2015	2015
2050WH	2015	2015	2050wh	2015	2015
2050NOWIND	2015	-	2015	-	2015
2050GRAZING	2015	2015	2015	2015	no grazing

3.3.3 Vegetation

We modelled the hydraulic resistance due to vegetation using the Baptist equation (Baptist et al., 2007), which distinguishes between flow-through and flow-over vegetation and links hydraulic resistance to vegetation parameters such as height, stem diameter, and density. The impact of vegetation on reduction of wave energy was modelled in the Delft3D WAVE module using the model developed by Suzuki et al. (2012), which requires the same vegetation parameters as the Baptist equation.

Initial simulations showed that changes in abiotic conditions during the scenario period (2015-2050) will likely not lead to significant vegetation succession in the area or an increase in vegetation cover in the currently sparsely vegetated area. On the contrary, some loss of vegetation is expected due to elevated water levels. We therefore decided not to include a separate vegetation growth module in the model simulations to periodically update vegetation patterns based on changes in abiotic conditions and vegetation succession knowledge rules. Instead, we used a fixed vegetation pattern for the entire period, based on the expected abiotic conditions halfway through the scenario period (2033). We constructed this vegetation cover as follows: first, we selected six representative vegetation types, and for each of these types a key species was selected to represent that type (Table 3.3). For each of the key vegetation species, the relevant parameters for the hydraulic roughness and wave damping formulations in Delft3D were defined based on Van Velzen et al. (2003), Oorschot et al. (2015) and Van der Werf (2016) (Table 3.3B). A distinction was made between summer and winter parameter values to account for the varying properties of certain vegetation types between the two seasons (leaves or no leaves, plants or no plants in the case of macrophytes). Next, we constructed a vegetation cover for these species according to the most recent local vegetation surveys (Everts and De Vries, 2011; Bijkerk and Davids, 2012), and assumed this to be representative for the 2015 vegetation cover (Table 3.3A). This 2015 vegetation cover is partly determined by the grazing of cows and geese, leading to the continued existence of patches of grass on the higher grounds and to a reduction of macrophytes and pioneer vegetation on the inundated flats. Because initial simulations showed that water depths in the wetland are likely to increase, we decided to use a realistic vegetation scenario for the 2015-2050 period, which would maximize sedimentation. This scenario assumes cows to be prevented from grazing, while the increased water depths would prevent the geese from removing all of the macrophytes on the flats, which lead to succession of grass by shrubs and growth of macrophytes on the inundated flats. We implemented this vegetation scenario by modifying the 2015 vegetation cover according to a set of numerical knowledge rules based on the work of Van der Werf (2016) that expresses habitat suitability in terms of abiotic conditions (Table 3.3A) to arrive at the fixed cover for the 2015-2050 scenarios (Table 3.3B).

Table 3.3: (A) Key vegetation species habit suitability rules and (B) key vegetation properties

vegetation type	Key species	Minimum required bed level	Maximum required bed level
Riparian forest	Salix alba	> 0m MHW	< 1.4m MHW
Helophytes	Phragmites australis	> 0m MW	< 0.2m MW
Shrubland	Urtica dioica	> 0.5m MHW	-
Submerged vegetation	Potamogeton	> -1.5m MW	< -0.2m MW
Pioneer herbaceus plants	Pioneer herbs	> 0m MHW	-
Grassland	Lolium perenne	> 0.2m MHW	-

	General		Summer			Winter		
Key species	diameter (m)	Cb ($m^{0.5}/s$)	stems (m^{-1})	height (m)	drag (-)	stems (m^{-1})	height (m)	drag (-)
Salix Alba	0.18	18	0.16	20	2	0.16	20	1.5
Phragmites australis	0.004	30	100	2.5	2	100	2.5	1
Urtica Dioica	0.008	30	100	1.5	2	32	1	1
Potamogeton	0.005	40	75	1	2	-	-	-
Pioneer herbs	0.003	30	50	1	2	50	0.15	1
Lolium perenne	-	30	-	-	-	-	-	-

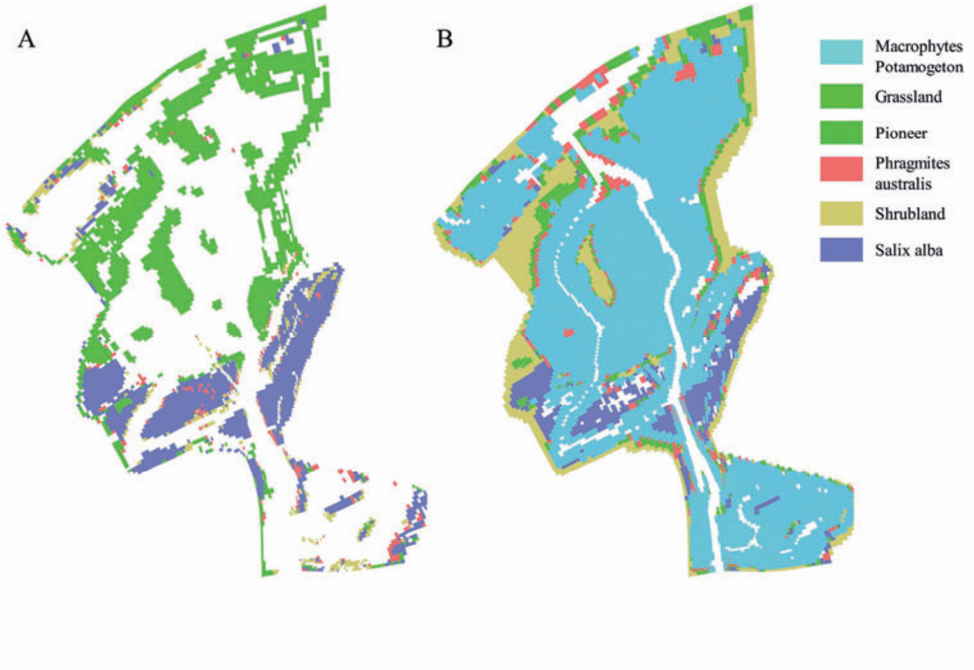

Figure 3.5: (A) Vegetation cover as surveyed in 2010/2011 and (B) as used in the summer calculations of scenarios 2050REF, 2050WH and 2050GL. The vegetation cover for the winter calculations is identical to that of the summer except for the absence of Potamogeton. The 2010/2011 survey did not include acrophytes.

3.4 Results

For all scenarios, most of the changes in morphology occur in the channel system between -0.5m NAP (Figure 6A) and 0.3 m NAP and below -3 m NAP (not shown in Figure 6): they become narrower and deeper. Compared to the 2050REF, the 2050WH and 2050GL scenarios both lead to enhanced sedimentation on the channel banks and an elevated bed level of the flats. Nevertheless, the difference between 2015 and 2050REF is much larger than the difference between 2050REF and 2050WH or 2050GL, implying that most of the morphological changes in the area can be attributed to morphological stabilization of the relatively recently reclaimed wetland, and not as much to the impact of climate change.

Figures 6B and 6C show the development of the average water levels as well as the 5^{th} and 50^{th} percentile bed levels for the three scenario runs. We assume these percentiles to be representative of channel bed and flat bed levels, respectively. For both climate change scenarios, the level of the flats is unable to keep pace with the rise in water levels (GL: 0.05 m versus 0.27 m and WH: 0.06 m versus 0.36 m). For all scenario runs, the evolution of both the channel bed and the flat bed is almost linear, indicating that the morphological system is still far from stable.

In the 2050REF scenario, most of the changes take place in and around the channel system (Figure 7A). Most of the channels have become narrower and slightly deeper, except for the western branch, which has filled up with sediment due to lower flow velocities compared to eastern channel. The 2050WH climate change scenario lead to more erosion in the eastern channel and more sedimentation in the western channel compared to 2050REF. The pattern of scenario 2050GL is very similar and is therefore not shown. The differences on the flats are limited to a slight increase in sedimentation on the flats in the NW and the SE, which are most protected from the wind.

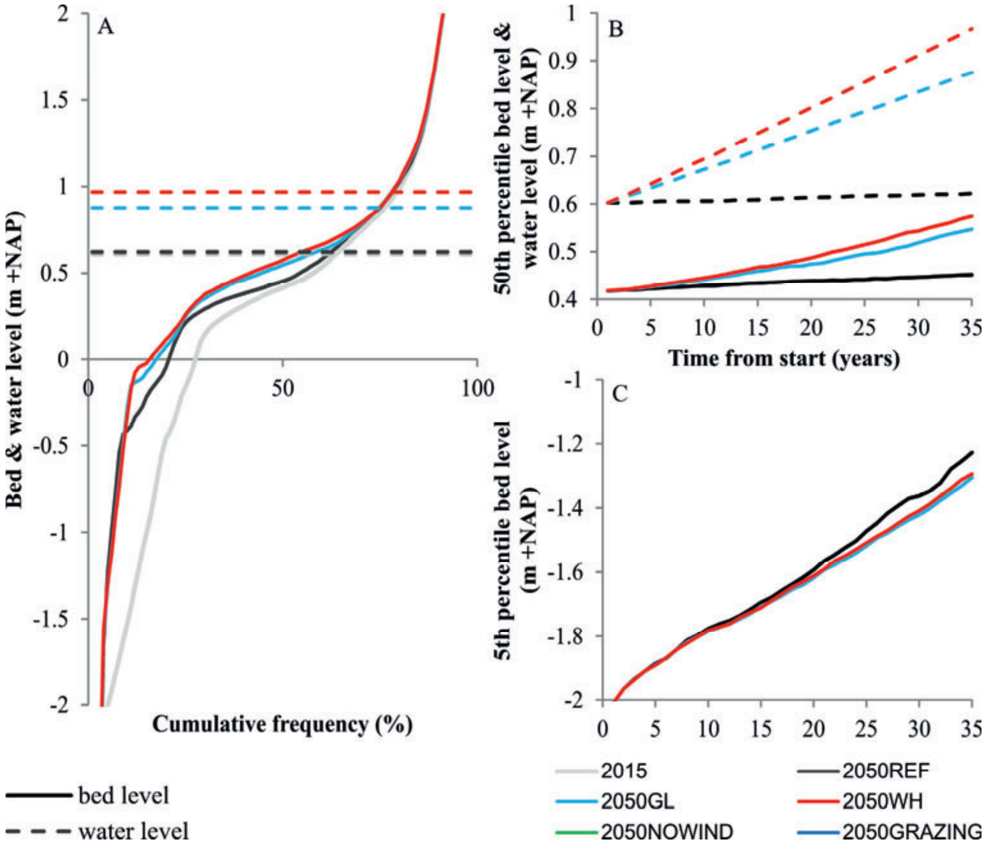

Figure 3.6: (A) 2015 and 2050 bed level cumulative frequency distributions and water levels for CC scenarios, (B) and (C) 5th and 50th percentile bed levels and water levels for CC scenarios

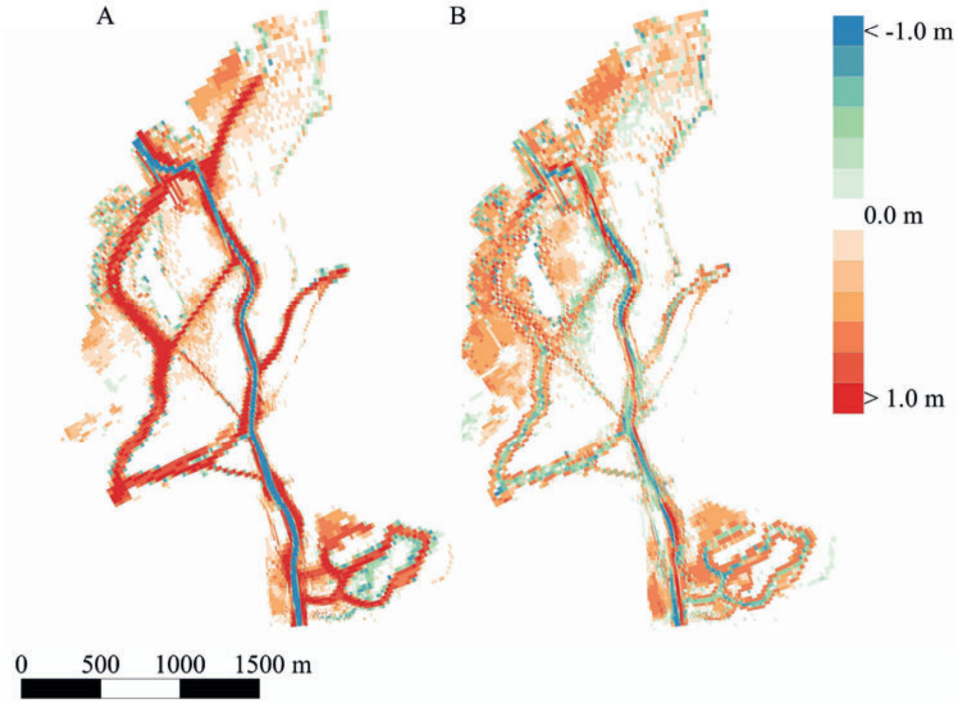

Figure 3.7: Sedimentation/erosion patterns of the scenario runs over the period 2015-2050. A) shows bed level changes for reference scenario 2050REF (2050REF minus 2015), B) shows impact of 2050WH compared to 2050REF (2050WH minus 2050REF).

3.5 Discussion

The current mean accretion rate on the intertidal flats in our study area is about 6 mm y^{-1}, which is just sufficient to keep up with the current rate of SLR (van der Deijl et al., 2017). However, our results show that this rate will quickly drop to about 1 mm y^{-1} for the period 2015-2050 for the two CC scenarios. These rates are substantially lower than the local rate of SLR (2050GL: 8 mm y^{-1} and 2050WH: 10 mm y^{-1}), which implies that this marsh will likely gradually convert to open water over decades.

Because the bed level changes of the 2050REF scenario are much larger than the difference between 2050REF and 2050WH or 2050GL scenarios, most of the morphological changes in the relatively recently constructed Kleine Noordwaard wetland over the period 2015-2050 can be attributed to morphological stabilisation and not to the impact of climate change. CC does however increase the rate of these changes, especially in the western branch of the channel system: these tend to fill up more rapidly under CC. We speculate that this process will likely continue beyond 2050, up to a point where it starts to limit the water discharge into the system and with it, the influx of sediment.

The current sedimentation rates in the study area fall within the range of rates reported for other sites along the lower Rhine branches, such as a de-embanked polder with the rate of 1-2 mm y^{-1} (Bleuten et al., 2009) and the floodplains along the River Waal with rates between 0.2 and 11.6 mm y^{-1} (Middelkoop, 1997). These values are low compared to accretion rates found for freshwater marshes in the USA which vary between 1 and 27 mm y^{-1} (Orson et al., 1990; Delgado et al., 2013; Mitsch et al., 2014). Sediment starvation often plays a large role in reduced sedimentation rates (Neubauer et al., 2002). This is also the case for the river Rhine, where upstream river regulation works have led to a significant drop in SSC over the last decades (Snippen et al., 2005; Vollmer and Goelz, 2006). Current SSC at the inlet of our study area averages at about 15 mg/L, which is very low compared to other TFWs (van der Deijl et al., 2017).

Our study is one of the first where the impact of climate change on the sediment budget of a microtidal freshwater wetland is quantified. Coastal wetlands have been studied more extensively, and often gain elevation at speeds similar to SLR due to ecogeomorphic feedback loops that cause increased deposition of both mineral sediment and organic material as the water depth increases (French, 2006; Kirwan and Megonigal, 2013). However, these feedback loops only occur until a certain flooding threshold, beyond which the vegetation dies off and the feedbacks are stopped, causing wetlands to drown (Kirwan and Megonigal, 2013). For coastal wetlands, this threshold can be reached in case of very high rates of local SLR, in some cases causing wetland submergence (Cahoon et al., 1995; Kirwan et al., 2010). For our constructed microtidal TFW, we speculate that design decisions made prior to the de-embankment have led to an immediate overtopping of the flooding threshold, prohibiting such feedback that may have promoted accretion, but instead have led to large scale vegetation die-off.

Wind has been identified as an important driver for erosion in coastal marshes and mud flats (e.g. Mariotti and Fagherazzi, 2010; Tonelli et al., 2010), but has received little attention in scientific studies on tidal freshwater wetlands. Verschelling et al. (2017) carried out a sensitivity analysis on the short term impact of wind events in the study area and concluded that wind-driven short waves indeed lead to resuspension and subsequent outflow of significant amounts of fine sediment from the area. It is therefore likely that wind also reduces the long term accretion rates under CC. We tested this hypothesis by running extra simulation 2050NOWIND, in which we switched off the wind forcing completely. This led to a relatively large increase in the 2015-2050 accretion rate (12.1 cm instead of 3.4 cm), which demonstrates the importance of including the impact of wind in the assessment of accretion rates in TFWs.

Our research suggests that it is important to ensure that abiotic conditions after de-embankment promote vegetation growth and succession in order to prevent drowning. This study also underlines the need to distinguish between the different components contributing to morphological changes: sedimentation patterns and rates are governed by a balance between boundary conditions (affected by external factors such as CC and anthropogenic modifications such as dams and gates), and internal conditions (such as the channel system and bed levels). Exciting future research directions would be to further assess the role of internal drivers such as wetland shape, channel configuration and inlet sizes on the long term accretion rates and patterns in TFWs.

3.6 Conclusions

We carried out a scenario analysis to gain insight in the impact of climate change (CC) on the morphology of a recently constructed tidal freshwater wetland (TFW) affected by a combination of tides, winds and riverine discharges. The main conclusions are:

- The scenario study shows that the simulated accretion rates over the scenario period are significantly lower than the rate of sea level rise (SLR) for the two CC scenarios. This means that the study area will gradually convert to open water;
- Nevertheless, CC leads to enhanced sedimentation on the channel banks and an elevated bed level of the flats.
- Most of the morphological changes that take place over the scenario period (2015-2050) can be attributed to morphological stabilization, and not to CC;
- Present-day abiotic conditions do not lead to vegetation succession and ecogeomorphic feedbacks that may promote increased accretion rates. Instead, the considerable water depth and inundation frequency lead to vegetation die-off and corresponding increase in wind shear;
- Neglecting the impact of wind leads to a significant overestimation of accretion rates.

3.7 Acknowledgements

This study was financed by the Dutch Technology Foundation STW (project no. 12431). We thank Staatsbosbeheer and Rijkwaterstaat-WNZ for the provided data. We thank Bert Jagers, Henk van den Boogaard, Sofia Caires and Karen Meijer (all from Deltares) for their help with Delft3D and the useful discussions. We thank Karianne van der Werf for her useful research on vegetation growth and succession in the study area.

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4 Sedimentation rates in a tidal freshwater wetland affected by river restoration measures and climate change

Abstract

Many tidal wetlands are at risk of drowning due to sea-level rise. A detailed understanding of the link between the hydro-morphodynamics and the layout of the wetland helps to predict the effectiveness of proposed restoration activities. This investigation takes the form of a case study of the Brabantse Biesbosch tidal freshwater wetland located within the lower Rhine and Meuse delta in the southwest of the Netherlands. The objectives were to determine how sedimentation rates and trapping efficiencies are affected by recent river diversions and to evaluate the effect of climate change (CC) and restoration of the tidal amplitude, which is currently reduced by a storm surge barrier downstream. We carried out a scenario analysis using a 1D model of the water flow and suspended sediment transport of all major river branches of the Rhine-Meuse estuary and the channel network of the Brabantse Biesbosch. The results show that the study area currently functions as a sediment sink except during periods of peak flow of the feeding rivers. Although the recently constructed river diversions supply the area with extra water and sediment during peak flow, the eroding power of the passing water causes increased resuspension from the wetland, which is far larger than the increase in sedimentation due to the extra influx of sediment. Climate change causes a drop in net sedimentation rates due to the more frequent overtopping of diversion structures and subsequent increase in resuspension during river floods. Restoring the original tidal range in the study area does not lead to enhanced sedimentation in the study area, because the increased tidal prism leads to increased bed shear stresses and a subsequent increase in resuspension during the transition from flood to ebb tide. The results suggest that the suspended sediment concentration (SSC) of the feeding river is a critical factor for wetland restoration because it controls the balance between the total sedimentation and resuspension of sediment: the SSC of the feeding rivers of the studied area is so low that it may limit the effectiveness of depoldering as a means of wetland restoration.

Unsubmitted manuscript: Verschelling E, Van der Deijl, E.C., Van der Perk, M., Middelkoop, H. Sedimentation rates in a tidal freshwater wetland affected by river restoration measures and climate change. Verschelling and Van der Deijl contributed to this chapter equally.

4.1 Introduction

Large-scale riverine, estuarine, and coastal restoration activities are currently proposed or implemented in delta areas over the world, for example in the Mississippi Deltaic Plain (DeLaune et al., 2003; Day et al., 2007; Paola et al., 2011), and the Tidal River Management projects in Bangladesh (Ibne Amir et al., 2013; Gain et al., 2017). These restoration activities are designed with the intention to compensate for the loss of land caused by a combination of sea-level rise, soil subsidence, and reduced sediment supply due to upstream river normalisation, construction of dams and sediment mining. Climate change (CC) is expected to increase the rates of sea level rise and peak river discharges, and therefore boosts the urgency for measures to compensate for the loss of land (Syvitski and Saito, 2007; Syvitski, 2008; Syvitski et al., 2009; Ibáñez et al., 2010; Giosan et al., 2014a). One of these measures is the diversion of water and sediment from major channels into adjoining areas to enhance sedimentation for land building. It is considered to be an effective strategy to prevent further wetland loss, especially in the case that accretion due to the production of organic material is limited (Hudson et al., 2008; Tessler et al., 2015).

Although several restoration projects with new river diversions have resulted in increased rates of accumulation (e.g. in the Breton Sound estuary, and the Wax Lake Delta in the Mississippi Deltaic Plain (DeLaune et al., 2003; Day et al., 2007; Paola et al., 2011), not all restoration projects have been effective, sometimes simply because the accumulation rate was too low or unfavourably distributed. In the Bangladesh Beel areas, uneven patterns in sedimentation created drainage congestion, which led to unequal economic opportunities and social conflicts for land owners, and resulted in the early termination of local river diversion projects (Ibne Amir et al., 2013; Gain et al., 2017). This demonstrates that detailed understanding of the link between the hydro-morphodynamics and the layout of the wetland is essential to predict the effectiveness of proposed restoration activities under current conditions and altered conditions due to CC.

