

## **Contents of Author's Response**

This document starts with the point-by-point response to the first referee of the second stage of review. This response is followed by a marked-up manuscript, which shows all the changes with respect to the first revision of the discussion paper. These comments and the new version of the manuscript have been taken on board in the evaluation of the second referee in this second stage of review. The second part of this document contains again the point-by-point response to the comments of this referee, and then the marked-up manuscript version showing all the changes with respect to the first second stage revision of the manuscript (mentioned above).

1. response to review 1 round 2
2. manuscript with track changes version 2a
3. response to review 2 round 2
4. manuscript with track changes version 2b

## Response to Reviewer #1, ESurf2017-22 revised

This paper has improved a lot. It is much clearer how things are calculated. However, I still have some difficulties with the calculation of the total sediment budget and the trapping efficiency. Although a major focus of this paper is on this trapping efficiency, this is not discussed properly.

The major focus of this paper is on the sediment budget of the study area. Although we attempted to determine the sediment trapping efficiency by combining the data presented in this manuscript with data from the upstream monitoring station at Lobith, we do not agree that trapping efficiency is a major focus of the manuscript. Given the issues about the calculated trapping efficiency raised by the reviewer (as discussed below), we have decided to remove this calculation of the trapping efficiency from the manuscript and - where relevant – refer to the trapping efficiency derived for the study area reported in a previous study (Van der Deijl et al., 2017)

The authors now describe the incoming and outgoing discharge at both the north and south inlet of the study site. But what is done with this information? The inflow in the south seems limited: 16 m<sup>3</sup>/s when water rises rapidly. So this inflow can be ignored? An estimate of this inflow to illustrate this could be useful. In- and outflow discharge is slightly different. Are there other outlets? Is this within the error of the measurements? No info is given

In response to the reviewers' comments on the previous version of this manuscript, we added the incoming and outgoing discharge and suspended sediment concentrations at the north and south inlet of the study site to the study site description to characterise the area, not to calculate a sediment budget in this paper. Apparently, and unfortunately, reporting the average discharges and sediment concentrations at both the inlet and outlet of the study area gave rise to some confusion because these are slightly different. The reason for this difference is that the water flow reverses at both the inlet and outlet during short periods of time – there are no other outlets in the central part of the study area. The relevance of this in the context of this paper is small, since we did not use these numbers for the calculations of the sediment budget. We have removed the discharges and concentrations for the outlet of the area. Instead, we added the average outgoing discharge in the north and the fraction of the time that outflow at the upstream location and inflow at the downstream location takes place.

**In and outflow discharges and concentrations are given, so based on this, trapping efficiency can easily be made. Why is this not done and discussed? With 89 m<sup>3</sup>/s and 26mg/l at inflow, and 86m<sup>3</sup>/s and 19mg/l at outflow, you get 30% trapping, half of what is in this paper. During peak events, with 191 m<sup>3</sup>/s and 114 mg/l at inflow and 178 m<sup>3</sup>/s and 62 mg/l, you get 50%. Would be interesting to discuss this.**

The simple calculation of the sediment trapping efficiency as suggested by the reviewer yields a biased outcome as the reported suspended sediment concentrations are time-averaged concentrations and not discharge weighted concentrations. The trapping efficiency for the period between July 2013 and March 2014 was already derived in the previous study by van der Deijl et al. (2017). We now refer to this trapping efficiency.

**The paper refers to the total load of the River Rhine at the German border. Now some additional information is given, but I still wonder how relevant this is. The SSC increases from 15 mg/l at the border to 26 mg/l at the inlet of the site. So on its way to the site, the water clearly changes a lot. Is there a nice correlation for SSC between both sites? During peak discharges, SSC increases 10fold at the German border, but only 5fold at the study site. How are SSC and sediment load at the border and the site correlated? With the provided information, I have strong doubts whether you can use the average 5.8%, calculated for the period July