Previous research has indicated that the supply of sediment is a major factor controlling sedimentation rates of wetlands along rivers, estuaries, and coasts (Neubauer et al., 2002; Mitsch et al., 2014; van der Deijl et al., 2017) It is controlled by the suspended sediment concentration (SSC) of the feeding river and flow paths to the wetland. Sedimentation rates and patterns inside wetlands are controlled by tide and wind (Orson et al., 1990; Delgado et al., 2013), vegetation cover (Pasternack and

Brush, 2001; Darke and Megonigal, 2003; Nardin and Edmonds, 2014), and wetland properties such as average water depth, distance to creeks, and wind fetch lengths (French, 1993; Siobhan Fennessy et al., 1994; Anderson and Mitsch, 2007; Hupp et al., 2008; Mitsch et al., 2014). However, still little attention has been paid to the hydro-morphodynamics within tidal freshwater wetlands. Furthermore, the response of the hydro-morphodynamics to CC and the development of new river diversions are not yet fully understood.

This study aims to further the understanding of the controls of sediment dispersal within tidal freshwater wetlands and to quantify the impacts of CC and river delta management on this internal sediment distribution. This investigation takes the form of a case study of the Biesbosch, a large tidal freshwater wetland (TFW) located within the lower Rhine and Meuse delta in the southwest of the Netherlands. The area comprises a complex network of tidal and flow-through channels, surrounded by wetlands. As part of a flood control project, water and sediment have been reintroduced in several previously embanked areas by means of newly created river diversions and partial removal of embankments. The research presented here provides one of the first investigations into the hydro-morphodynamics of a distributed fluvial system with a tidal component. Van der Deijl et al., (in review) carried out field surveys to identify the flow pathways and deposition patterns within the Biesbosch TFW. However, these results were based upon field data collected during low or average river discharges. Because of the lack of conditions with high flows during the monitoring period, it was not possible to establish long-term sediment budgets, or the response of the hydro-morphodynamics to changing boundary conditions, such as climate change. Therefore, the objectives of this research are threefold: 1) to determine contemporary accumulation rates and patterns of sediment deposition within the Biesbosch channel-wetland system, the total volume of trapped river sediment, and trapping efficiencies for the present situation including the recently developed wetlands, 2) to assess the effect of the recently constructed river diversions on sediment dispersal and accumulation, and 3) to assess the effect of climate change and restoration of the original tidal amplitude on the accumulation rates.

For this study we used an existing and calibrated 1D SOBEK3 hydrodynamic model of all major river branches of the Rhine-Meuse estuary, which we extended with a suspended sediment transport module. We used this model to carry out a scenario analysis to identify the quantity and pattern of accumulation of river supplied sediment in the Biesbosch area for the present situation, the situation before the wetland restoration, three CC scenarios, and a river delta management scenario. The model results for these scenarios in terms of sediment budgets, trapping efficiencies, and the sediment distribution patterns were compared to the present situation.

4.2 Methods

4.2.1 Study area

The study area comprises the Brabantse Biesbosch, a tidal freshwater wetland located between the River Nieuwe Merwerde in the north and the River Amer in the south, which are the downstream reaches of the respective Rivers Rhine and Meuse (Figure 4.1). The hydraulic regime in the study area is mixed semi-diurnal with an average period of 12.5 hours, of which the tide rises on average 5 hours. At longer timescales, water levels are determined by the discharge of the Rivers Rhine and Meuse, which generally have concurrent river discharge patterns, especially during the larger events, and storm surges at sea.

The flow regime in the Brabantse Biesbosch is strongly affected by human interventions, including polder embankments within the area, upstream weirs in the Rivers Rhine and Meuse, and the Haringvliet sea barrier in the Haringvliet estuary downstream. This barrier, which has been operational since 1970, has reduced the tidal range in the study area from approximately 1.9 m to 0.2 – 0.4 m (de Boois, 1982). The reduction in tidal range led to the formation of shallow lagoons, the filling in of deeper channels, a large decrease in intertidal area, and erosion of levees and banks. Consequently, channel banks are now often steep and - especially along the larger northeast-southwest oriented channels - have been armoured by riprap to prevent further erosion. Over the years, former areas with rush or reed culture developed to lush willow woods, grasslands, or overgrown reed lands, while other areas were turned into embanked agricultural space (De Bont et al., 2000).

Since 1999, water and sediment have been diverted from River Nieuwe Merwede to previously embanked areas in the northern section of the Biesbosch. These diversions were constructed for tourism, nature development, or as part of the Room for the River (RfR) project, a large national flood prevention programme aimed at improving the discharge capacity as well as the economic and environmental quality of the Dutch rivers (Rijkswaterstaat, 2018). The last diversions were constructed in 2015, when several dead-end channels in the northern part of the wetland were converted into feeding channels that connect the River Nieuwe Merwede to the existing channel network inside the wetland. A number of spillways at the river side of the new connections ensure that the channels only discharge water and sediment during peak discharge events, effectively lowering flood water levels along the upstream river branch (Boven Merwede). It is expected that the newly developed wetlands have a major influence on the hydro-morphodynamics of the Biesbosch area, because: 1) the total storage area of the Biesbosch has been doubled, 2) there is now a permanent upstream supply of water and sediment from the river Rhine, and 3) several embankments have been lowered, so water and sediment of the rivers Rhine and Meuse can spill over and provide an extra input of water and sediment during peak discharge events. The new upstream river connection is therefore expected to result in an enhanced upstream supply of sediment, a better connectivity of the channel sections in the Biesbosch, and a concomitant higher sedimentation rate in the Biesbosch area, than in the situation with only the downstream supply of sediment.

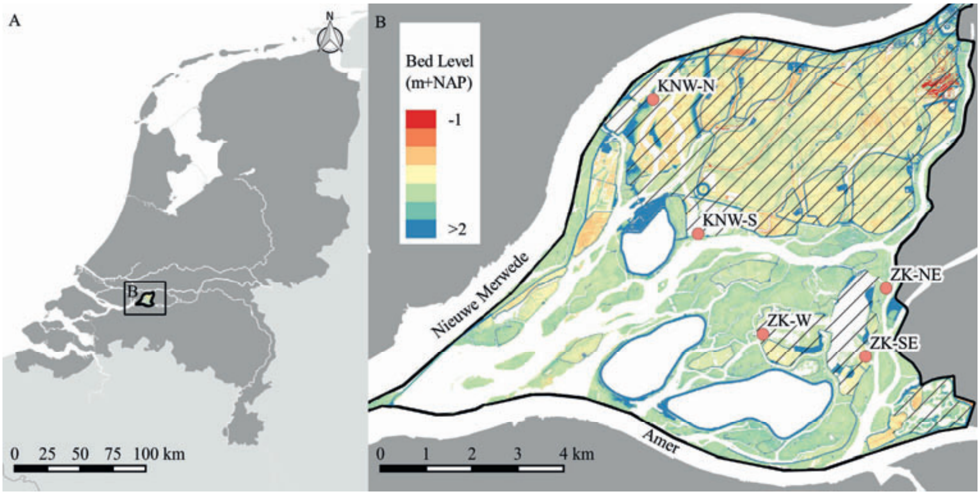

Figure 4.1: Study area. Locations KNW-N, KNW-S, ZK-W, ZK-NE and ZS-SE denote measurement stations in the area. The dashed areas indicate former polder areas that were turned into new wetlands.

4.2.2 Model set-up

For this study, we used the SOBEK3 software suite (Deltares, 2018b) to model hydrodynamics and sediment transport in the study area. The following sections describe the set-up of the hydrodynamic and sediment transport model in detail.

Hydrodynamic model

We used an existing and calibrated hydrodynamic model of all major river branches of the Rhine-Meuse estuary, described in Deltares (2016), as a basis to simulate hydrodynamics in our study area (Figure 4.1). The composite cross sections include adjacent intertidal flats, marshes, and floodplains, and were defined at an interval of approximately 500m, and additionally close to structures such as weirs and gates. Cross sections comprise both a flow area (the main channels) and a non-conveying storage area (e.g. the tidal flats or the floodplains). The division between flow and storage area was determined for each cross section by using a 2D model to simulation a range of stationary discharges and evaluate flow velocity patterns at the corresponding (tide-averaged) water levels. The model contains all major structures and associated operation rules, most importantly the storm surge barriers in Haringvliet and Nieuwe Waterweg. The model has upstream discharge boundaries at Hagestein on the river Lek (HS in Figure 4.2), Tiel on the river Waal (TI), and Lith at the river Meuse (LI), and downstream water level boundaries at the river mouth of Nieuwe Waterweg (MM) and at Haringvliet estuary (H1 and H2). The computational time step is one minute. The model was calibrated for the entire Rhine Meuse estuary for the year 2016 (Deltares, 2016). It already contained the larger branches in the Brabantse Biesbosch. However, some (smaller) branches that were also important for our research were missing. Therefore, we added these to the network using bathymetric data (provided by the Dutch National Water Authority, Rijkswaterstaat), and the Digital Elevation model of the Netherlands ('AHN2'). Furthermore, cross sections in the Zuiderklip area were updated to represent the present situation of this newly depoldered area. The adapted hydrodynamic model was evaluated against the original model for the mean error (ME) and the root mean squared error (RMSE) between the predicted and measured water levels at the Rijkswaterstaat measurement locations of Moerdijk, Keizersveer, and Werkendam.

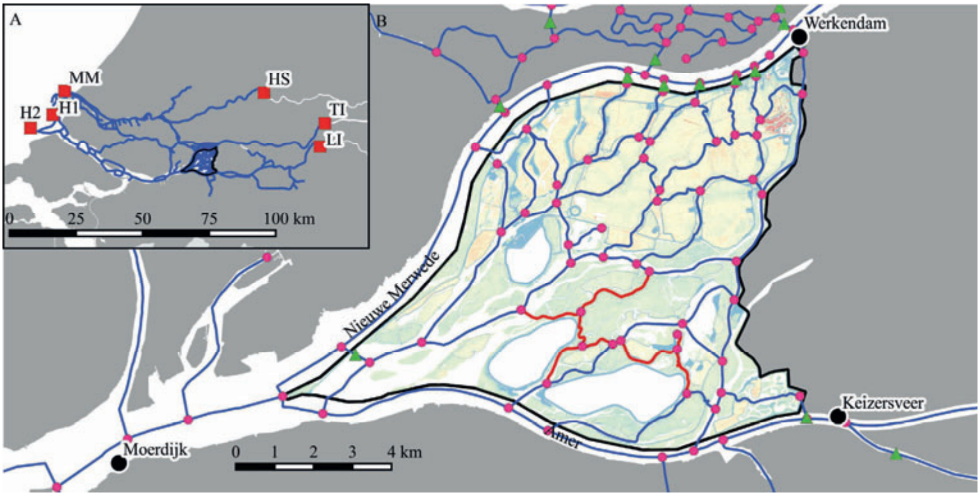

Figure 4.2: Model set-up. (A) Extent of the 1D model and locations of the 1D model boundary conditions: Maasmond (MM), Haringvliet estuary (H1, H2), Hagestein (HS), Tiel (Ti), and Lith (Li). (B) Visualisation of the 1D branch network inside the study area.

Sediment transport model

Suspended sediment transport, resuspension and settling of the cohesive sediment were modelled with the Krone-Partheniades equations (Partheniades, 1965), available in the SOBEK3 framework with the DELWAQ water quality module (Deltares, 2018a). Following the model parameterization used by Verschelling et al. (2017) for a morphological model of the Kleine Noordwaard area, we defined one cohesive sediment fraction with properties specified in Table 4.1. We used the approach developed by Sanford and Haika (1993), Winterwerp (2007), and van Maren (2011) to model sedimentation in depositional systems, in which the deposition flux depends on the settling velocity and suspended sediment concentration only. The erosion flux is computed with an excess bed shear stress (Tb > Tcr) and a resuspension parameter (EP). The calibration parameters and their range are specified in Table 4.2.

A constant SSC of 11.0 and 6.8 mg/l was applied at the downstream located boundaries of Nieuwe Waterweg and Haringvliet estuary. These values are the average SSCs as measured by Rijkswaterstaat at the SSC monitoring stations Beerkanaal midden and Haringvlietsluis for the period between 01-01-2000 and 31-12-2017. Sediment rating curves at the upstream boundaries (see Figure 4.3) were constructed following the procedure described by Asselman (2000), using discharges and SSCs from Rijkswaterstaat monitoring stations Tiel and Vuren for the river Rhine and stations Megen and Keizersveer for the river Meuse for the period between 01-01-2000 and 31-12-2017. These stations are the closest at the upstream model boundaries. Discharge monitoring stations Tiel and Megen are located at the model boundary, but the SSC monitoring stations of Vuren and Keizersveer are located at respective distances of 38, and 60 km downstream of the upstream model domains. To account for these differences in location, a synthetic rating curve was established for the model boundary based on the measured discharges and SSCs predicted using a linear relation between discharge and the loss of sediment between the upstream model boundary and the SSC measurement stations.

Table 4.1 Settings FLOW and DELWAQ models

Parameter	Unit	Value
Computational time step FLOW model	min	1
Computational time step DELWAQ model	min	5
Bulk density sediment fraction (mud)	kg/m^3	504
Effective settling velocity	mm/s	0.04

Table 4.2 Sediment transport model calibration parameters and range

Parameter	Unit	Min	Max
Critical shear stress for resuspension	N/m^2	0.15	0.25
Resuspension parameter	kg/m^2/s	0.00001	0.01

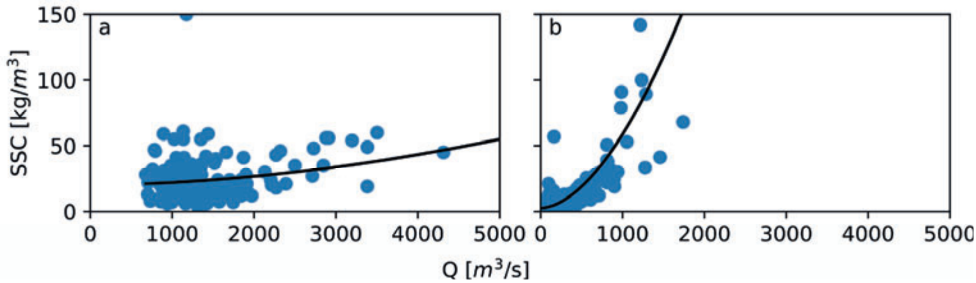

Figure 4.3: Sediment rating curves at the upstream boundaries Tiel (a) and Lith (b), established using discharges and SSC's from Rijkswaterstaat monitoring stations Tiel and Vuren for the river Rhine and stations Megen and Keizersveer for the river Meuse

A simple calibration of the sediment transport model was carried out manually following the approach described by van Maren et al. (2011) for observed SSCs at five fixed gauging stations in the study area (see van der Deijl et al. (2017), and Figure 4.1), using the calibration parameters and a-priori ranges described in Table 4.2. These ranges were based on a combination of available literature and expert judgement. We used both the root mean square error (RMSE) and the mean error (ME) as calibration criteria and selected the set of calibration parameters that gave the lowest average value of these two parameters. Unfortunately, a calibration on bed level changes was not possible because these are also affected by bed load transport of coarser material, a process that is not included in the current modelling approach. We believe that this is not an issue because this research focuses primarily on trends in sedimentation patterns rather than bed level changes.

4.2.3 Scenario analysis

Present situation

Suspended sediment transport, resuspension and settling of the cohesive sediment have been modelled for the present situation of the Biesbosch study area (see Figure 4.1) for the period March 2014 - March 2018. This period was selected because it contained both the 2014-2016 monitoring and model validation period with relatively low and average river discharges, and the peak discharge event of January 2018 that had a magnitude associated with a five-year recurrence time. Rijkswaterstaat had provided time series of measured discharge (1-hour) for the upstream boundaries at Hagestein on the river Lek, Tiel on the river Waal (TI) and Lith at the river Meuse (LI), and the 10-minute variation in water levels at boundaries at the river mouth of Nieuwe Waterweg (MM) and at Haringvliet estuary (H1 and H2). Suspended sediment concentrations (SSC) were specified for the upstream boundaries using the sediment rating curves described in section 2.2.2.

The total supply, the trapping efficiency, and the distribution of the trapped sediment in the Biesbosch study area were analysed for the period 2014-2016. The upstream supply of river sediment was determined from the modelled discharge and SSC at the sections in the Rivers Boven-Merwede and Amer, located just upstream of the first inlets of the Biesbosch study area. In the same way, the total amount of sediment imported in the Biesbosch study area was determined from the sum of the incoming discharge and SSC at the first channel section of each inlet of the Biesbosch study area. Similarly, the export of sediment from the Biesbosch area was determined using the outgoing discharge and the SSC at the channel sections at each inlet of the Biesbosch study area. The trapping efficiency of the Biesbosch was determined by dividing the total amount of accumulated sediment by the total import of sediment in the Biesbosch study area. To determine the contribution of the accumulation in the channels and surrounding wetlands of the newly developed areas (see Figure 4.1) to the total accumulation in the Biesbosch study area, the budget for these channels was determined separately and included in the analysis as the budget of newly developed wetlands.

Effect of newly developed wetlands

Two scenarios were defined to analyse the combined effect of the expected larger water flow corresponding increase in bed shear stresses sediment supply resulting from the implementation of the newly developed wetlands. To assess the effect of the newly developed wetlands on the hydro-morphodynamics of the Biesbosch for the years 2014-2018, the hydro-morphodynamics of the present modelled situation was compared to a model scenario without the newly developed wetlands. For this the scenario *No new wetlands* was defined, in which the newly developed channels and wetlands were excluded from the present model schematisation.

The *Lowered dikes* scenario was defined to examine whether a further reduction in height of the dikes of the newly developed wetlands with a concomitant extra upstream supply of water and sediment and increased shear stresses will result in enhanced net sedimentation or net erosion in the Biesbosch area. In this scenario, the upstream located dikes of the newly developed wetlands, which were lowered to 2 m above Dutch Ordnance Datum (NAP) during the development of the new wetlands, were further lowered by 1 m to 1 m +NAP in the model schematisation.

The SSCs in the Rivers Rhine and Meuse with median values on the order of 20-30 mg/l, and therefore the supply of sediment to the Brabantse Biesbosch is relatively low compared to the sediment supply to other delta wetlands. To test whether the patterns in sedimentation are consistent for an increase in SSC, the supply of sediment of the River Rhine and Meuse was increased 10 times for the *present* situation and the *No new wetlands* and *Lowered dikes* scenarios.

Effect of climate change & future management options

The effect of climate change on sedimentation patterns was analysed for the so-called *2050GL* and *2050WH* climate change scenarios developed by the Dutch meteorological institute KNMI (Van den Hurk et al., 2014). These scenarios were developed specifically for the Netherlands and translate predicted changes in global air circulation patterns and temperatures into local changes in hydro-meteorological parameters over the period 2010-2050. The 2050GL scenario couples a 4 % increase in precipitation with 0.15 to 0.3 m increase in mean sea level at the North Sea coast compared to the reference climatic period (1981-2010), and the 2050WH scenario a 5 % increase in precipitation with 0.2 to 0.4 m increase in mean sea level. For this research, we assumed a) 2050 as the horizon year, because this fits well with the KNMI scenarios and is frequently used in other studies (e.g. IPCC, 2007; Verschelling et al., 2018) and

b) the most extreme values of the expected SLR for both scenarios (i.e. 0.3 m for 2050GL and 0.4 m for 2050WH). A 2050 scenario without any climate change (2050REF) was included as reference scenario, giving a total of three climate change scenarios (2050REF, 2050WL and 2050GH).

The three climate scenario runs were carried out using yearly synthetic time series of discharges at the upstream model boundaries (locations Li, Ti and Ha in Figure 4.2), water levels at the downstream boundaries (H1, H2 and MM), and WSW winds over the entire model domain (Table 4.3). These synthetic time series were constructed using the following approach, adopted from Verschelling et al. (2018): First, starting with scenario-specific time series of daily discharges at Hagestein, Tiel and Lith for the period 1-1-1967 to 1-1-2007 (Verschelling et al., 2018), we applied an iterative optimization algorithm using random seeds to construct yearly time series of discharges. Because it was ensured that certain statistical properties (the marginal probability density distribution and auto-covariance function of the signals) were identical to those of the original 40-year time series, the synthetic time series are representative for the characteristics of the original time series. Second, for the water level time series at the downstream boundaries, first a distinction between the so-called carrier signal (setup) and a residual signal (tide) was made, and the same optimization algorithm was applied to the carrier signal of measured water levels over the period 1-1-1967 to 1-1-2007 (Verschelling et al., 2018) after which a harmonic tidal signal was superimposed to arrive at the yearly time series of water levels for the three climate change scenarios. Third, for the wind speeds at the predominant wind direction (WSW), the time series developed by Verschelling et al. (2018) were used for the same three scenarios directly.

Tidal amplitude in the study area has been artificially reduced by construction of the downstream Haringvliet barrier, operational since 1970. In order to study the effect of this barrier on sedimentation in the study area, we carried out the three additional climate scenario runs, in which we completely removed the barrier from the model (Table 4.3).

The suspended sediment concentrations at the upper model boundary locations were defined using the sediment rating curves discussed previously.

Table 4.3: Overview of scenarios, their boundary conditions and management options with respect to the Haringvliet barrier ("2015": standard operation rules as used in 2015, "removed": structure completely removed).

Scenario	**Q & h**	**wind**	**Haringvliet barrier**
2050REF	2015	2015	2015
2050GL	2050gl	2015	2015
2050WH	2050wh	2015	2015
2050REF_no_barrier	2015	2015	removed
2050GL_no_barrier	2050gl	2015	removed
2050WH_no_barrier	2050wh	2015	removed

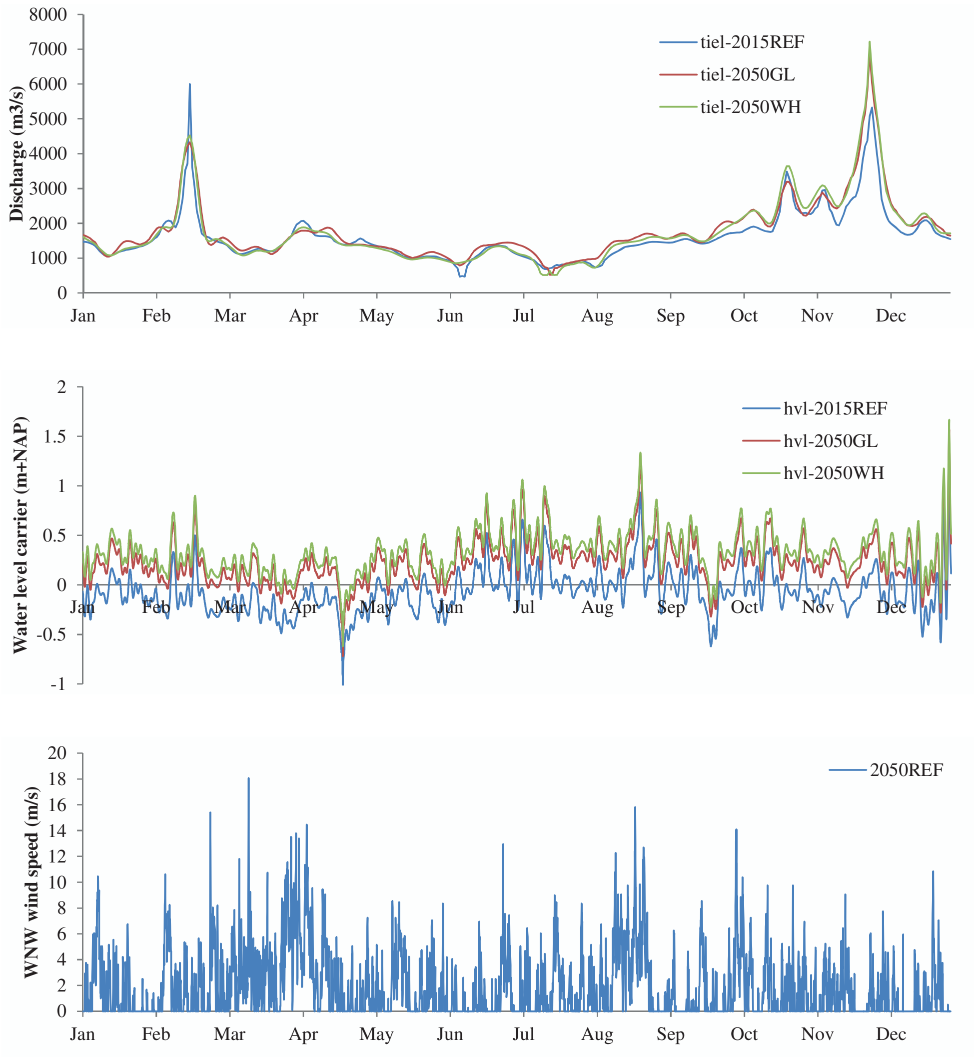

Figure 4.4: Yearly synthetic time series of discharge, water level (carrier) and wind velocity for 2050REF, 2050gl and 2050wh. The series at the other upstream boundary locations (Hagestein, Lith) and downstream boundary locations (Hoek van Holland) show similar differences between the scenarios and are therefore purposefully omitted.

4.3 Results

4.3.1 Model performance

Hydrodynamic model

Table 4.4 shows that the adaption of the hydrodynamic model has resulted in a decrease of both the mean error (ME) and the root mean squared error (RMSE) between the predicted and measured water levels at the Rijkswaterstaat measurement locations of Moerdijk, Keizersveer, and Werkendam. Furthermore, Figure 4.5 shows that the deviation between the predicted and measured water levels at the measurement locations within the Biesbosch area is comparable with the deviation at the Rijkswaterstaat water level monitoring locations. Therefore, it had been decided to accept the current adapted hydrodynamic model without a new calibration procedure.

Table 4.4: The Mean Error (ME) and Root Mean Squared Error (RMSE) in mm between the predicted and measured water levels at the Rijkswaterstaat measurement locations of Moerdijk, Keizersveer, and Werkendam for the reference and adapted hydrodynamic models.

	ME reference	ME adapted	RMSE reference	RMSE adapted
Moerdijk	0.064	0.061	0.069	0.060
Keizersveer	0.086	0.078	0.090	0.054
Werkendam	0.057	0.053	0.077	0.070

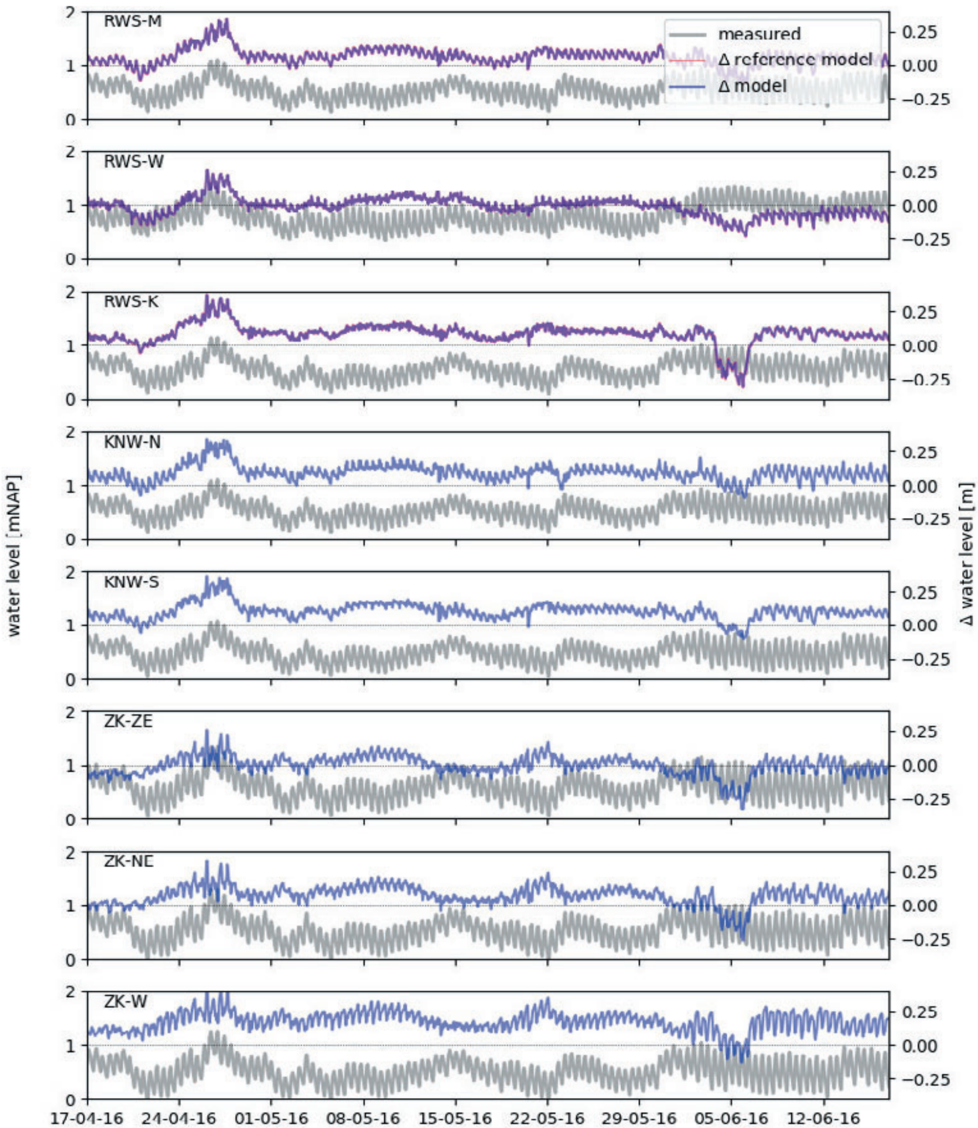

Figure 4.5: Plotted in grey on the left vertical axis: measured water levels at the Rijkswaterstaat monitoring locations of Moerdijk (RWS-M), Keizersveer (RWS-K), and Werkendam (RWS-W), and the monitoring locations in the newly developed wetlands of the Brabantse Biesbosch (Kleine Noordwaard North and South, and Zuiderklip, Southeast, Northeast, and West). Plotted on the right vertical axis (note the different scale): deviation between the predicted water levels of the reference model (in red) and the adapted hydrodynamic model (in blue) with respect to these measurements (simulated minus measured). Due to the large overlap between the red and blue lines, they show purple in the figure.

Sediment model

Figure 4.6 shows both the ME and RMSE between the predicted and measured SSC at the five measurement locations in the Biesbosch area for the calibration period 2014-2016. From this figure it is apparent that the ME is in general the lowest for locations KNW-N, and KNW-Z, which are located relatively close to the River Nieuwe Merwede. However, Figure 4.7 shows that although the ME is the lowest at location KNW-N, the tidal signal in the SSC is missing in the model predictions, resulting in a relatively large RMSE for this location. The tidal signal is probably missing at this location because it is not implemented in the SSC at the upstream model boundaries, where sediment rating curves were used. The tidal variation was visible in the measurements, used to establish the rating curves, but it resulted only in scatter along the rating curve (see Figure 4.3), which cannot account for hysteresis between a rising and falling discharge and the SSC.

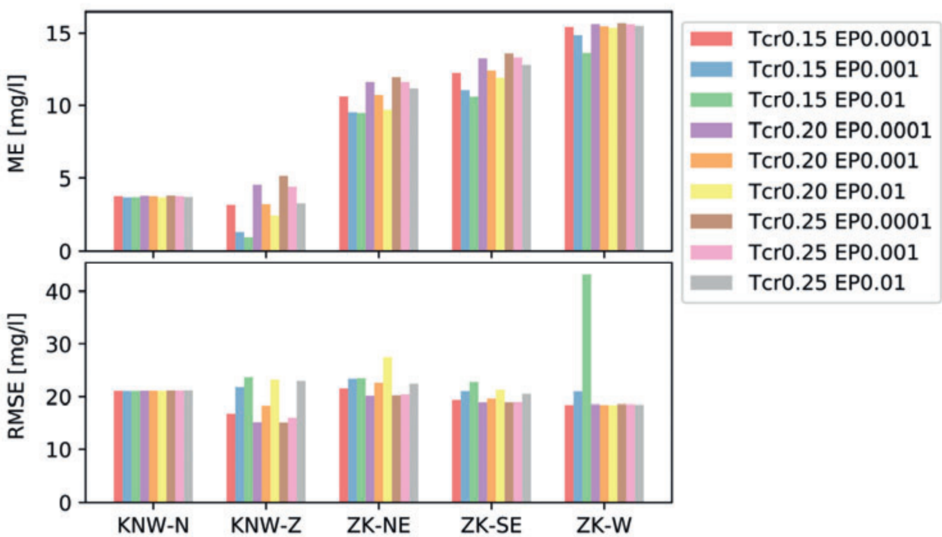

Figure 4.6: The Mean Error (ME) and Root Mean Squared Error (RMSE) in mg/l between the predicted and measured suspended sediment concentrations at the five Biesbosch monitoring locations for the nine calibration combinations of Tcr, and EP.

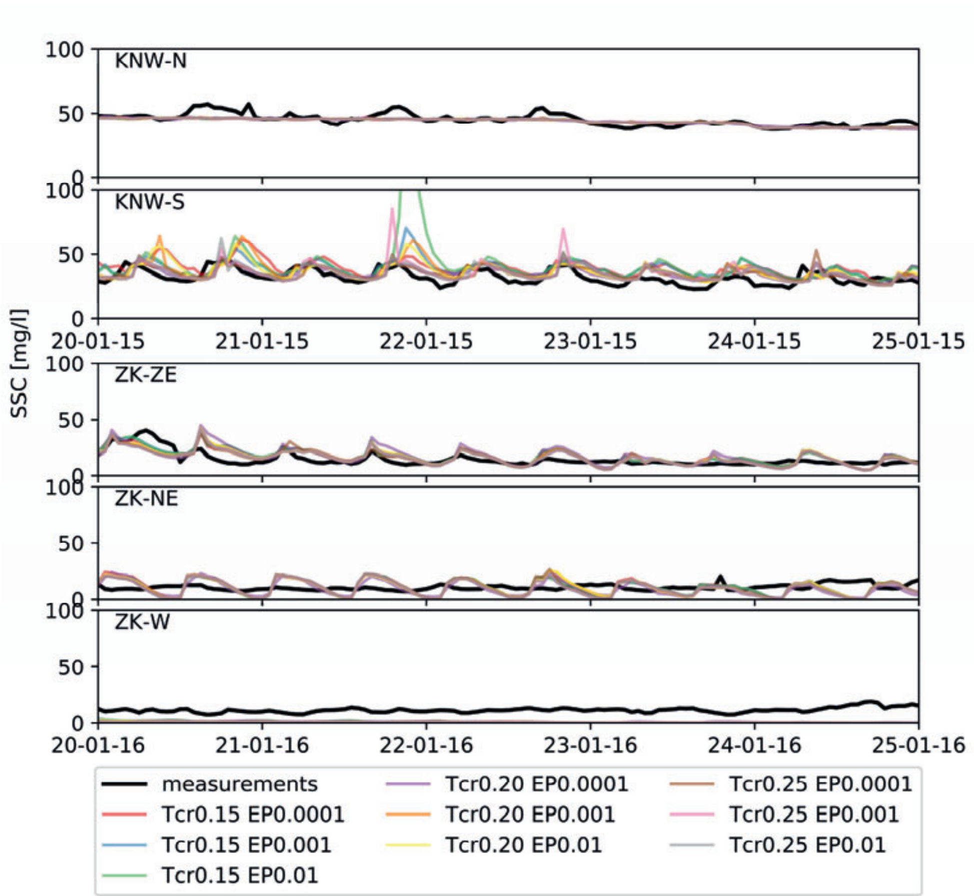

Figure 4.7: Measured suspended sediment concentration (SSC) at the monitoring locations in the newly developed wetlands of the Brabantse Biesbosch (Kleine Noordwaard North and South, and Zuiderklip Southeast, Northeast, and West). Predicted SSC is shown for the nine calibration combinations of Tcr, and EP.

Further away from the rivers, at locations KNW-S and ZK-ZE, the model predictions of all combinations of Tcr and EP do result in a tidal variation in the SSC. However, predicted SSCs are in general lower than measured and they are even approaching zero for the most distal locations (ZK-NE, and ZK-W), during this period. This suggests that in the model too much sediment becomes deposited in the proximal channels, and that sediment becomes depleted in the more distal sections. Figure 4.7 shows that a lower critical shear stress for erosion does not result in larger SSCs at the more distal locations. Furthermore, it can be observed that there is no increase in the average SSC at the more distal locations, even though higher values for EP result in relatively large spikes in the short-term SSC predictions for the moments that shear stresses increase, i.e. at the onset of flood and ebb tide, or for raised river discharges. It can therefore be concluded that the simple calibration of the sediment transport model, using the calibration parameters and ranges as described in Table 4.2 will not result in a good approximation of the average SSC at the most distal locations in the model. Still, van der Deijl et al. (2017) already pointed out that the measurement errors at these more distal SSC monitoring locations were relatively large, compared to the more proximal locations (KNW-N and KNW-S). This larger error may be attributed to the relatively low SSC, the relatively small sediment fraction (the coarser fraction is already lost in the more proximal channel sections), and by internal production of organic matter due to algal growth or resuspension of inorganic matter by wind waves or the presence of birds or cows. The model does not include the internal production of inorganic matter or the resuspension by other factors than flow related shear stresses. Therefore, it was decided to focus mainly on the locations KNW-N, KNW-S and ZK-ZE for the calibration procedure. The combination of a Tcr of 0.15 and EP of 0.0001 was selected as the best combination, since this combination gave the lowest average ME and RMSE. Furthermore, the predicted SSC variation of this combination resembled the measurements the best. The SSC prediction of this set of parameters, and the SSC measurements for all monitoring locations during the calibration period are shown in Figure 4.8.

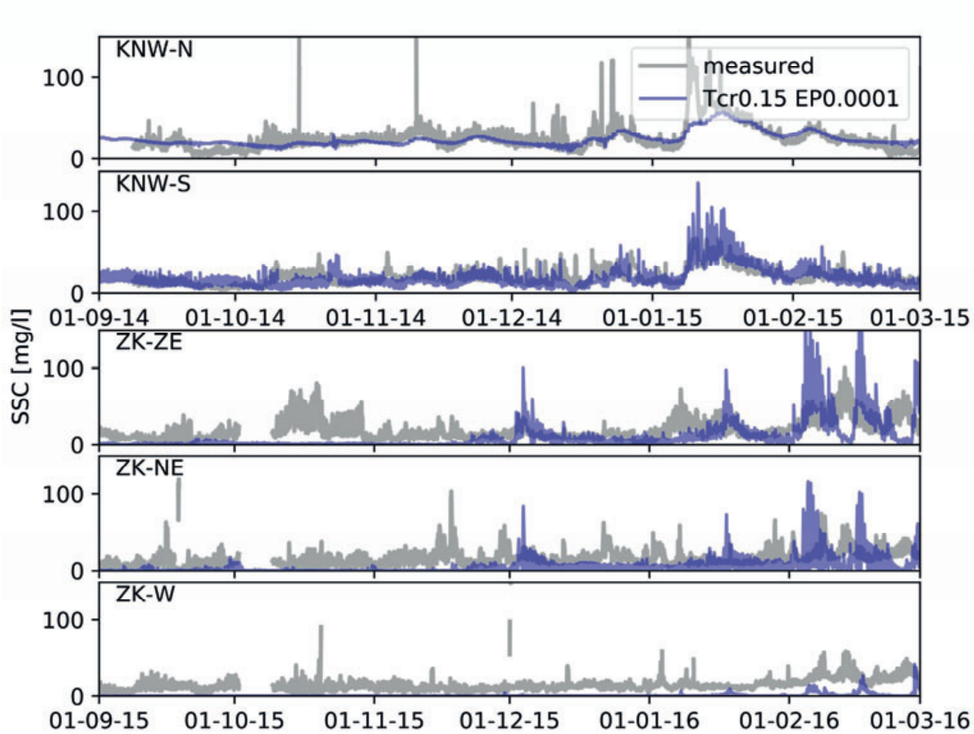

Figure 4.8: Measured suspended sediment concentration (SSC) at the monitoring locations in the newly developed wetlands of the Brabantse Biesbosch for the entire calibration period. Predicted SSC is shown for the chosen calibration combination of Tcr=0.15 and EP=0.0001.

4.3.2 Scenario analysis

Present situation

During the period 01-03-2014 to 01-03-2018 the Rivers Rhine and Meuse had supplied 2.31 and 0.83 Mt suspended sediment to the branches Nieuwe Merwede and Amer. From this sediment 28.3% entered the Biesbosch study area, and 12% of this incoming sediment was trapped inside the Biesbosch (see Table 4.5).

Table 4.5: Effect of the newly developed wetlands on sediment balance of Biesbosch area, for the situation with the present and the raised suspended sediment concentrations

Scenario	River supply	Import	Import	Export	Budget	budget new wetlands	Trapping efficiency
	[Mton/yr]	[Mton/yr]	[%]	[Mton/yr]	[Mton/yr]	[Mton/yr]	[%]
Present	0.786	0.222	28.3	0.196	0.027	0.018	12.0
No new wetlands	0.823	0.059	7.2	0.024	0.035		59.5
Low dikes	0.787	0.229	29.1	0.203	0.026	0.016	11.2
Present SSC10	7.864	2.254	28.7	1.592	0.663	0.406	29.4
No new wetlands SSC10	8.230	0.587	7.1	0.192	0.395		67.3
Low dikes SSC10	7.867	2.281	29.0	1.636	0.645	0.397	28.3

Figure 4.9 indicates that this net accumulation takes mainly place at bifurcations, locations of slack water (van der Deijl et al., in review), and in proximal tidal channel sections, whereas almost no accumulation occurs in the rest of the area.

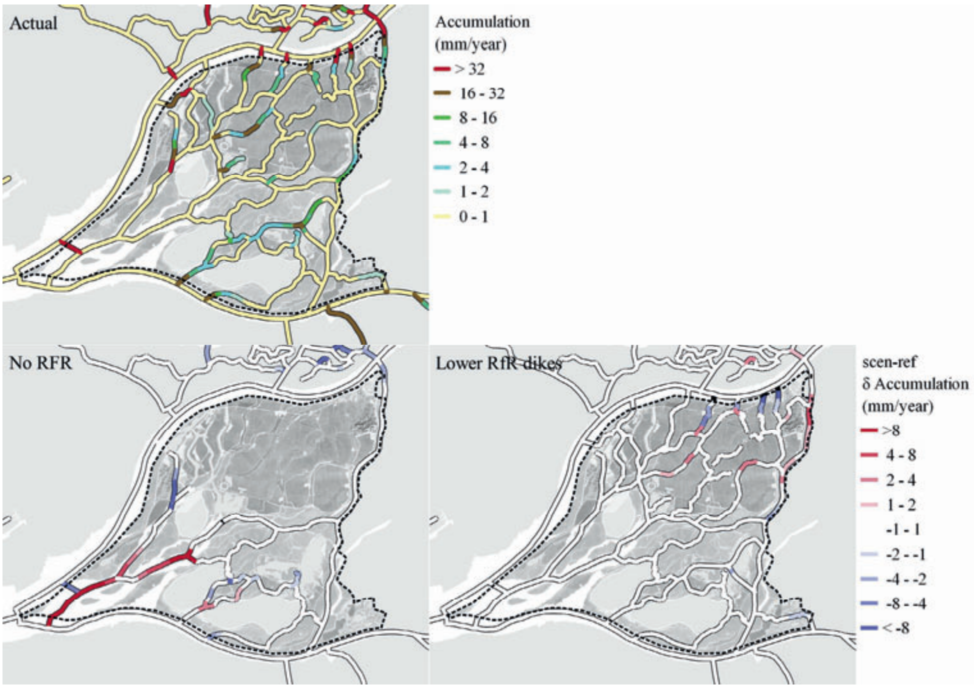

Figure 4.9: Net sediment accumulation in the Biesbosch area during the period 01-03-2014 to 01-03-2018 (Present), the effect of scenario 'no new wetlands' (‘no new wetlands’ minus ‘present’), and the effect of scenario ‘lower dikes’ (‘lower dikes’ minus ‘present’)

Figure 4.10 shows the net sediment accumulation of the Biesbosch over the period 01-03-2014 to 01-03-2018. From this figure it is apparent that the Biesbosch functions as a sink for sediment most of the time, with an increase in the total accumulation during flood tide and a decrease during ebb tide. However, there is a large drop in the net accumulation in the Biesbosch during the short periods of higher river discharge.

During low to average river discharges accumulation takes mainly place in channel sections at a relatively short distance from the rivers (Figure 4.11). High rates of accumulation are also found at the downstream end of the two major side channels of the River Nieuwe Merwede (in the south and north west of the area). In these situations flow velocities in the channels are mostly too low to cause resuspension of sediment. During periods of higher discharges, a large part of the previously deposited sediment becomes resuspended. The sudden erosion in these channels is caused by the increase in bed shear stress: shear stresses increase up to 5.1 N/m^2 in the newly developed river diversion in the north of the area during the peak discharge event in January 2018, and shear stresses around 0.4 N/m^2 are found in the sections downstream of this new diversion. These shear stresses are much higher than the threshold for resuspension of the newly deposited fine sediment. Meanwhile, there is during these periods a 4-fold increase in the accumulation rate in the dead-ending and distal tidal channel sections.

To summarize, channel sections close to the feeding river system experience deposition during low flows and flood tide, and erosion during higher flows and ebb tide (Fig. 3.7 periods 1 and 3). During periods in increased river flow, the area of channel erosion is shifted further into the system (Fig 3.7. periods 2, 4, 5). Previously deposited sediment is moved then further into the system during flood, but part of this resuspended sediment leaves the system during ebb. Channel sections in the wetland interior experience little sedimentation during medium flows; during higher flow, flow velocities in these sections remain below the threshold for resuspension and increased deposition occurs. This sediment comprises both sediment directly conveyed from the feeding river and resuspended sediment from the proximal channels. It can therefore be concluded that the area is an inefficient sediment trap.

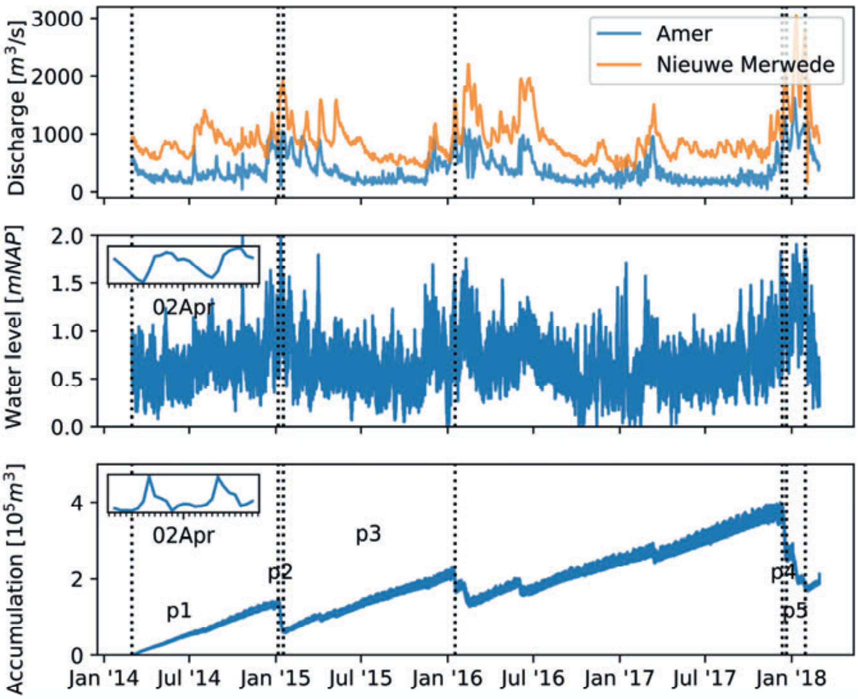

Figure 4.10: The river discharge, water level variation, and the cumulative sediment budget of the Biesbosch study area for the period 01-03-2014 to 01-03-2018. Periods p1 and p3 represent low to medium river discharges, and p2, p4 and p5 higher discharges (Nieuwe Merwede over 1900 m^3/s, Amer over 1000 m^3/s).

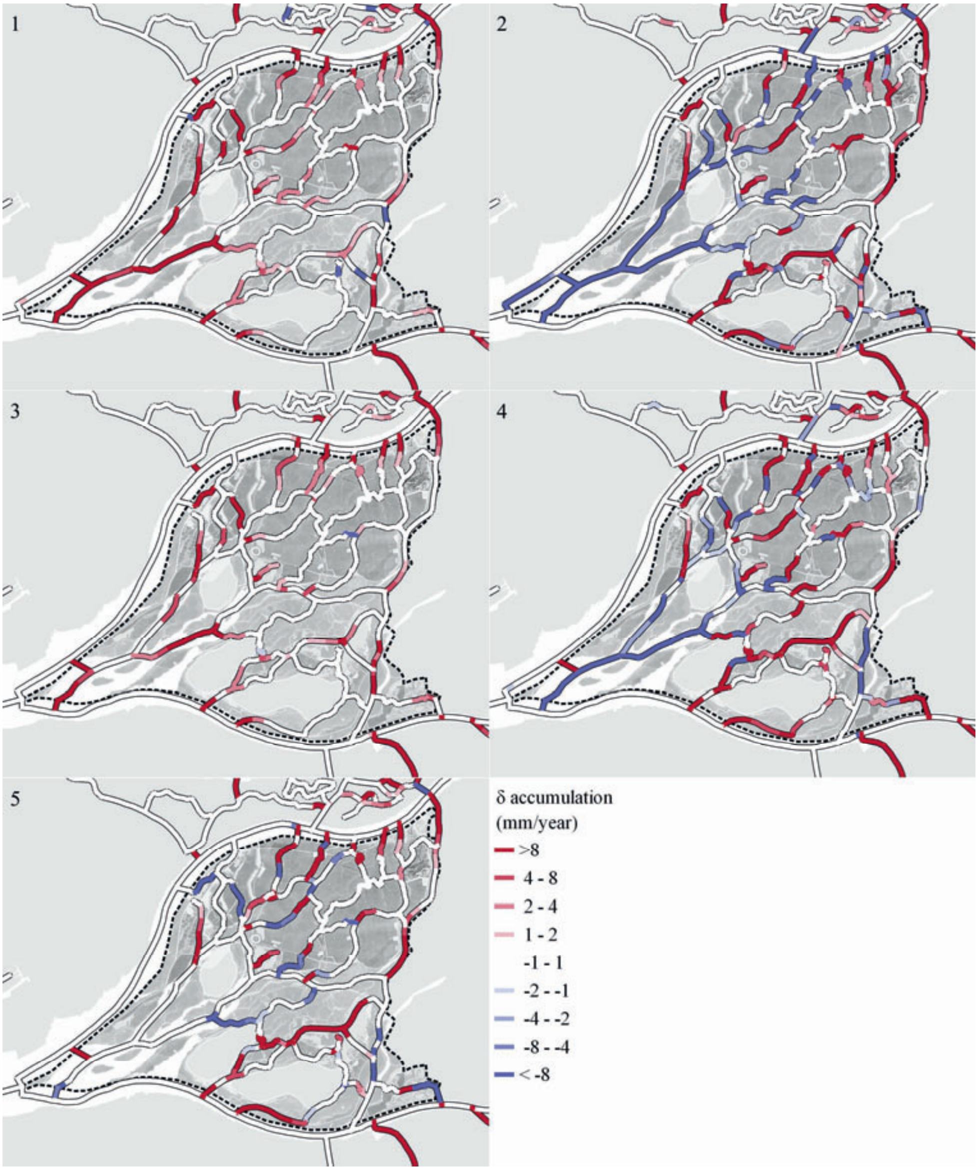

Figure 4.11: The budget [mm/year] within the respective periods 1, 2, 3, 4, and 5 as presented in Figure 4.10. Period 1 and 3 are characterised with a relatively low or average river discharge, while raised or even peak discharge events take place during periods 2, 4, and 5.

Effect of newly developed wetlands

Table 4.5 shows the magnitude of the net annual sediment accumulation in the Brabantse Biesbosch for both the present situation, the scenario without the newly developed wetlands, and the scenario with lowered dikes. The newly developed wetlands have doubled the total accommodation space for water and sediment. Table 4.5 shows that they account for approximately 64 % of the total accumulation in the Biesbosch study area in both the present situation and the scenario with lowered dikes. Remarkably, more sediment is trapped in the scenario without the newly developed wetlands, in spite of the reduced connectivity of the area to the Merwede river. Conversely, less sediment is trapped in the scenario with lowered dikes, while the total import of sediment in this scenario slightly increased due to the more frequent upstream inflow of water and sediment (see Table 4.5). These somewhat counter-intuitive results imply that the effect of the increase in shear stress and resulting increase in resuspension is stronger than the effect of the larger sediment supply towards the area.

The difference in the spatial pattern of the accumulation between the two scenarios and the present situation is shown in Figure 4.9. Without the upstream supply of Rhine water and sediment (scenario *No new wetlands*), significantly more sediment accumulates in the tidal channels in the southwestern part of the study area, especially close to those locations where the tidal channels merge with the River Meuse. However, less sediment becomes trapped in channel sections close to the new river diversions, at bifurcations, and at slack water locations in the middle and northeast of the area. There is no upstream connection to the river Nieuwe Merwede in this scenario and, therefore, the sediment is mainly supplied by the tidal flow in the southwest. Furthermore, the shear stresses are low in these channels: even during peak discharge in January 2018 the shear stress reached a maximum value of only 0.28 N/m^2. This causes less resuspension to take place than in the present situation.

For a more frequent upstream supply of Rhine water and sediment than in the present situation (scenario *Lowered dikes*) less sediment accumulates at the inlets of the newly developed wetland in the northwest of the study area. In contrast, more sediment accumulates in the central part of this newly developed wetland (Figure 4.9), owing to a more frequent upstream river inflow to this central the area. However, because the higher flow velocities increase shear stresses and enhance resuspension, the total net accumulation is lower in the channel sections directly downstream of the new river diversions.

Figure 4.12 shows the cumulative sediment budget over time for the present situation and the scenario without the newly developed wetlands. During periods of relatively low or average river discharges and low SSC, sediment accumulation for the scenario without new wetlands is smaller than that for the present situation with wetlands. However, the sediment budget increases relatively fast during and after a raised river discharge event with increased SSC (periods 2, 4, and 5). Owing to the large peak river discharge event, with concomitant large amounts of resuspension at the end of the simulation period, the final sediment budget is larger for the scenario without new wetlands then for the present situation. These results indicate that the net sediment accumulation in the area is controlled by a balance between the enhanced sediment input and increased flow-induced shear stresses causing resuspenson, both the result of new or increased supply of river water.

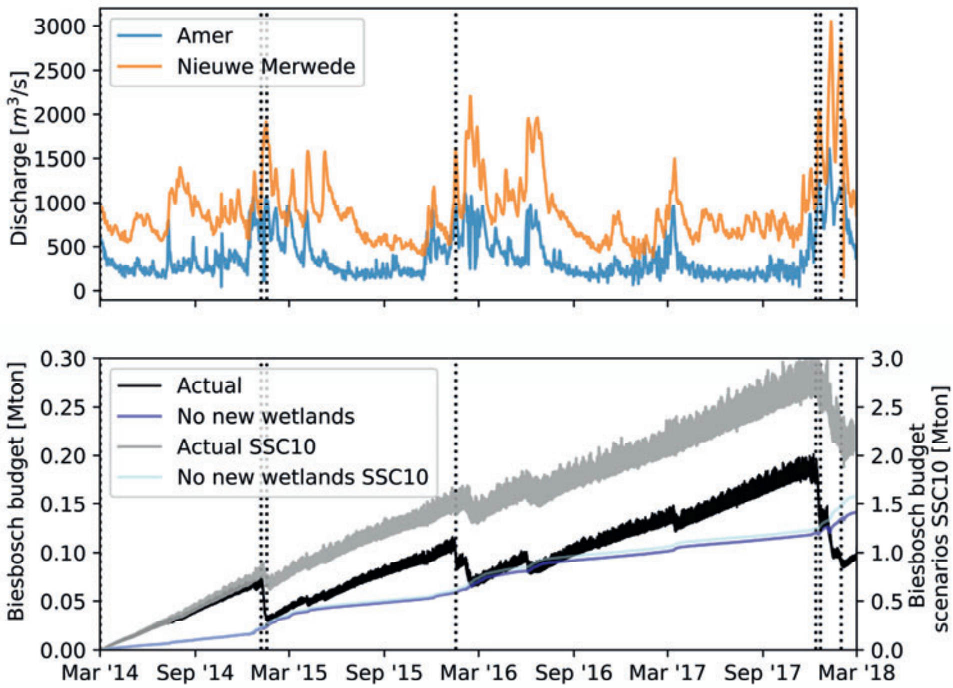

Figure 4.12: The cumulative sediment budget of the Biesbosch area for the present situation and the scenario no new wetlands with the current and a raised SSC of the feeding rivers. The scenario with lowered dikes is not included in this figure, because of the small difference and thus resembling patterns of the cumulative sediment budget of this scenario and the present situation. The river discharge (top figure) is included for reference.

Increasing the SSC in the feeding rivers has a considerable effect on the sediment budgets and trapping efficiencies of the Brabantse Biesbosch and does not show a straight-forward increase in net sediment accumulation (Table 4.5, Figure 3.8). The trapping efficiency increases by a factor of 2.5 in both the present situation and in the scenario with lowered dikes, but only by a factor 1.1 for the scenario without the new wetlands. Over time the magnitude of the sedimentation increases approximately by a factor of 10 for the scenarios with newly developed wetlands when compared to the situation without the new wetlands (Figure 4.12). However, the magnitude of the resuspension/erosion during higher river discharges remains the same when compared to the scenarios with normal SSCs, because shear stresses remain unchanged for the scenario of increased SSC in the feeding rivers. As a result, both sediment accumulation (Figure 3.9) and trapping efficiency are over the entire simulation period (so during low, average and peak discharge events) higher for the scenarios with newly developed wetlands. There is no significant change in the distribution of the sediment over the area, since the (absolute) increase in accumulation is highest at the locations with already high initial rates of accumulation (in the scenarios without the increase in SSC of the rivers), while the magnitude increases only slightly for the locations with low initial rates of accumulation.

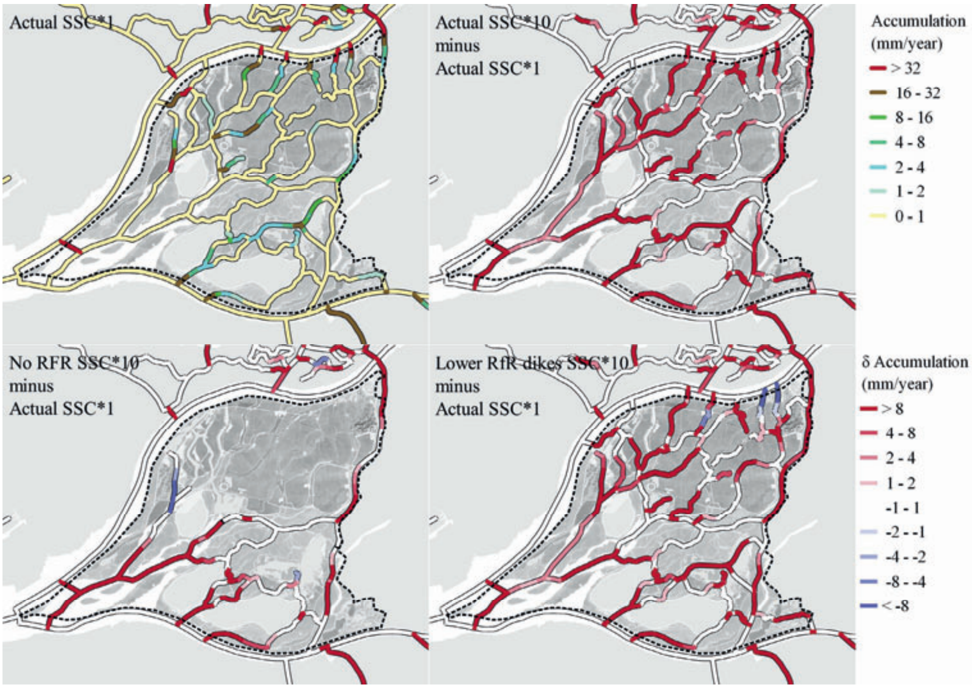

Figure 4.13: The effect on the net sediment accumulation in the Biesbosch area during the period 01-03-2014 to 01-03-2018 of an increased SSC (Actual SSC*10 minus Actual SSC*1), the effect of scenario 'no new wetlands SSC10' (no RfR SSC*10 minus Actual SSC*1), and the effect of scenario 'lowered dikes SSC*10' (Lower RfR dikes SSC*10 minus Actual SSC*1). The baseline case (Present) is included for reference.

It can be concluded that the development of new wetlands has resulted in a minor decrease in trapping efficiency of the area. The trapping efficiency of these wetlands is high during conditions of low and average river discharges, but sharply decreases during periods of peak discharge events. This effect remarkably reverses if the SSC in the feeding rivers would be much higher (Table 4.5, Figure 4.12): then the new river diversions and wetlands result in an enhanced sediment accumulation and increased trapping efficiency during all conditions of river discharge. This indicates that the SSC in the river is a major factor determining the efficiency of a newly developed wetland with the purpose of land building.

Effect of climate change & alternative management

The reference scenario for current climate conditions (2050REF) leads to slightly different balance terms than scenario 2014-2018 (Table 4.6 versus Table 4.5). These differences are mostly caused by differences in river discharges, which were in the period 2014-2018, significantly lower than in the reference period 1967-2007 on which synthetic discharge time series were based.

Compared to 2050REF, the 2050WH and 2050GL scenarios both lead to a slight increase in influx of sediment from the rivers as well as a reduction in trapping efficiency (Table 4.6). This last result is somewhat surprising, as larger water depths usually lead to higher sedimentation rates and thus to higher trapping efficiencies. This can be explained as follows: the increase in water levels leads to more frequent overtopping of the dikes between River Nieuwe Merwede and Brabantse Biesbosch and thus to higher flow velocities in the major conveying channels through the wetland. This causes higher bed shear stresses and thus more erosion, which more than compensates for the slight increase in sedimentation caused by the extra influx of sediment due to the more frequent overtopping.

Removal of the Haringvliet barrier restores the tidal range inside Brabantse Biesbosch; for example, at location ZK-NE in Figure 4.1, the tidal range increases from 0.3-0.4m (2050REF) to 1.1-1.2m (2050REF no HVLSL). The increase in tidal range causes more exchange of water and sediment at the downstream boundaries between the wetland and the surrounding river system. This leads to a corresponding increase in sediment influx (and outflux) (Table 4.6). However, the increased influx of sediment does not lead to an increase in sedimentation rates and trapping efficiencies. On the contrary, the trapping efficiencies drop around 50%. This can be attributed to the increased tide-driven interaction with the surrounding river system, which causes a large increase in flow velocities and thus in bed shear stresses inside Brabantse Biesbosch (Figure 4.14). This prevents the sediment from settling and causes a larger percentage of the sediment to leave the area.

Table 4.6: Effect of CC on sediment balance of Biesbosch area, for situation with and without Haringvliet barrier

Scenario	River supply [Mton/yr]	Import [Mton/yr]	Import [%]	Export [Mton/yr]	Budget [Mton/yr]	Trap.eff. [%]
2050REF	1.124	0.310	28	0.281	0.029	9
2050WH	1.457	0.406	28	0.384	0.022	5
2050GL	1.415	0.395	28	0.372	0.023	6
2050REF no HVLSL	1.170	0.529	45	0.51	0.019	4
2050WH no HVLSL	1.503	0.700	47	0.683	0.017	2
2050GL no HVLSL	1.461	0.668	46	0.65	0.018	3

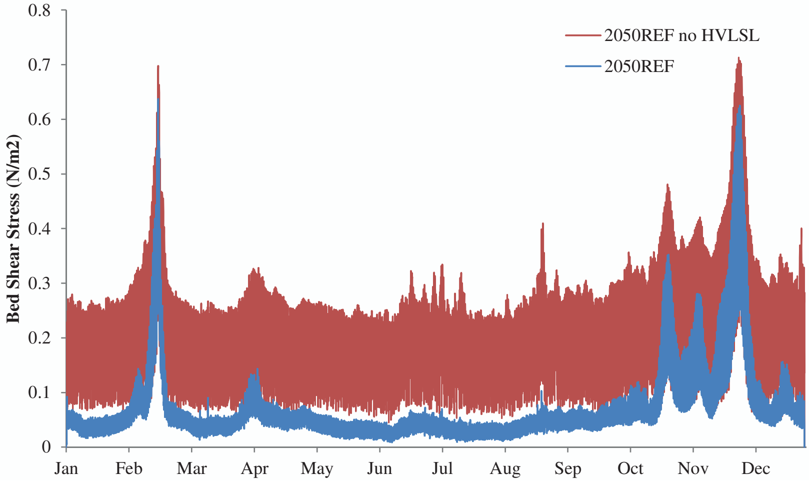

Figure 4.14: Average bed shear stress in Brabantse Biesbosch for scenarios 2050REF and 2050REF no HVLSL.

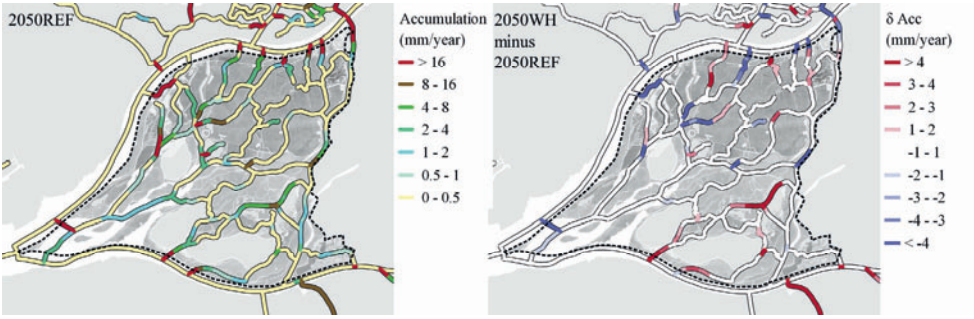

Figure 4.15: Sedimentation patterns for the situation with Haringvliet barrier for reference scenario 2050REF and for 2050WH (2050WH minus 2050REF). The figure with the results for 2050GL was similar to 2050WH and therefore purposefully omitted.

Accumulation rates inside the wetland range from 0 to 6 cm/yr for 2050REF (Figure 4.15). Neither 2050WH nor 2050GL cause significant changes in sediment patterns in most of the wetland. Differences occur especially at the interfaces between the wetland and the River Nieuwe Merwede, where the increased water levels lead to more frequent overtopping of the dikes and higher flow velocities, thus limiting the accumulation there. Removal of the Haringvliet barrier causes a slight decrease in sedimentation along the main flow paths through the study area, especially in the channels that are directly connected to the main river system to the south-west (Figure 4.16). This is consistent with the increase in shear stresses caused by the larger tidal amplitude (Figure 4.14).

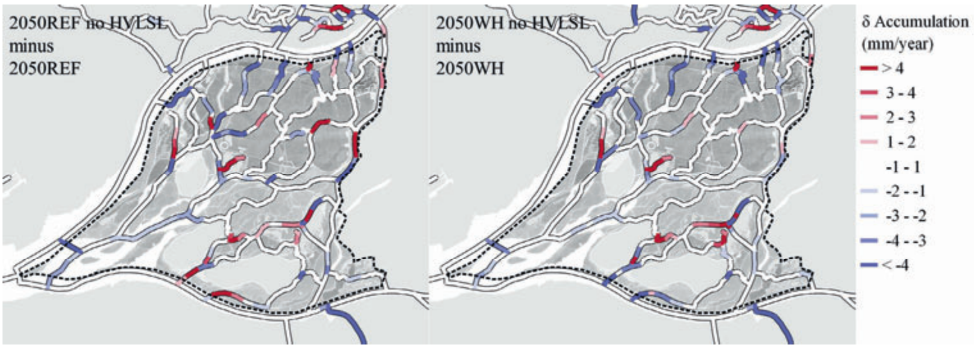

Figure 4.16: Effect of removal of Haringvliet barrier on sedimentation patterns for scenarios 2050REF and 2050WH, expressed as the difference with the reference scenario. The figure with the results for 2050GL was similar to 2050WH and therefore purposefully omitted.

4.4 Discussion

Our results show how sedimentation rates and trapping efficiencies inside the main channels of the Brabantse Biesbosch study area are impacted by the creation of new pathways resulting from the local wetland restoration measures, and how they are affected by changing boundary conditions due to management decisions or climate change. The study area works as a sediment sink most of the time, except for periods of peak river floods when the erosive power of the water flow within the wetland channels is so high that a large portion of the previously settled material is remobilised and leaves the area.

4.4.1 New flow pathways and the importance of SSCs

Our model results suggest that the present and future sediment trapping in the area are controlled by the balance between the enhanced sediment input and increased flow induced shear stresses, which are both resulting from the new or extra upstream supply of river water after the creation of new pathways in the framework of local wetland restoration. We hypothesize that the negative balance for the entire Biesbosch area is due to the low suspended sediment concentration of the incoming river water; as a result sediment accumulation in de deposition areas within the Biesbosch is smaller than the sediment loss from the proximal channels by erosion. With increasing SSC a point may be reached at which the sedimentation starts to become larger than erosion during peak flows. The 10*SSC test scenario showed a sharp increase in sediment trapping efficiency for the current situation with extra pathways, but not for the old situation without the extra pathways. The increased trapping efficiency results from an increase in the magnitude of the sedimentation, while the magnitude of the resuspension/erosion remains the same, because there is no increase in shear stress for an increase in sediment supply. This illustrates that resuspension plays a dominant role in the sediment balance in this area: at low SSC's, resuspension is much larger than deposition. As the SSC increases, deposition starts to increase, tilting the sediment balance at some critical concentration. Indirectly, the trapping efficiency be therefore be limited by the low SSC of the feeding rivers. Our study area has become a very inefficient sediment trap; this fits the original purpose of the new pathways, which were created to increase river conveyance capacity, and not to enhance sedimentation (Rijkswaterstaat, 2018).

4.4.2 Water levels, tidal range and flow-through wetlands

The results show that climate change may not enhance accumulation rates in the study area. This is somewhat surprising, as larger inundation depths (associated with sea level rise) usually lead to a reduction in wind-driven resuspension (Siobhan Fennessy et al., 1994; Anderson and Mitsch, 2006; Mitsch et al., 2014) as well as to higher sedimentation rates, therefore increasing trapping efficiencies (French, 1993;

Temmerman et al., 2004). However, sedimentation of fine sediment can only take place if the residence time of the water is large enough for the settling of this sediment (Asselman et al., 2003). Because the inlet structures towards the new wetlands will start to spill more and more often due to the increased river water levels caused by climate change, shear stresses in the main channels of the wetland will increase and residence times will decrease, thus lowering accumulation rates.

The Haringvliet scenarios of this study indicate that the recovery of the tidal range by the possible future removal or further opening of the downstream located Haringvliet storm surge barrier will cause an increased exchange of water and sediment at the downstream boundaries of the Biesbosch and the surrounding river system. However, this increased influx of sediment does not lead to enhanced sedimentation rates and trapping efficiencies - on the contrary, they drop about 50 % relative to the current situation with the reduced tidal range. Although an increase in tidal range results in an increased hydroperiod and increased wetland area that receives water and sediment during flood, the Biesbosch contains mainly through-flowing tidal channels, where maximum tidal currents during mid to low tide are generally an order of magnitude larger than those in dead-end channels that peak at bank-full conditions. Hence, the increased tidal prism of the Biesbosch area mainly results in increased bed shear stresses, and increased resuspension in the channels during the transition from flood to ebb tide. This pattern counteracts the development of shallow lagoons, whereas a filling-in of channels took place after the reduction in tidal prism by the installation of the Haringvliet storm surge barrier in 1970 (de Boois, 1982). This means that until the channels reach morphodynamic equilibrium, channel bed erosion will exceed the enhanced sedimentation in the increased intertidal wetland area.

4.4.3 Limitations and challenges

For a number of practical reasons (e.g. calculation times, limitations in 2D grid generation), a 1D model was used instead of a 2D or 3D model to simulate hydrodynamics and sediment transport in the braided channel network. This may somewhat limit the applicability of the results, mainly because the model assumes one uniform flow velocity for the entire cross section. In case of composite cross sections, for example a river with an adjoining floodplain, this approach leads to the introduction of certain errors, for example: all sediment that is deposited is available for resuspension, causing a possible overestimation of sediment loss during seasonal discharge events.

A second limitation of this study is that soil consolidation and the effect of vegetation on critical bed shear stresses were not taken into account. Erodibility of newly deposited sediment is therefore overestimated, which again leads to a possible overestimation of sediment loss during seasonal peak discharge events.

A third limitation of this study is that the role of wind on the resuspension of sediment could not be taken into account properly due to limitations in the modelling software. As pointed out previously by for example van der Deijl et al. (2017) and Verschelling et al. (2017), wind plays a very important role on sediment dynamics in this particular area, although primarily on the shallow and bare mud flats during conditions of low or average river discharge. However, in this research we focus primarily on the channel network, in which wind has less impact on bed shear stress due to the larger water depth, as also pointed out by Verschelling et al. (2017).

We argue that the implications of these shortcomings for our results are relatively small for the following two reasons: 1) to some extent, the effects of the individual shortcomings balance each other out over longer periods: sediment loss is overestimated during peak river discharge events (by the assumption of a uniform flow velocity in a cross section and by the exclusion of the effects of soil consolidation and vegetation) while it is underestimated during wind storms (by the exclusion of the effect of wind); 2) In the existing Brabantse Biesbosch channel network, there are very few intertidal flats along the channels, and the connectivity between the channels and the densely vegetated marshes on higher ground is limited by relatively steep banks that developed after the reduction in tidal prism by the closure of the Haringvliet barrier. Furthermore, the vegetated marshes are mainly located along the more distal channels sections, where most sediment has already been lost from the water. These factors somewhat limit the errors introduced by the 1D approach (with a uniform flow velocity in the cross section) and by not taking the effect of the wind on resuspension on the flats into account.

More research is needed to fully understand the implications of these three model limitations, and to incorporate the mentioned underlying processes properly in morphodynamic models. Further modelling might explore the inclusion of a deeper bed layer, where newly deposited sediment can be stored over time to cover the decrease in erodibility by consolidation. Also, the surrounding floodplains/flats can be modelled separately from the main channel system, allowing more flexibility in the parameterisation of the model. Finally, the effects of wind and vegetation on bed shear stress could be included in the 1D model as is already more common in 2D models, for example with approaches by Baptist et al. (2007) and Suzuki et al. (2012).

4.4.4 Implications for management

Enhancing sedimentation by removing embankments or redirecting part of the river discharge towards wetlands is a measure that is often used to prevent drowning (e.g. Giosan et al., 2014b). However, the findings of this study raise intriguing questions regarding the effectiveness of this type of measure at the delta-scale, since they suggest the existence of a balance between the enhanced sediment input and increased flow induced shear stresses, both the result of new or increased supply of river water. This study shows the importance of considering the role of sediment loss through resuspension compared to the SSC of the feeding river when designing wetland restoration projects: together they control the balance between the total sedimentation and resuspension of sediment. Any future decrease in SSC of the feeding river (for example by the development of new upstream located dams, or river diversions) should also be accounted for, because this may further lower the trapping efficiencies of delta wetlands: sedimentation decreases, while the total amount of resuspension may remain unchanged.

This study also shows that sedimentation in tidal systems with large flow velocities is a two-step process: under low to average flow conditions, net accumulation takes place close to the feeding rivers during the tidal cycle. During flood tide and medium flows, this sediment is remobilised and gets transported from these outer sections to the wetland interior where may settle, depending on flow conditions. Delta restoration by river diversions therefore requires not only new or additional upstream supply of water and sediment, but also a sufficiently long residence time inside the wetland to allow the sediment to settle. In addition, flow and wind induced shear stresses should be kept as low as possible to prevent too much resuspension. Measures that reduce bed shear stress, such as the planting of vegetation, can be used to reduce the erodibility and resuspension of the freshly accumulated material (Möller, 2006; Turner et al., 2007; Kearney et al., 2011; Delgado et al., 2013; Fagherazzi et al., 2013). For the study area, the effects of sea level rise combined with the eroding power of the flow pathways through the wetland and the low SSC of the feeding rivers will likely lead to the gradual drowning of the lower sections of the Biesbosch wetland.

4.5 Conclusions

This study reports a first attempt of quantification of sedimentation rates and patterns at the scale of the entire inland delta of the Biesbosch, a large tidal freshwater wetland in the Rhine-Meuse delta in the Netherlands. This study also analyses how these rates and patterns are impacted by wetland restoration measures, river management strategies and climate change.

Under low to average flow conditions, the study area works as a sediment sink. Most of the sediment is deposited close to the feeding rivers and at the downstream end of the two major side channels. Little sedimentation normally takes place in the interior channels of the wetland because the water is depleted of sediment by the time it reaches these channels. Medium discharge events cause some sediment redistribution by remobilising part of the sediment along the edges of the wetland and transporting it further inland. Peak river floods cause a large net loss of sediment from the wetland, because the erosive power of the currents is too high for the settling of sediment while a large portion of the previously settled material is remobilised and leaves the area.

This resuspension during peak floods is partly caused by large-scale river diversions that were constructed as part of a programme to reduce flood hazards along the Dutch rivers. Although the increased influx of water also brings more sediment into the study area, the increase in resuspension due to the eroding power of the passing water is far larger than the increase in sedimentation.

Net sedimentation rates in the study area are expected to further decrease under climate change. This is caused by the increased water levels in the surrounding river system (due to a combination of sea level rise and increased peak river discharges), which leads to more frequent overtopping of the new diversion structures between the rivers and the wetland, thus exacerbating the effect of the diversion structures on the sediment balance during floods due to the increase in bed shear stresses.

The tidal range in the study area is currently artificially reduced because of a large storm surge barrier in the estuary downstream. Our results show that removal of this barrier will not lead to enhanced sedimentation in the study area, because the increased tidal prism would lead to increased bed shear stresses and the subsequent increase in resuspension during the transition from flood to ebb tide.

For the study area, the effects of sea level rise combined with the eroding power of the flow pathways through the wetland and the low SSC of the feeding rivers will likely lead to the gradual drowning of the lower sections of the Biesbosch wetland. We hypothesize that restoring the original tidal amplitude by alternative management (or removal) of the Haringvliet barrier may lead to enhanced sedimentation in the inner wetland channels, but only if measures are taken to convey a larger proportion of the incoming sediment into the central part of the system, and prevent it from resuspension and subsequent removal from the system. For this purpose, the flow velocities in these wetland channels should decrease gradually towards the wetland interior, and residence times should be long enough to allow complete settling before the return tidal flow starts

The findings of this study raise intriguing questions regarding the effectiveness of delta restoration by river diversions, since they suggest the existence of a balance between the enhanced sediment input and increased flow induced shear stresses, which are both resulting from the new or extra upstream supply of river water. This is especially the case in tidal systems with relatively high flow velocities, where high suspended sediment concentrations are needed to compensate sediment loss by resuspension.

4.6 Acknowledgements

This study was financed by the Dutch Technology Foundation STW (project no. 12431). We thank Staatsbosbeheer and Rijkwaterstaat-WNZ for the provided data. We thank Henk van den Boogaard and Michelle Jeuken (both from Deltares) for their help and support on the derivation of the boundary conditions and the use of the SOBEK3 modelling software.

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5 Rising land: sedimentation rates in tidal freshwater wetlands depending on shape, size, orientation and bathymetry

Abstract

Sediment deposition inside tidal freshwater wetlands (TFWs) is a key mechanism to prevent them from drowning due to rising sea level or anthropogenic modifications to the river system. The effectiveness of this strategy depends on what factors determine sedimentation rate and how these factors can be manipulated by landscaping and sediment management. We carried out a scenario analysis using a numerical model of 2D water flow and sediment dynamics for a schematic TFW to gain insight in the relation between selected initial conditions and short term sedimentation rates and trapping efficiencies in constructed TFWs. Our model results show that the average sedimentation rate and trapping efficiency of a TFW increase with factors such as a larger wetland length/width ratio, a longer and more complex channel network and a lower wetland elevation. Interaction effects of initial conditions are largely the result of the non-linear relation between the water depth and the effect of the bed shear stresses due to wind and currents on sedimentation and erosion. The main insights have been captured in an empirical relation that links four wetland-specific parameters (representative water depth, wetland orientation with respect to the main wind direction, hydrologic load and wetland length/width ratio) to the trapping efficiency of the wetland. An overarching factor determining the trapping efficiency is the average water depth. These relations are useful to understand how sediment accumulation in newly established delta wetland areas can be controlled by the design of wetland layout, boundary conditions and landscaping measures, in order to prevent such wetlands from drowning.

Submitted manuscript: Verschelling, E., Kleinhans, M. G., Van der Perk, M., Middelkoop, H.(under review). Rising land: sedimentation rates in tidal freshwater wetlands depending on shape, size, orientation and bathymetry. *Ecological Engineering*.

5.1 Introduction

Enhancing sedimentation inside tidal freshwater wetlands (TFWs) is currently the main strategy to prevent them from drowning under rising sea level or anthropogenic modifications to the river system (e.g. construction of levees, upstream dams, downstream tidal gates) (Darke and Megonigal, 2003; Paola et al., 2011; Kirwan and Megonigal, 2013). However, the question whether this strategy is effective depends critically on what factors determine sedimentation rate, and how these factors can be manipulated by landscaping and sediment management. Sedimentation and erosion are determined by bed shear stress, critical shear stresses for erosion and deposition, sediment particle fall velocity and concentration (Partheniades, 1965). These are governed by currents and waves, which are in turn affected by the interplay between boundary conditions (water discharge, tide, wind, sediment influx) and initial conditions (e.g. creek pattern, vegetation, bed levels, bed composition, fetch lengths)(Verschelling et al., 2018). Previous research on boundary conditions stressed the role of wind as an important driver of erosion (Scarton et al., 1998; Temmerman et al., 2003), and demonstrated the importance of considering the joint effect of river discharges, tides and wind during short-term events (van der Deijl et al., 2017; Verschelling et al., 2017).

Previous research of tidal flats has shown that sedimentation rates decrease further away from the tidal creeks and from the inlet (e.g. Temmerman et al., 2003; Mitsch et al., 2014) and with increasing intertidal surface elevation (Temmerman et al., 2003). The trapping efficiency (defined as the percentage of incoming sediment that is deposited in the wetland) is partly controlled by vegetation characteristics (Nardin et al., 2016), since larger wind fetch lengths enhance wave-driven erosion and re-suspension (Verschelling et al., 2017) and hamper the settling of sediment particles. Still, effects of combinations of boundary conditions and initial conditions on sedimentation rates and trapping efficiencies at the scale of entire wetlands remain poorly understood. This understanding is urgently needed for the quantification of sedimentation processes in TFWs and for the design of measures to prevent wetlands from drowning.

Our objective is to understand and quantify relations between initial conditions (i.e. topographical layout), and sedimentation rates and trapping efficiencies in restored tidal freshwater wetlands. To this end, we construct and use a numerical model that describes morphodynamics of a schematic TFW with idealized initial conditions that capture the most prominent topographic wetland features. Boundary conditions and general area characteristics are inspired by an existing model of a TFW located in the Rhine-Meuse delta (cf. Verschelling et al., 2017). Next, we analyse effects on sedimentation rates of initial conditions of wetlands such as creek configuration, in- and outlet configuration and wetland length-width ratio, henceforth called main effects. We then study effects of combined and interacting imposed conditions, henceforth called *interaction effects*. Finally, we capture some of the main insights of this study in an empirical metamodel that relates key morphometric properties to the trapping efficiency.

We analyse idealized tidal freshwater wetlands that are separated from the surrounding water system by embankments, with (a) a limited number of connections to the surrounding water system, (b) geometries with tidal flats intersected by a simple channel system and (c) a fixed total area without the possibility of lateral wetland migration. We neglect the effect of a) the contributions of subsidence and autogenic production of organic material, b) variations in grain size, erodibility and cohesion of bed sediment and c) changes in boundary conditions. We apply a range of conditions that represent one year to analyse the effect of varying initial conditions on accretion rates. This relatively short period allows us to use fast non-morphodynamic simulations, meaning that hydrodynamics remains unaffected by changes in morphology due to erosion and sedimentation.

5.2 Methods

5.2.1 Schematic tidal freshwater model

The general properties of the baseline idealized model were inspired by the morphodynamic model of the TFW ‘Kleine Noordwaard’ (KLNW), described in detail in Verschelling et al. (2017) and Verschelling et al. (2018). Here we first describe the general characteristics of the KLNW wetland, and then we explain the model setup.

The KLNW is located in the Rhine-Meuse delta in the Netherlands. It is a former polder area with a surface area of about 500 ha, of which the embankment was opened at several places to restore the flow of water and sediment through the area. The area consists of inundated muddy flats, a vegetated island in the middle, and a man-made channel system that is connected at two locations with the surrounding river network. Suspended sediment is supplied from the surrounding river system with concentrations that typically vary between 10 to 40 mg/l during normal flow conditions and may reach up to 140 mg/l during peak flows (Asselman, 2000). Vegetation is very sparse and consists mostly of softwood riparian forests and shrubland on the elevated areas, reed fields and pioneer herbs on the intertidal areas, and macrofytes on the inundated flats (Van der Werf, 2016).

To simulate water flow, sediment transport and bed level changes in our synthetic TFW, we used the depth-averaged version of the Delft3D morphodynamic model (Lesser et al., 2004) We used one sediment fraction to model changes in cohesive sediment transport rates and corresponding bed level changes, using the Krone-Partheniades equations (Partheniades, 1965). We chose to neglect the coarser non-cohesive sediment fraction because: 1) previous research revealed the dominant contribution of the cohesive sediment fraction in the morphological processes in the original study area (Verschelling et al., 2017; Verschelling et al., 2018), and 2) the large number of simulations required us to limit per-scenario simulation time as much as possible. The effect of wind-generated waves on morphodynamics was modelled with the SWAN short wave model (available in Delft3D through Delft3D WAVE). The computational grid of the baseline model consists of a grid with 110x115 cells of 20x20m each, giving a total model area that is roughly the same as the KLNW wetland. The most important model settings are listed in Table 5.1. The values of these settings were chosen identical to the values of the previously constructed morphodynamics model of the KLNW wetland.

Table 5.1: Model settings. After Verschelling et al. (2017)

Parameter	Unit	Value
Horizontal eddy viscosity	m^2/s	0.5
Horizontal eddy diffusivity	m^2/s	2
Computational time step FLOW model	min	0.5
Computational time step WAVE model	min	60
JONSWAP coefficient WAVE model	m^2/s^3	0.038
Specific density of sediment fraction (mud)	kg/m^3	2650
Dry bed density of sediment fraction (mud)	kg/m^3	500
Critical shear stress for sedimentation	N/m^2	0.1
Critical shear stress for erosion	N/m^2	0.3
Erosion parameter	$kg/m^2/s$	0.001
Effective settling velocity	mm/s	0.04

Idealized initial and boundary conditions were defined as follows. The bathymetry was constructed using the 2015 hypsometric curve of the KLNW wetland to define the bed levels and assuming one straight channel (Figure 5.1A). We assumed that initially, there is no sediment present in the system. Hydraulic resistance due to vegetation and wind is modelled according to the approaches of Baptist et al. (2007) and Suzuki et al. (2012), respectively. We used the same key vegetation species, properties and habitat suitability rules as used earlier for the KLNW example wetland (Verschelling et al., 2018) to define the vegetation cover for our synthetic case (Figure 5.1B) and corresponding roughness field parameters. We used the set of boundary conditions previously derived by Verschelling et al. (2018) for a one-year event that is considered representative for current climate conditions in the KLNW wetland, including a) the discharge hydrograph at the northern boundary of the channel, b) the water level time series at the southern boundary, and c) wind blowing from the west (Table 5.2).

Table 5.2: Statistical properties of boundary conditions. Avg = average, SD = standard deviation.

Parameter	**Unit**	**Avg**	**SD**	**Min**	**Max**
Upstream discharge	m^3/s	54.30	61.37	11.49	279.38
Downstream water level	m+NAP	0.50	0.27	0.13	1.90
Wind speed	m/s	0.88	3.51	0.00	18.07

Suspended sediment concentration (SSC) at the upstream boundary was defined using the sediment rating curve previously constructed by Verschelling et al. (2018):

$$SSC = \begin{cases} -1.99\times10^{-7}Q^2 + 1.12\times10^{-4}Q + 2.91\times10^{-2} & \text{for } Q \leq 181\,\mathrm{m^3/s} \\ -1.57\times10^{-7}Q^2 + 9.46\times10^{-4}Q - 1.24\times10^{-1} & \text{for } Q > 181\,\mathrm{m^3/s} \end{cases} \tag{5.1}$$

Where SSC is the suspended sediment concentration (g/L) and Q is the upstream water discharge (m^3/s).

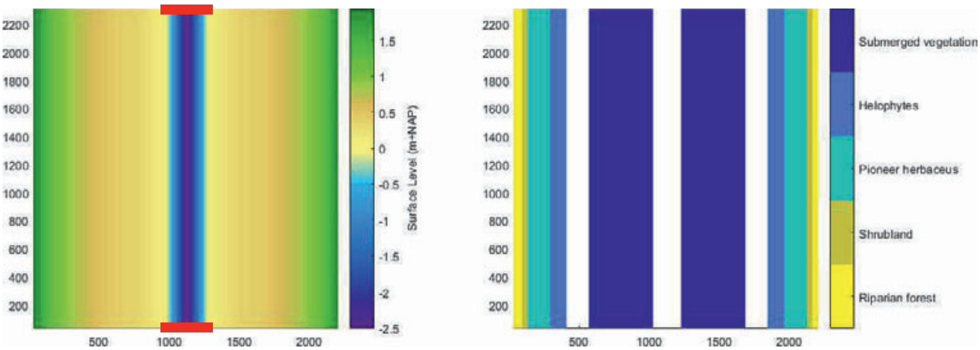


Figure 5.1: Baseline model bathymetry (A) and vegetation types (B). The red lines in figure A indicate the locations of the open boundaries. The white areas in figure B are zones without any vegetation.

5.2.2 Main effect and interaction effect analysis

The main effects show the direct effect of a change in single input variable on an output variable, while the interaction effects show the additional effect due to interactions with another variable. We calculated these effects as follows. First, we constructed a shell around the Delft3D model that enabled us to carry out the simulations in batch mode. Before every simulation run, this shell modifies the relevant components of the baseline model to reflect a change in a certain initial setting (e.g. changed polder wetland area or shape, bathymetry, vegetation pattern & corresponding friction definitions, or boundary condition configuration). Next, the shell calls the Delft3D computational core to carry out the simulation, and collects the results after each simulation. This process was repeated for 129 scenario runs (which include: 1 baseline, 16 main effects, and 112 interaction effects). The results were then post-processed to give a) overall sediment balance terms (sediment supply, area-averaged sedimentation rate and trapping efficiency), b) the median sedimentation rate as a representation of the typical sedimentation rate in the area, and c) two indicators of spatial variability: the interquartile range (IQR) of the sedimentation rate and vertical distribution curves of sedimentation rates as a function of bed level. Finally, we analysed the effect of the applied changes in initial conditions on the sedimentation rates and patterns to determine and explain dominance of certain variables and interactions between variables. Given the categorical nature of some of the variables, a formal ranking in terms of sensitivities using some form of sensitivity index was not possible.

To select the initial conditions for the effect analysis, we first defined four categories of characteristics of the wetland that can be modified from the baseline model and that are likely to affect sedimentation rates and patterns through their effect on flow patterns and waves: a) wetland shape, b) stream network, c) wetland connectivity to the feeding river and d) local perturbations in the wetland surface topography. Next, we defined relevant characteristics for every category, and specified for each up to four settings (Table 5.3). The chosen characteristics and settings bracket the likely initial conditions of a wide range of constructed wetlands, while their limited number keeps the simulation times manageable.

Apart from three exceptions, we assumed that the upstream water discharge boundary conditions were not affected by modifications inside the wetland, and applied the baseline upstream water and sediment inflows to all scenarios. This implies that the total water and sediment inflows are identical for most of the scenarios. Exceptions are the two inlet scenarios (*Inl_Sm* & *Inl_la*), and the closed outlet scenario (*Outl_Clsd*). For the first two, a multiplier was applied to incoming water discharge to simulate an alternative inlet size. For *Outl_Clsd*, the downstream boundary was removed and the upstream water discharge boundary was replaced by the baseline downstream water level boundary, leaving the model to calculate the exchange of water and sediment at the upstream boundary itself based on gradients in the water level and sediment concentrations.

Table 5.3: Wetland characteristics and settings. Settings of the baseline scenario (scenario ID 'Base') are included for reference.

Category	Characteristic	ScenID	Setting description	unit	Setting
Wetland shape	Width/length ratio	Sh_Na_Lo	Narrow	-	0.5
		Base	Medium	-	1
		Sh_Wi_Sh	Wide	-	1.5
	Elevation offset	El_Lo	Low	m	-0.4
		Base	Medium	m	0
		El_Hi	High	m	0.4
	Winddir	Base	West	cardinal	W
		Wind_N	North	cardinal	N
		Wind_S	South	cardinal	S
Stream network	Configuration	Netw_Fl	Flat	-	(see descr)
		Base	1 Channel	-	(see descr)
		Netw_Bif	Bifurcation	-	(see descr)
		Netw_Par	Bifurcation & Confluence	-	(see descr)
	Channel width	ChW_Na	narrow	-	0.5
		Base	medium	-	1
		ChW_Wi	wide	-	1.5
In and outlets	Outlet	Base	yes	-	(yes)
		No_Outl	No	-	(no)
	Inlet	Inl_Sm	Small	-	0.5
		Base	Medium	-	1
		Inl_La	Large	-	1.5
Islands & Ponds	Islands	Base	no islands	-	(see descr)
		6Islands	6 islands	-	(see descr)
	Ponds	Base	no ponds	-	(see descr)
		6Ponds	6 ponds	-	(see descr)

[1] For all scenarios, including Shape_Na_Lo and Shape_Wi_Sh, the total wetland area remains constant.

[2] See Figure 5.2. The elevation offset was applied to the hypsometric curve of the baseline scenario, and the corresponding vegetation cover was defined using the habitat suitability rules.

[3] See Figure

[4] The channel width multiplier in ChW_Sm and ChW_Wi was applied to all channel below 0.2m +NAP.

[5] For No_Outl, the closure of the outlet was modelled by applying the default downstream boundary condition (a water level boundary) as the upstream boundary, and removing the downstream boundary.

[6] Modifications to the inlet size Inl_Sm and Inl_La were represented as a multiplier on the incoming discharge hydrograph.

[7] The islands and ponds (6Islands & 6Ponds) were configured as six circular islands/ponds, three on both sides of the wetland channel.

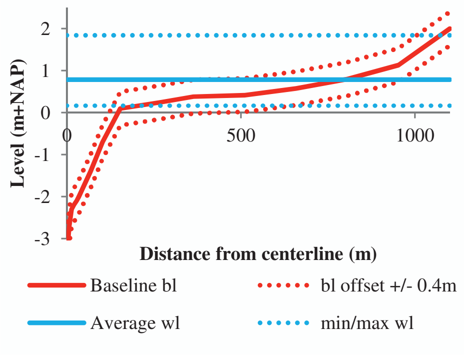


Figure 5.2: Hypsometric bed level (bl) curves of Baseline, El_Lo and El_Hi scenarios, and the average, minimum and maximum values of the water level (wl) time series imposed at the downstream boundary during the one-year event.

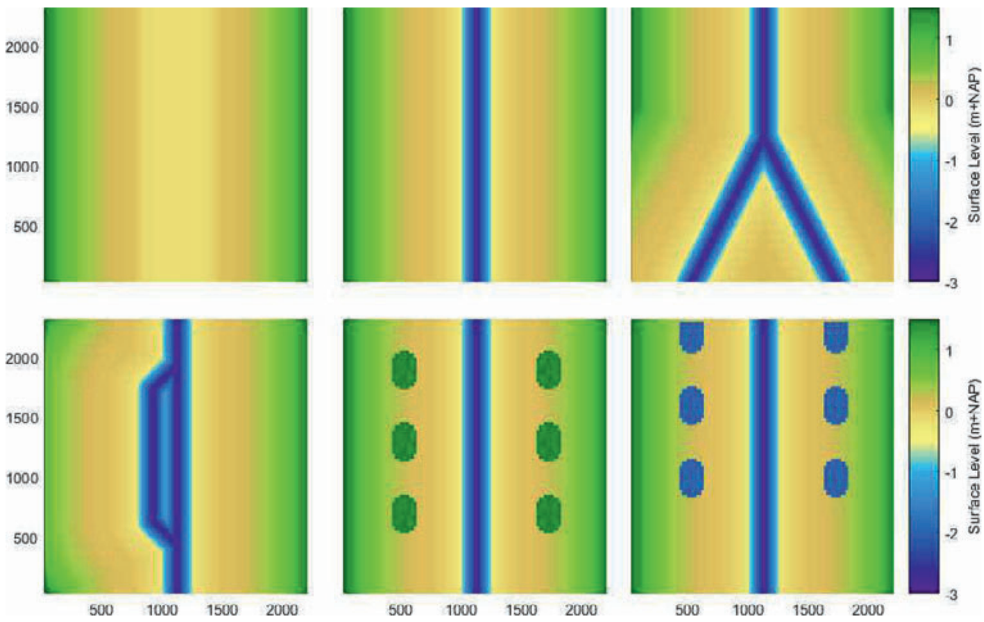


Figure 5.3: Bathymetries of stream network and local perturbations scenarios (*Netw_Fl, Base, Netw_Bif, Netw_Par, 6I, 6P*) plotted on the default (baseline) square wetland shape. Compared to 6I, the perturbations of 6P (ponds) were shifted slightly to the North to facilitate the simulation of combined effects of interactons.

5.2.3 Metamodel

We carried out a stepwise linear multivariate regression analysis to construct a simple metamodel that predicts the trapping efficiency of a TFW. For this, we defined a list of candidate explanatory variables based on the findings of the main and interaction effect analysis. We chose the trapping efficiency as our dependent variable because it is dimensionless, which makes it more easy to apply our metamodel to other areas. The regression was carried out in a stepwise fashion, in which we started with all candidate variables and progressively removed the variable that was most insignificant (lowest individual p-value), until we arrived at a relation in which no further variables could be removed without a loss of accuracy ($\bar{R}^2$, the adjusted coefficient of determination), and contained only statistically significant variables ($p<0.05$).

5.3 Results

5.3.1 Main effects

The baseline scenario leads to a spatially averaged sedimentation rate of 5.6 mm per year (Figure 5.5B), which corresponds to around 20% of the supply of sediment to the area (Figure 5.5A & C). The highest sedimentation rates occur in and around the channel system (Figure 5.4), at surface elevations between -0.5m NAP and +0.5m NAP (Figure 5.6). Interestingly, the average value of the sedimentation rate is higher than the third quartile (Figure 5.5B). This is the result of the sedimentation rates in a relatively small area (i.e. the channel system) being much higher than in the rest of the area, showing that the channel and wetland are far from being in a morphological equilibrium with the water flow. This also results in a typical (median) area-wide sedimentation rate that is much lower than the average value: 0.4 mm per year (Figure 5.5B).

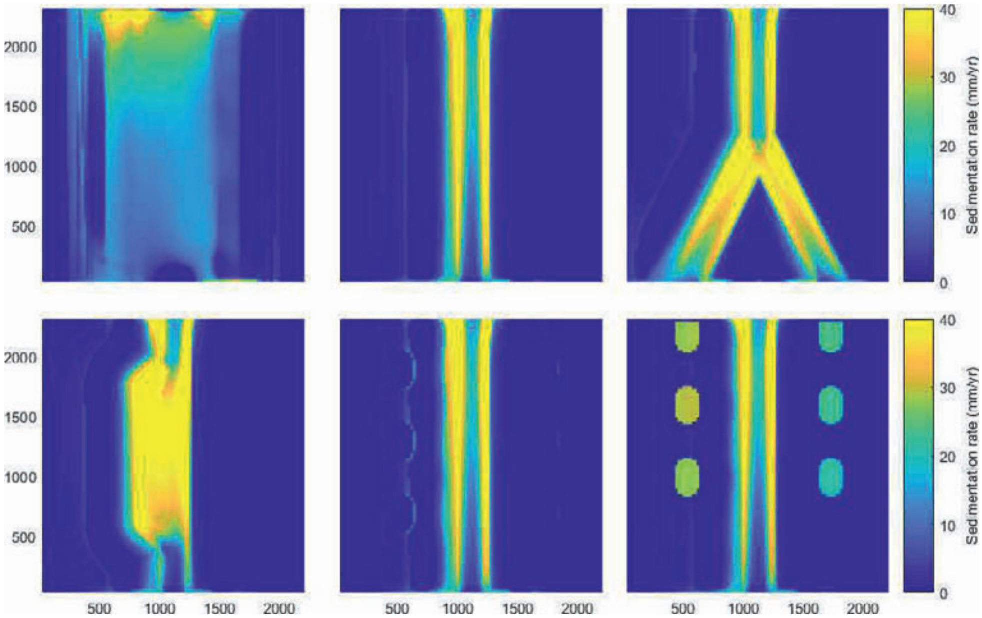


Figure 5.4: Sedimentation patterns for stream network and local perturbations scenarios (*Netw_Fl, Base, Netw_Bif, Netw_Par, 6I, 6P*)

Wetland shape, elevation and orientation

Changing the wetland shape from a square to an elongated rectangle (*Shape-NaLo*) leads to an increase in average and median sedimentation rates as well as a larger IQR (Figure 5.5B), indicating that the sediment spreads out over a larger section of the wetland. A wider and shorter wetland (S*hape-WiSh*) has the opposite effects. This can be explained as follows: sedimentation takes place mostly at the interface between the channel and the flats due to the large lateral gradients in flow velocities and the relative abundance of suspended sediment. A longer and narrower wetland has longer channel-flats interfaces and will therefore lead to more sedimentation, in case of adequate sediment supply. The result is a negative relation between the width/length ratio of a wetland and the sedimentation rate. Because the supply of sediment stays the same as for the baseline scenario (Figure 5.5A), changes in the trapping efficiency are similar to the changes in sedimentation rate (Figure 5.5B vs. 5C).

Lowering the average wetland surface level (*Elev_Lo*) increases the average and median sedimentation rates, and trapping efficiency, whereas the opposite occurs for higher surface levels (*Elev_Hi*). This negative correlation between surface level and sedimentation rate is caused by the following: 1) inundation depth is larger in lower wetlands, resulting in lower average flow velocities, while a deeper flow occurs also over the flats, conveying more sediment to these areas - especially the lower sections of the flats between 0.0 and 0.5m NAP (Figure 5.6) - without settling at the channel-flat interface (Figure 5.5B), 2) The effect of the wind as a driver of resuspension (and potential loss of sediment) is more limited at larger water depths, as the surface waves lose more energy on their way to the bed level.

In the baseline scenario, the wind blows in a direction perpendicular to the main flow direction. An alternative wetland orientation leads to more sedimentation, a much larger spread in sedimentation amounts, and a higher trapping efficiency in the case of tailwind (*WndD-N*). Conversely, headwind (*WndD-S*) leads to less sedimentation and a lower trapping efficiency. For headwind, this is caused by the maximum wind fetch that occurs close to the inlet and thus exactly in the area where normally most of the sedimentation takes place. The increased shear stresses lead to resuspension and a subsequent loss of sediment. Tailwind leads to increased shear stresses close to the outlet where sedimentation rates are generally lower anyway, meaning that the eroding impact of the wind is limited in this case.

Channel network

All analysed channel modifications (channel removal, adding a bifurcation, adding a parallel channel) lead to more sedimentation and a higher trapping efficiency than the baseline scenario with one straight channel. In addition, the channel removal and the bifurcation scenarios result in an enhanced dispersal of sediment across the area (Figure 5.5B). For the scenarios with a bifurcation and parallel channels (*Netw_Bif* & *Netw_Par*), enhanced sedimentation is caused by the combination of a longer channel-flats interface and more sedimentation inside the channel system as a result of a larger channel system, bends and a bifurcation (Figure 5.6). The complete removal (*Netw_Fl)* of the channel system causes all the incoming water to spread out immediately over the flats, leading to sedimentation over a much larger area (Figure 5.5B and Figure 5.4).

A wider channel (*ChnW_Wi*) results in an increase in sedimentation rate, corresponding trapping efficiency and spread, whereas a narrower channel (*ChnW_Na*) has the opposite effect. Most of the changes in sedimentation take place within the channel itself: a narrow channel leads to a sharp decrease in sedimentation in the higher section of the channel between -1,0 and 0.0 mNAP, and a wide channel leads to more sedimentation at levels below -1.0 mNAP (Figure 5.6). In both cases, the changes in sedimentation rates can be linked directly to the changes in flow velocity in the channel due to the change in conveyance capacity.

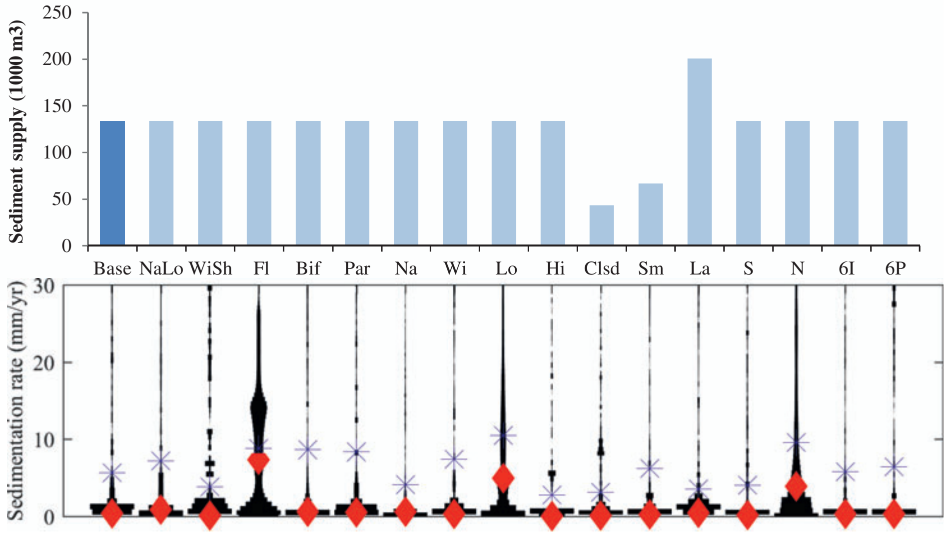
Wetland connections

The baseline scenario describes a flow-through wetland. Closing the outlet (*Outl-Clsd*) strongly decreases the sediment supply into the area, but the trapping efficiency increases. Because the wetland has only one opening in this case, it functions as a reservoir-type system with a much lower gradient that is driven only by the tide and the wind, and not by river discharge anymore. This causes a major decrease in sediment supply into the area when compared to the baseline scenario (Figure 5.5A), and hence a decrease in sedimentation rate. The limited dispersal of sediment into the area is the result of the quick reduction in flow velocities further away from the inlet (Figure 5.5B), which also causes the larger percentage of the supplied sediment to settle in the area (Figure 5.5C).

A smaller inlet to the wetland reduces the sediment supply, but leads to a slightly increased sedimentation rate and a corresponding large increase in trapping efficiency. A larger inlet on the other hand brings more sediment into the system, but leads to a decrease in sedimentation rate and a much smaller trapping efficiency. This somewhat counter-intuitive effect of inlet size can be explained as follows. A larger inlet leads to higher bed shear stresses in the channel, which considerably reduces sediment settling in the deeper parts of the channels (Figure 5.6). This more than compensates for the slight increase in sedimentation on the flats as a result of the increased supply of sedimentation. A smaller inlet, on the other hand, leads to a large increase in sedimentation in the channels, and only a slight drop in sedimentation on the flats.

Perturbation of the wetland topography

The tested configurations of islands and ponds have a small effect on the sedimentation rates. The scenario with the six islands (*Isl_6I*) leads to a slight increase in sedimentation on the flats in the lee of the islands, while the scenario with six ponds (*Pond_6P*) causes a large increase in sedimentation inside the ponds themselves, at the cost of a slight decrease in sedimentation on the flats (Figure 5.6). Apparently, total water and sediment flow into the area neither flow patterns within the wetland are affected to such extent that it substantially influences total sedimentation.



	Base	NaLo	WiSh	Fl	Bif	Par	Na	Wi	Lo	Hi	Clsd	Sm	La	S	N	6I	6P
Avg	5.6	7.2	3.8	8.8	8.6	8.4	4.1	7.4	10.5	2.8	3.1	6.2	3.5	4.0	9.5	5.8	6.4
Med	0.37	0.86	0.13	7.33	0.60	0.56	0.63	0.30	4.94	0.05	0.11	0.27	0.45	0.19	3.90	0.28	0.30

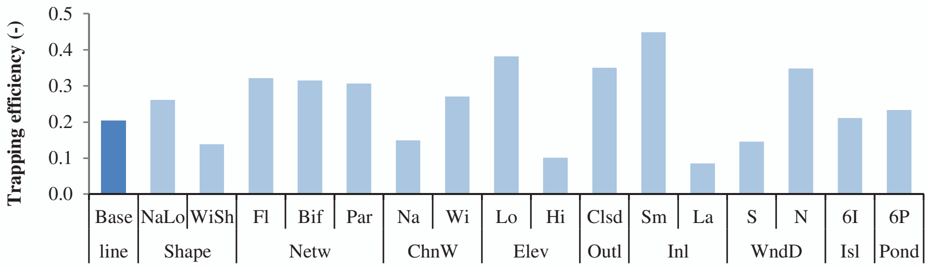


Figure 5.5: (A) Total sediment supply, (B) probability density of the sedimentation rate and (C) trapping efficiency of main effect cases. The baseline sedimentation rate is included for reference. In figure B), the blue asterisk indicates the average value and the red diamond the median value.

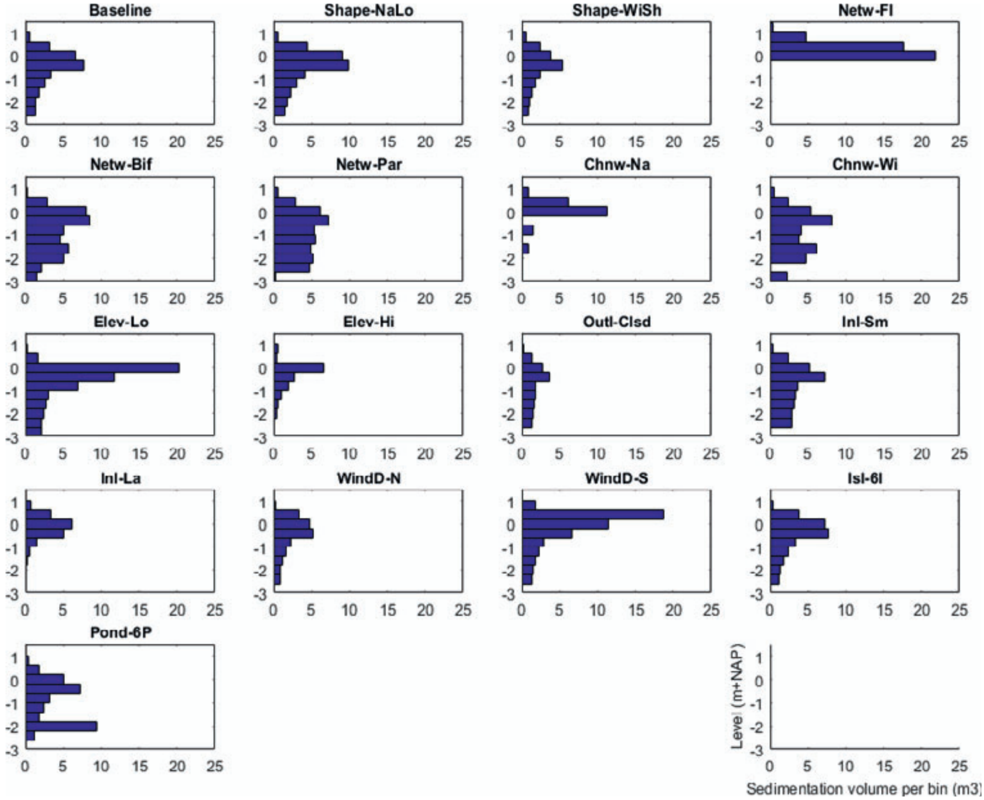


Figure 5.6: Sedimentation volume (in 1000 m3 per bin) as a function of elevation (in m NAP) for all isolated initial condition scenarios. Every vertical bin has a height of 0.4m. The baseline scenario is included for reference. The sum of the individual bin values equals the total volume of deposited sediment in the area during the scenario event.

5.3.2 Interaction effects

Channel network

Here we only discuss the combinations of scenarios that resulted in a significant secondary effect on the average sedimentation rate, starting with combinations that include the scenario without a channel network (*Netw-Fl*). A wetland topography without channels (*Netw-Fl*) substantially enhances the primary effects of varying inlet size (*Inl_Sm* and *Inl_La*) (Figure 5.7). This can be explained as follows. Channel sedimentation within the channel is low due to high bed shear stresses, limiting deposition regardless the size of the inlet. However, in the polder without channel, these high channel shear stresses do not occur, now allowing sediment to settle. As a result, sedimentation rates have become supply-limited, and hence deposition has become dependent on the inlet size. A flat wetland topography (scenario *Netw-Fl*) also changes the effect of dominant wind direction (scenario *WndD_N* and *WndD_S*, but for another reason: due to the absence of a deep channel, wind waves cannot develop fully anymore in the flat system. This limits the effect of wind and causes a drop in resuspension, which leads to less extra sedimentation in case of tailwind and less extra erosion in case of headwind. Differences in elevation in a flat wetland (combining scenarios *Elev_Lo* and *Elev_Hi* with scenario *Netw_Fl*) are smaller than in the wetland with a channel, while deposition rates are lower in both cases. An increase in water depth in a wetland with a channel (*Elev_Lo*) causes the bed shear stress in the channel to fall below the critical shear stress, which leads to an increase in net sedimentation. The same increase in water depth on a flat system, however, does not cause the bed shear stresses to fall below the critical value in this case. This reduces the positive effect of the lowering of the system on the sedimentation rates somewhat. On the other hand, raising the bed level in a flat system (combining *Netw_Fl* & *Elev_Hi*) causes the flow velocities in a large part of the former channel area to rise to such an extent that the critical value for the bed shear stress is exceeded, and thus leads to a large drop in sedimentation.

Wetland connections

Combinations involving the scenario with a closed outlet (*Outl_Clsd*) lead to large interaction/ counteraction effects. By itself, a single inlet causes a significant drop in sedimentation compared to the baseline scenario with two connections. Combined with almost any other wetland configuration, it effectively reduces the primary effect of variations in elevation, inlet size, or channel layout, causing the combined effect to be almost identical to the primary effect of *Outl_Clsd*. This is due to the completely altered nature of the flow of water and sediment into the wetland.

Combining a smaller inlet (*Inl_sm*) with a lower bed level (*Elev_lo*) reduces the primary effect of the latter scenario, while a larger inlet (*Inl_la*) increases sedimentation rates both for low and high wetlands (combined with scenarios *Elev_hi* and *Elev_lo*). This can be explained as follows: *Inl_sm* and *Elev_lo* both cause the system to become more supply-limited. Combining them does not cause the system to become more supply-limited, thereby causing counteraction. The combination of a small inlet (*Inl_sm*), representing a supply-limited system with a high wetland elevation (*Elev_hi*) leads to an interaction effect due to the lowering of the shear velocities close to the smaller inlet. A large inlet in a high wetland (combination of scenarios *Inl_la* and *Elev_hi*) also leads to an interaction effect, but for a different reason: close to the inlet and in the main channel, the shear stresses in both single scenarios were already very high (supply-unlimited), and combining them does not change this. However, a larger inlet also slightly distributes the sediment further over the flats, which in this case leads to a slight increase in the total sediment deposition.

The interaction effects between these scenarios illustrate the importance of the water depth as a control of the sedimentation rate: the effect of altering the inlet size (and hence the average inlet discharge) on the sedimentation rate becomes larger for lower wetland platforms (and hence larger average water depths) (Figure 5.8A).

Wetland orientation

The sedimentation rate of the combined tailwind scenario (*WndD_N*) and higher wetland elevation scenario (*Elev_hi*) is significantly smaller than the sum of the primary sedimentation rates. *WndD_N* by itself lowers the wave-induced bed shear stress close to the inlet; however this is more than compensated for by the increase in current-driven bed shear stress due to the higher bed levels of *Elev-hi*. Again, the interaction effect strongly depends on the average water depth (Figure 5.8B).

Figure 5.7: Interaction effects on the sedimentation rate. The interaction effect is defined as the scenario effect minus the sum of the two main effects. Dot size and colour indicate the magnitude and sign of the effects. Red is negative, meaning counteraction resulting in less sedimentation than the summed sedimentation rate of the two isolated characteristics, blue is positive meaning interaction resulting in more sedimentation than the summed effects.

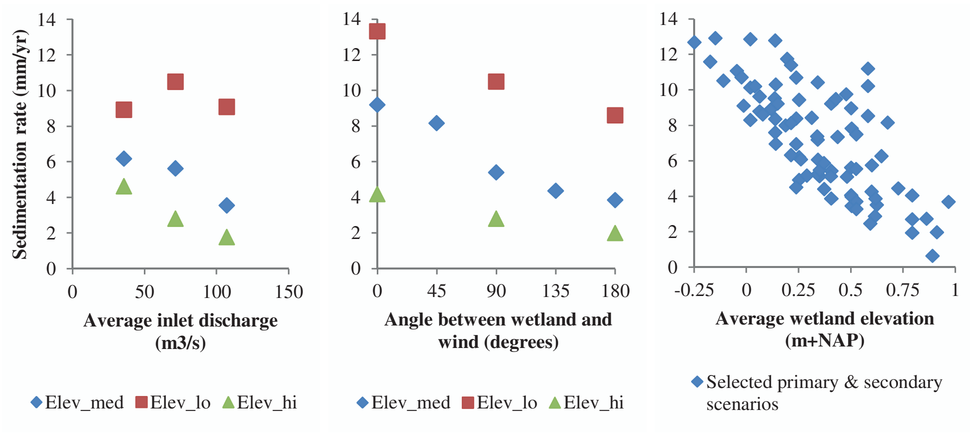


Figure 5.8: A) Relation between average inlet discharge and sedimentation rate for all combinations of wetland elevation and inlet size scenarios. B) Relation between wetland orientation (with respect to the wind direction) and sedimentation rate for all combinations of wetland elevation and wetland orientation scenarios. C) Relation between average wetland elevation and average sedimentation rate for all main and interaction effect scenarios with identical boundary conditions. Scenarios with modified boundary conditions (*Inl_Sm, Inl_La, Outl_Clsd*) have been purposefully omitted. Every point represents one scenario.

5.3.3 Metamodel

Based on the results of the main and interaction effects analysis, we defined a list of candidate explanatory variables for the regression analysis. These variables together encompass 12 wetland characteristics that have demonstrated to significantly affect sedimentation amounts and patterns. Four characteristics were discarded a priori: the ponds and islands (scenarios *Isl_6I* and *Pond_6P*), because they do not significantly affect the total sedimentation, and the closure of the outlet (scenario *Outl-Clsd*) and the flat system without any channel (*Netw_Fl)* because of their extreme dominance over the other variables. Based on the sensitivity analysis of deposition for varying wetland characteristics and their combined effects, we defined the following candidate explanatory variables:

1) The *representative water depth*, defined here as the difference between the time-average of the downstream water level and the average wetland platform elevation. This variable was selected based on the hypothesis that most characteristics pertaining to wetland shape and channel network (*Netw_Bif, Netw_Par, Netw_Na, Netw_Wi, Elev_Lo, Elev_Hi*) is represented to some extent by the average elevation of the wetland. When we plot this variable against the sedimentation rate, they indeed prove to be correlated (Figure 5.8C). We chose to use it in the form of the representative water depth, because this

form has the advantage that the metamodel can be more easily applied to other study sites.

2) The *hydrologic load* of the wetland, defined as the incoming discharge divided by the wetland area (Brueske and Barrett, 1994). This variable is determined directly by the inlet size (*Inl_Sm, Inl_La*). We originally modelled the inlet size as a coefficient on the upstream discharge hydrograph. We can therefore express this variable in terms of the hydrologic load by calculating the average discharge and dividing this by the wetland area.
3) The wetland orientation with respect to the main wind direction.
4) The ratio between wetland length and width.
5) The product of the hydrologic load and representative water depth.
6) The product of the wetland orientation and the representative water depth.
7) The product of the wetland shape ratio and the representative water depth.

We carried out the multivariate linear regression analysis for the following empirical relation:

$$T = \beta_1 + \beta_2 h + \beta_3 q + \beta_4 w_1 + \beta_5 w_2 + \beta_6 qh + \beta_7 r + \beta_8 w_1 h + \beta_9 w_2 h + \beta_{10} rh \tag{1}$$

Where T is the trapping efficiency (-), h is the representative water depth (m), w_1 and w_2 are dummy variables representing the three settings for wetland orientation (tailwind: $w_1=w_2=0$; crosswind: $w_1=1$ and $w_2=0$; headwind: $w_1=0$ and $w_2=1$), q is the yearly averaged hydrologic load (m/s), r is the ratio between wetland length and width (-), and β_1 to β_8 are regression constants. Input values for q ranged from $7.1*10^{-6}$ to $2.1*10^{-5}$ m/s and for h from -0.3 to 0.9 m, and for r from 0.5 to 2. The results of the regression analysis show that only the last three terms of equation 1 can be deleted without a loss of overall fit, that the remaining terms have a degree of significance well below the criterion ($p<0.05$), and that the overall adjusted coefficient of determination is very high ($\bar{R}^2=0.93$) (step 4 in Table 5.4).

Table 5.4: Summary of stepwise regression analysis. Table A shows individual p-values for all remaining explanatory variables as well as the overall modified coefficient of determination ($\bar{R}^2$) for every regression step. Individual p-values for β_1 to β_6 have been purposefully omitted because they were very small (p<0.005). Table B shows the individual regression coefficients β_1 to β_x for all remaining x coefficients. Step 4 gives the optimal result according to the criteria.

Step	$p(\beta_7)$	$p(\beta_8)$	$p(\beta_9)$	$p(\beta_{10})$	$\bar{R}^2$
1	0.10	0.13	0.26	0.58	0.93
2	0.00	0.13	0.26		0.93
3	0.00	0.30			0.93
4	0.00				0.93
5					0.92

Step	β_1	β_2	β_3	β_4	β_5	β_6	β_7	β_8	β_9	β_{10}
1	0.578	0.721	-20834	-0.094	-0.151	-18975	-0.026	-0.125	-0.069	-0.027
2	0.584	0.694	-20841	-0.093	-0.151	-18970	-0.032	-0.125	-0.069	
3	0.603	0.630	-20847	-0.114	-0.170	-18953	-0.032	-0.062		
4	0.604	0.626	-20842	-0.114	-0.188	-18967	-0.032			
5	0.565	0.645	-20753	-0.115	-0.188	-19206				

This leads to equation 2, which gives a reasonable agreement when used to predict trapping efficiencies for the selected scenario runs (Figure 5.9).

$$T = w + 0.626h - 20842q - 18967qh - 0.032r \qquad (2)$$

With w=0.604 for tailwind, w=0.491 for crosswind and w=0.416 for headwind.

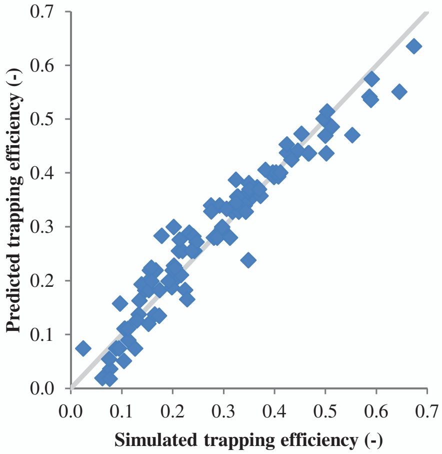


Figure 5.9: Simulated trapping efficiency (according to the simulation output results) versus predicted trapping efficiency (according to equation 2) for all scenario runs selected for the regression analysis.

5.4 Discussion

This study investigates main and interacting effects of selected initial conditions on sedimentation rates and trapping efficiencies in an idealised tidal freshwater wetland using a numerical model. The main insights were captured in an empirical time-averaged relation that links four wetland specific parameters (the representative water depth, wetland orientation with respect to the dominant wind direction, the hydrologic load and the wetland length/width ratio) to the trapping efficiency (Equation 2 and Figure 5.10).

Our results contribute to our understanding of how dissimilar sets of initial conditions lead to different trapping efficiencies in different TFWs. It is generally agreed that larger water depths in a system lead to an increase in residence time and a corresponding increase in sedimentation rate and trapping efficiency (e.g. Nichols, 1983; Brueske and Barrett, 1994), however our research also shows exactly how the inlet size (or the hydrologic load) and wetland orientation together control the trapping efficiency as a function of the average water depth (or the representative water depth): the lowest trapping efficiency occurs in wetlands with small average water depths, a main flow direction that is opposite to the predominant wind direction, and a relatively large inlet (Figure 5.10). At larger average water depths, the inlet size starts to become a more important control in the trapping efficiency, while the role of wetland orientation with respect to the predominant wind direction diminishes.

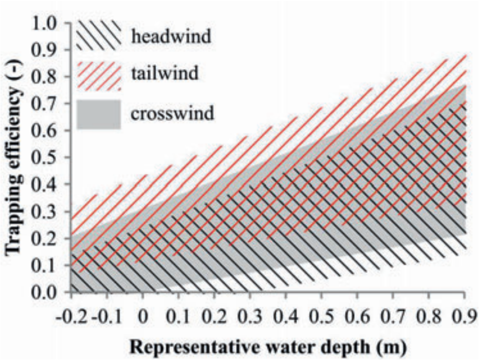


Figure 5.10: Relation between the representative water depth h, wetland orientation with respect to wind direction, and the trapping efficiency for a synthetic TFW according to equation 2 with r=1 (square). The shaded/hatched areas show the effect of the min-max range of the hydrologic load on the trapping efficiency. Due to the nature of the simulations on which equation 2 is based, this relation is only valid for combinations that lead to positive values of the trapping efficiency.

The effect of alternative wind conditions on sedimentation rates has been studied extensively in a range of systems. Wind has been reported as a significant driver of erosion in shallow water, where the magnitude of the erosion had been linked to wind fetch (Van der Wal et al., 2008), wind duration (Fagherazzi and Wiberg, 2009) and water depth (Brueske and Barrett, 1994; Kelderman et al., 2011). Our results show that the angle between the dominant wind direction and the main flow direction is an important control in the overall sediment balance of the area: because most of the sedimentation takes place close to the inlet of the wetland, the highest overall trapping efficiencies occur in wetlands where the main flow direction is more or less the same as the dominant wind direction (tailwind).

In this study we use a set of boundary conditions originally derived for a specific TFW in the Rhine-Meuse delta. The assumption that the upstream discharge is unaffected by modifications inside the TFW limits the applicability of our conclusions to a certain range of TFWs, specifically those where we can assume (near) supercritical flow at the entry point to the wetland, for example in case of a culvert connected to a river with a higher water level. More research is needed to investigate the effect of backwater on inflows in those cases where this cannot be neglected, for example in a wetland without any channel system. For the other types of initial conditions covered in this research however, our modelling study provides more insight in the way that initial conditions interact and control sedimentation rates in (constructed) TFWs.

For our synthetic TFW with boundary statistics derived for a location in the Biesbosch area in the Netherlands, the highest sedimentation rate of all analysed scenarios was 13.4 mm/yr, while the rate of sea level rise in the Netherlands is expected to range between 3.0 and 12.5 mm/yr in 2085 (Van den Hurk et al., 2014). This suggests that it may be possible to shape a constructed TFW in the Biesbosch area in such a way that it will not drown due to SLR. In reality however, sedimentation rates will gradually change as the bed levels in the area slowly adapt to the boundary conditions. Since most of the sedimentation is deposited in the channel system and on the tidal flats close to the inlet, the channel conveyance capacity will gradually decrease, which in turn will gradually reduce the inflow and distribution of water and sediment over the area. This long-term feedback mechanism between bed level changes and hydrodynamics was not included in the current research. Furthermore, it is likely that sedimentation rates are affected by changes in boundary conditions under influence of climate change, while our analysis was carried for present-day climate boundary conditions only. Combining the effect of variations in initial conditions (such as carried out in this study) and boundary conditions under influence of climate change on the morphology of a wetland is therefore an interesting topic for future research.

In our study, the role of vegetation was taken into account in a limited way by assuming a fixed vegetation pattern according to the average abiotic conditions of the scenario (depth and velocities) and a set of local knowledge rules, and including the effect on hydraulic and bed shear stresses. Interesting future research on the topic of long term survivability of TFWs in the face of climate change through hydro-morphodynamical modelling would be to include a coupled vegetation module that handles the relevant ecological processes (vegetation succession, stem growth, colonization and mortality), for example as developed by van Oorschot et al. (2015).

Our study has practical implications for the restoration of microtidal TFWs under risk of drowning due to climate change. The results show that trapping efficiencies are highest for areas with a) an elongated shape, b) a large and wide channel network, c) a dominant flow direction more or less the same as the dominant wind direction, d) a relatively low wetland platform elevation, and e) a relatively small inlet. However, a low wetland platform elevation also causes the vegetation to die off and the conversion of the system from an intertidal flat into a lacustrine wetland. The reduction of sedimentation rates at smaller water depths is partly caused by wind-wave generated shear bed stresses. It is therefore important to reduce wind fetch as much as possible, for example by vegetation or small topographical perturbations. The inlet should be designed in such a way that local shear stresses stay as low as possible, while at the same time allowing as much water and sediment to enter and spread out over the area .This could be achieved by constructing multiple small inlets instead of one large inlet.

5.5 Conclusions

We carried out a scenario analysis using a synthetic TFW lay-out to gain insight in the relation between the lay-out of constructed tidal freshwater wetlands (TFWs) and annual sedimentation amounts and trapping efficiencies. Our model results show that sedimentation amounts increase for a) a larger wetland length/width ratio, b) a longer and more complex channel network, c) larger channel width, d) a small angle between the main wetland direction and wind direction, e) lower wetland elevation and f) smaller inlets. Annual sedimentation in single inlet wetland areas is considerably smaller than in wetlands in which a water flow occurs from a separate inlet to an outlet. Small bathymetric perturbations such as islands and ponds hardly increase the spatially averaged sedimentation rates. Trapping efficiencies follow the trends found in the sedimentation rates for all wetland layouts except when the outlet is closed, in which case the trapping efficiency increases significantly.

Interaction effects of initial conditions are largely the result of the non-linear relation between the water depth and the effect of the bed shear stresses due to wind and currents on sedimentation and erosion. The closure of the outlet is a dominant type of initial condition, because it effectively negates the primary effect of any other primary condition. Any initial condition that has a large effect on the water depth generally also causes large secondary effects. Examples are lowering or elevating the wetland platform and the inclusion of a more complex channel network.

The main insights have been captured in an empirical relation that links four wetland-specific parameters (the representative water depth, wetland orientation with respect to the main wind direction, the hydrologic load and the wetland length/width ratio) to the trapping efficiency. A main factor determining the trapping efficiency is the average water depth within the wetland. For different TFWs these relations are useful to understand possible effects of setup, conditions and measures on sedimentation rate that may help prevent wetlands from drowning.

5.6 Acknowledgements

This study was financed by the Dutch Technology Foundation STW (project no. 12431). We thank Staatsbosbeheer and Rijkwaterstaat-WNZ for the provided data. We thank Bert Jagers, Eveline van der Deijl and Karen Meijer for the useful discussions.

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6 Synthesis

6.1 Introduction

The objectives of this research were the following:

1) Assess how different configurations of boundary conditions together control sedimentation rates, patterns and trapping efficiencies in a tidal freshwater wetland affected by riverine discharges, tides and wind.
2) Evaluate the effect of climate change (CC) on morphological developments and sedimentation rates in a tidal freshwater wetland.
3) Assess how different configurations of wetland characteristics together control sedimentation rates, patterns and trapping efficiencies a generalised tidal freshwater wetland affected by riverine discharges, tides and wind

To this end, I constructed a high-resolution hydro-morphological model of the study area, the polder-turned-into-wetland *Kleine Noordwaard*, and used it to carry out a scenario analysis for a number of different hydro-meteorological events. This revealed how the interplay of river discharge, tide, and wind controls sedimentation in the wetland. The model was then used under changed boundary conditions associated with two climate scenarios. This demonstrated the long-term effect of CC on sedimentation rates and trapping efficiencies and on morphological changes in the former polder. Next, I considered the entire *Brabantse Biesbosch* channel-wetland area and analysed the effect of CC on sediment patterns and trapping efficiencies in the channels of the wetland. Finally, I focused on understanding and quantifying the relations between wetland characteristics (i.e. topographical layout) and sedimentation rates and trapping efficiencies of TFWs in general by analysing the effect of alternative characteristics of a synthetic TFW with idealized initial conditions and boundary conditions. In section 6.2, the main findings of this PhD research are summarised and discussed according to the above objectives. In sections 6.3 and 6.4 I give my perspective on the use of numerical models for wetland management and the application of the findings to other wetlands. In section 6.5 I present an outlook for future research challenges, and I conclude this thesis with recommendations for wetland management (6.6).

6.2 Interpretation of main findings

How boundary conditions control sedimentation rates

Combining the insights from the Kleine Noordwaard, Brabantse Biesbosch and synthetic model studies lead to the following conclusions on how sedimentation rates in TFWs are affected by boundary conditions:

1. For the *Kleine Noordwaard* study site, net sediment deposition rates increase with water discharge magnitude due to the extra influx of sediment, and decrease with windstorm magnitude due to the wave-induced bed shear stress and corresponding resuspension. Changes in tidal conditions (neap, spring) have a considerably smaller effect, mostly due to the presence of a saltwater barrier (Haringvliet sluices) downstream of the wetland, which severely dampens the tidal signal. The trapping efficiency in the study site decreases with water discharge magnitude and wind velocity (chapter 2).
2. For the *Kleine Noordwaard* study site, wind leads to a) a net transport of sediment from the flats towards the channels, b) a net transport from the downwind sections of the flats to other sections and c) an increased outflow of sediment from the area. This is caused by the large-scale resuspension of fine sediments on the inundated mud flats due to the large fetch lengths in most wind directions, similar to processes taking place in shallow lakes (chapter 2).
3. Combinations involving certain boundary conditions (closure of the outlet, average platform elevation, channel network complexity) lead to significant inter/counteracting effects, which are largely the result of the non-linear relation between the water depth and the effect of the bed shear stresses due to wind and currents on sedimentation and erosion (chapters 2 and 5).
4. Diverting river water from rivers towards wetlands may lead to a reduction in net sedimentation instead of an increase in case the suspended sediment concentration of the feeding river is very low and the erosive power of the currents through the major flow pathways is relatively high (chapter 4).

These findings have the following implications for how boundary conditions affect sedimentation rates and trapping efficiencies in tidal freshwater wetlands in general. Discharge through the inlet has a major effect on sedimentation because it controls a) the amount of sediment conveyed into the area, b) the trapping efficiency (which depends on the residence time of the conveying water within the area), and c) the shear stresses that occur within the area depending on local flow velocities. Although

TFWs depend on riverine discharges for inflow of water and sediment, more discharge therefore does not automatically mean more sedimentation. In both of our study areas (*Kleine Noordwaard* and the entire *Brabantse Biesbosch*), larger discharge events generally lead to a net loss of sediment due to resuspension and outflow of previously settled material (chapters 2 and 4). This is however partly caused by the low suspended sediment concentration (SSC) in the surrounding rivers (20mg/l on average), which severely limits the amount of sediment available for sedimentation, especially further away from the rivers. Many other wetlands have a higher riverine SSC, which would lead to more net sedimentation and further inside the wetland for higher discharges - assuming other factors are not much different from our study area (e.g. resuspension due to current shear stresses).

Wind has a major negative effect on sedimentation and trapping efficiencies due to the wave-induced bed shear stress, corresponding resuspension and outflow of sediment along with the currents. It is therefore essential to include wind-driven resuspension in the analysis of bed level changes, especially in shallow lacustrine-type TFWs with large fetch lengths (chapters 2 and 5).

The effect of tidal range on net sedimentation rates is smaller than the effect of wind and river discharge; however this strongly depends on the location of the wetland in the delta (chapters 1 and 5). Coastal wetlands are almost completely controlled by tidal levels and range. For those systems, river discharge is a less important control of sedimentation rates than tidal dynamics. Further away from the coast, such as the *Brabantse Biesbosch*, river discharge, especially during discharge waves increasingly becomes a stronger control of wetland morphodynamics.

How climate change affects morphological developments and sedimentation rates

The effect of CC on morphology and sedimentation rates in TFWs was studied by means of two case studies: *Kleine Noordwaard* (chapter 3) and *Brabantse Biesbosch* (chapter 4). From the case studies, the following conclusions can be drawn with respect to the effects of CC:

1. In the *Kleine Noordwaard* tidal freshwater wetland, the simulated accretion rates (expressed in mm per year land rise) over the period 2015-2050 are significantly lower than the rate of sea level rise (SLR) for two extreme CC scenarios (with water levels corrected for SLR and river discharges corrected for changes in rainfall

and evaporation). This causes the study area to gradually convert to open water. Nevertheless, the increase in water depth leads to enhanced sedimentation on the channel banks and an elevated platform level of the flats (chapter 3).

2. Most of the morphological changes that take place in the *Kleine Noordwaard* study area over the scenario period (2015-2050) can be attributed to morphological stabilization of this relatively recently constructed area, and not to CC (chapter 3).
3. Present-day abiotic conditions in the *Kleine Noordwaard* study area do not lead to vegetation succession and bio-geomorphic feedbacks that may promote increased accretion rates. Instead, the considerable water depth and inundation frequency lead to vegetation die-off and corresponding increase in wind shear (chapter 3).
4. In the *Brabantse Biesbosch* tidal freshwater wetland, CC leads to a reduction in net sedimentation rates, caused by the more frequent overtopping of the diversion structures between the rivers and the wetland causing high bed shear stresses, in combination with the low SSC in the feeding river (chapter 4).

For other TFWs, the effect of CC on sedimentation rates may be very different. Unfortunately, direct comparisons are difficult because this research is one of the first where the impact of CC on the sediment budget of a microtidal freshwater wetland is quantified. Coastal wetlands often gain elevation at speeds similar to SLR due to ecogeomorphic feedback loops (French, 2006; Kirwan and Megonigal, 2013). These feedback loops only occur until a certain flooding threshold, beyond which the vegetation dies off and the feedbacks are stopped, causing wetlands to drown (Kirwan and Megonigal, 2013; Cahoon et al., 1995; Kirwan et al., 2010). For the *Kleine Noordwaard*, we speculate that design decisions made prior to the de-embankment in 2007 have led to an immediate overtopping of the flooding threshold, prohibiting such feedback that may have promoted accretion, but instead have led to large scale vegetation die-off. Given the predictions for the accretion rates in the area, *Kleine Noordwaard* study area is likely to further drown due to SLR.

How different configurations of wetland characteristics control sedimentation rates and trapping efficiencies

The key findings with respect to how wetland characteristics control sedimentation rates and trapping efficiencies in TFWs are the following:

1. Sedimentation rates are generally highest close to the inlets of the wetland and on the flats close to the channel system. Local sedimentation patterns are affected by irregularities in the topography, particularly former polder drainage channels that

act as sediment sinks and old embankments that alter flow patterns (chapters 2, 4 and 5).

2. Wetland characteristics affect the sedimentation rates inside TFWs as follows. They increase for a) a larger wetland length/width ratio, b) a longer and more complex channel network, c) larger channel width, d) a small angle between the main wetland direction and wind direction, e) lower wetland elevation and f) smaller inlets. Sedimentation in single inlet wetland areas is considerably smaller than in wetlands in which a water flow occurs across the wetland from a separate inlet to an outlet (chapter 5).
3. Interaction effects of wetland characteristics are largely the result of the non-linear relation between the water depth and the effect of the bed shear stresses due to wind and currents on sedimentation and erosion. The closure of the outlet is a dominant type of characteristic, because it effectively negates the primary effect of any other characteristic. Any characteristic that has a large effect on the water depth generally also causes large interaction effects (chapter 5).
4. The trapping efficiency of a TFW can be estimated based on four wetland-specific parameters, which are: the representative water depth, wetland orientation with respect to the main wind direction, the hydrologic load and the wetland length/width ratio. (chapter 5).

A main factor determining the trapping efficiency is the average water depth within the wetland. A relatively shallow TFW with one large inlet and a main flow direction opposite to the predominant wind direction has the lowest trapping efficiency. Deeper TFWs with a small inlet and a flow direction more or less the same as the dominant wind direction trap relatively more sediment. As the depth increases, the inlet size becomes an increasingly important control in the trapping efficiency, while the role of wetland orientation with respect to the predominant wind direction diminishes.

6.3 Recommendations for future research

With the methods and results presented in this thesis, further advances can be made in the modelling and understanding of hydro-morphological processes in tidal freshwater wetlands. However, the modelling experiences in this research gave rise to a number of issues that require further research. This section is dedicated to research recommendations that may solve these issues.

2D modelling of wetlands

Part of the research presented here was carried out with a high resolution curvilinear 2D model of the hydro-morphological processes in a TFW. With ever increasing opportunities in terms of data collection techniques and computational power, utilising such models becomes more and more feasible. On the positive side, such models usually offer accurate numerical solutions of the 2D shallow water equations as well as a wide range of sediment transport equations that can be used to model a wide range of morphodynamic processes. Furthermore, the newest generations of these models offer ever improving physically-based means to handle processes such as soil compaction, extra hydraulic shear stresses due to vegetation, and the impact of wind driven short waves on resuspension of fine sediment, all of which are processes that are important for wetland dynamics.

On the negative side, accurately solving the equations at the level of smaller channels or perturbations of the marsh platform requires a corresponding high-resolution grid that in turn leads to large calculation times. In this research, this proved to be a significant obstacle that required substantial model simplifications, especially in terms of processes included and complexity of the boundary conditions. While still in development, 2D models featuring unstructured grids instead of rectangular or curvilinear grids (used in this research) such as the D-FLOW FM model (Deltares, 2018) become more and more common, especially for non-morphodynamic simulations. Such models will allow the user to construct mixed high-low resolution grids, applying small grid cells only where needed (i.e. the channels), and using large cells in the rest of the area (i.e. the flats). Completion of these models, including morphology, structure formulations and wind-wave impact, is urgently needed because it will lead to both faster model construction with less time spent on boundary and process simplification and on grid construction, and shorter calculation times.

1D modelling of wetlands

For two practical reasons, part of this research was carried out with a 1D model of hydrodynamics and sediment transport instead of with a 2D model: first, a complete and calibrated 1D model of hydrodynamics in the main river system, including major Biesbosch channels, was already available and second, the 2D model used for the rest of this research (Delft3D) was impractical due to inherent limitations of a curvilinear grid: it would have required very small grid cells – and thus long calculation times - for the 2D curvilinear model to sufficiently represent hydrodynamics and sediment transport in the complex, braided channel network of the study area. This research however showed that the 1D model used instead also had some shortcomings, especially with respect to the accurate representation of sediment transport in a 1D system consisting of channels and flats. This is partly because of the inherent '2D' nature of the Biesbosch system, where the direction of water flows may be different under elevated flow conditions than under low-medium flow conditions. Another issue was an inherent aspect of any 1D model: the flow velocity is the same for the entire conveying part of the cross-section. If the floodplains or flats are included in the cross section, as was the case in the schematisation used in this research, it becomes impossible to separate net deposition on the flats from deposition in the channels. It is therefore recommended to further explore possibilities to model sediment deposition in channels and on flats separately in a 1D model, for example to model overbank deposition in riverine wetlands which are possibly less '2D' in nature than the area studied in this research.

Wind

When analysing sedimentation and erosion in tidal freshwater wetlands, it is important to take the effect of wind into account, especially in shallow lacustrine wetlands: in shallow wetlands with long fetch lengths, wind-generated short waves can lead to large scale resuspension and subsequent outflow of fine sediment, especially in flow-through wetlands. Adequate modelling of this process currently requires the use of a separate wave model such as SWAN (Deltares, 2014) to derive the wave parameters necessary to approximate wave related bed shear stresses. It is not always feasible to use such a coupled morphodynamic-wave model since they usually require very long calculation times. It would therefore be interesting to further explore options to quickly estimate these wind-wave parameters, similar to the research carried out by Bretschneider (1958) for wind waves over the continental shelf, but then applied to the situation of shallow, small water bodies and corrected for the presence of vegetation.

Vegetation

In the *Kleine Noordwaard* study area, the combination of a relatively large water depth on the flats and the constant removal of vegetation in the intertidal zone by grazing (cows and geese) has led to a system where feedbacks between morphodynamics and vegetation are largely non-existent. In more vegetated wetlands however, these feedbacks play a major role and cannot be neglected. In general, vegetation affects hydro-morphodynamics in numerous ways: it increases hydraulic shear stresses (e.g. Baptist et al., 2007), its root system increases erosion resistance

(Pollen and Simon, 2005), and it reduces wind-driven bed shear stresses (Suzuki et al., 2012).

More research on the modelling of these processes is needed, especially on the topic of erosion resistance due to the heterogeneity of plant root systems. Over the seasons, vegetation properties change through ecological processes such as seed dispersal, plant growth, succession and mortality (Solari et al., 2016), thereby necessitating the need to model the evolution of the wetland vegetation in conjunction with the wetland morphology. A similar model was recently developed for riparian vegetation in river corridors (van Oorschot et al., 2017). This model could be extended to include a number of wetland-specific representative vegetation types and tested for a tidal freshwater wetland. Challenges will arise from the fact the original model by van Oorschot et al. (2017) was developed for a highly dynamic floodplain with occasionally high flow velocities, coarser bed material (sand and gravel) and bed load transport, as opposed to a low-energy wetland system with low flow velocities and sediment transport dominated by the suspended transport of fine fractions.

Correlated boundary conditions

Studying the impact of CC on the morphology of tidal freshwater wetlands can be challenging because it requires a smart way of dealing with boundary conditions (i.e. river discharges, tides and wind) that are all important, change over time and are also statistically significantly correlated. In chapter 3, an approach was introduced to overcome this challenge. The approach consisted of first constructing synthetic yearly time series of discharge, water level, and wind with similar statistical properties (auto and cross correlations) as the original – but much longer - time series, and then carrying out transient yearly scenario runs for a certain number of years with gradually changing boundary conditions. Further research should focus on the applicability of this approach to assess long-term morphological changes in other areas where the boundary conditions are similarly correlated and change over time.

6.4 Implications for wetland management

Enhancing sedimentation is currently one of the main strategies to prevent wetlands from drowning due to sea level rise. This thesis provides insight in the processes that control sedimentation rates in tidal freshwater wetlands (TFWs), which may help to evaluate the effect of measures on sedimentation rates.

Because sedimentation rates in TFWs are controlled by the interplay between river discharges, tides, wind, and wetland characteristics, it is important to take these factors into account when evaluating proposed measures to enhance sedimentation in a drowning wetland. The factors also interact with each other, making it difficult to predict beforehand which measures will be most effective in enhancing sedimentation rates. This implies that there is not a single ‘perfect measure’ that can be applied everywhere to enhance sedimentation rates. For example, limiting the fetch length may significantly enhance net sedimentation, but only in lacustrine-type wetlands where resuspension of fine sediments by wind is a major driver of erosion. Another example is the construction of river diversions towards wetlands: this measure is only effective in case the SSC of the feeding river is sufficiently high to counteract the eroding effect of the incoming water flow. Otherwise, it may even lead to a drop in net sedimentation.

If the goal is to maximise the sediment trapping efficiency of an area, it is therefore advisable to thoroughly analyse the relative importance of the different hydro-meteorological controls and layout of the wetland before deciding on restoration measures. This can be done by monitoring key parameters (SSC, tidal range, discharges) at key locations (connections with feeding rivers) during selected events (average, neap and spring tidal cycle, range of river discharges, storm conditions) in order to determine how SSCs vary under different hydro-meteorological conditions. The layout of wetland is also important: small inlets (as opposed to one large inlet), a large intertidal zone, a flow direction more or less the same as the dominant wind direction, and facilities that limit fetch length (in case of lacustrine wetlands) all promote sedimentation.

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Dankwoord

Dit boekje had er nooit gelegen zonder de hulp van begeleiders, collega's, vrienden en familie in de afgelopen jaren. Die hulp was heel divers – van het passen op mijn dochter, Imme, zodat ik me terug kon trekken op zolder om verder te werken aan mijn proefschrift, tot het brainstormen over een innovatieve manier om met lange tijdreeksen om te gaan – en allemaal even waardevol voor mij. Op deze plek wil ik deze mensen persoonlijk daarvoor bedanken.

Allereerst mijn begeleiders. Hans en Marcel, jullie hebben mij op de juiste momenten een duwtje in de juiste richting gegeven. Ik dank jullie voor het vertrouwen dat jullie in mij hadden, de interessante discussies die we hebben gevoerd over velerlei onderwerpen, en de juiste begeleiding op die vlakken waar dat nodig was. Marcel, jouw stem klinkt nog steeds met regelmaat in mijn hoofd als ik aan het schrijven ben ("Dat kan veel korter!"), en dat bedoel ik dan positief. Hans, jouw laagdrempelige manier van begeleiding heb ik altijd enorm gewaardeerd: de deur stond bij jou altijd open, je was altijd redelijk, en ik heb nooit het gevoel gehad dat je je boven anderen plaatste. In veel opzichten was jij voor mij de ideale promotor. Maarten, jouw ongebreidelde enthousiasme en creativiteit heeft me op belangrijke momenten geholpen met het vinden van originele invalshoeken. Jouw reacties waren altijd op het scherpst van de snede geformuleerd ("klinkt epistemisch terwijl ik hier ontologisch wil weten."), en daar heb ik altijd enorm om moeten lachen ☺. Dank voor dat alles! Ten slotte Kees, jij was voor mij een onuitputtelijke bron van kennis voor wat betreft het opzetten van morfologische modellen, en als je iets onverhoopt niet bleek te weten, wist je wel precies bij wie binnen Deltares ik moest gaan shoppen om kennis. Mijn dank daarvoor!

Mijn onderzoek is uitgevoerd in het kader van NWO/STW project 'Delta Engineering: drowning or emerging'. Bij deze dank ik alle leden van de begeleidingscommissie voor jullie enthousiaste en nuttige input gedurende het hele project. Hans de Boois, dank voor al je hulp 'in het veld'. Karianne van der Werf voor het mooie onderzoek dat je hebt uitgevoerd naar de invloed van vegetatie op de morfodynamica van de Kleine Noordwaard. Dank aan een heleboel collega's van Deltares die me hebben geholpen. Bij naam noem ik Bert Jagers voor je hulp bij Delft3D, Sofia Caires voor je hulp bij WAVE en Henk van den Boogaard voor je hulp bij de statistiek van langjarige reeksen.

Daarnaast dank ik Hanneke van der Klis, Gerard Blom en Lucas Janssen, voor het mogelijk maken van mijn onderzoek. Ten slotte dank aan Eveline: dank voor je vele veldbezoeken waarin je de noodzakelijke gegevens hebt verzameld voor ons beider onderzoek, en daarnaast voor het wegwijs maken in de wondere wereld van regeltjes en weetjes van de Universiteit Utrecht.

Vervolgens wil ik iedereen bedanken die mij niet direct hebben begeleid, maar zeer zeker wel op een andere manier (al dan niet bewust) hebben geholpen. First of all my paranimfen, Andre and Daniel: thank you both for supporting me during my defence! I am sure everything will go smoothly thanks in no small part to your stupid jokes, which I know for a fact you are both very capable of making. Next, a big thanks to my office mates at the university the last years: Jude (Dutch coffee break etiquette!), Daniel (sorry about the whiteboard!) and Sebastian ("is dit slagerij van Kampen?"), for generally being very good office mates and/by making stupid jokes. Thanks to all colleagues at the coffee machine for the very-frequent-indeed coffee breaks, which, admittedly, I did not frequent very often but rather enjoyed when I did. Marcel voor het geweldige veldwerk in Belgie, Duitsland & Zwitserland, waar ik veel van je heb geleerd over de ontstaansgeschiedenis van de Rijndelta.

Pa en ma, jullie hebben me altijd gesteund en geholpen. Ik ben jullie heel erg dankbaar voor al die keren dat jullie op Imme hebben gepast zodat ik extra tijd had voor mijn onderzoek; ik heb goede herinneringen aan het werken op pa's kamer en jullie beneden met z'n drieën plezier te horen maken, om vervolgens 's avonds tijdens een goede maaltijd de dag door te nemen. Harald en Cathrien, hartelijk dank voor jullie support op velerlei vlakken de afgelopen jaren. Dat er nog maar vele Sinterklazen (en chocolade!) samen mogen volgen!

Mijn kleine Imme. Jij leert me op een frisse manier te kijken naar de wereld om me heen. Beslommeringen op de werkvloer waren zo vergeten als ik aan het einde van de middag het kinderdagverblijf binnenliep en jij op me af kwam rennen. '..papa is boven…' zei je het afgelopen jaar zo vaak, als ik weer eens op zolder zat te werken in het weekend. Wel, dat is nu gelukkig voorbij!

Ten slotte mijn lieve Karen. Dank voor al je liefde. Dank voor al je steun, bij teveel dingen om op te noemen!

Rijswijk, 26 oktober 2018.

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Verschelling, E., van der Deijl, E. C., van der Perk, M., Sloff, K., and Middelkoop, H. (2017), Effects of discharge, wind, and tide on sedimentation in a recently restored tidal freshwater wetland, Hydrol Process, 31(16), 2827–2841. DOI:10.1002/hyp.11217.

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About the author

Eelco Verschelling was born on the 24th of October, 1972, in Leiden, The Netherlands. He studied at the faculty of Civil Engineering at Delft University of Technology, and finished his Master of Science (MSc) in 1999 with a specialization in Hydrology. For his thesis, he developed a new model concept for rainfall-runoff and erosion processes in steep catchments in the Philippines. He has been employed at Deltares (previously Delft| Hydraulics) since 1999. During his career, he developed a strong preference for research & consultancy projects in developing countries, which gave him the opportunity to train others in the topics he is passionate about: hydrology, hydraulics, and how to set up numerical models of these processes. Always working together with local counterparts, his role in those projects has mostly been the supervision of hydrologic/hydraulic model construction, quality control and knowledge transfer. In 2013, he accepted a part-time PhD position at Utrecht University next to his job at Deltares in order to contribute to scientific understanding of the morphology of freshwater wetlands. Through this research project, he got further acquainted with hydrodynamics and morphology in areas affected simultaneously by river discharge and tides, and improved his academic writing skills. Now that he has (almost) finished his PhD project, he will continue to work at Deltares.

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ISSN 2211-4335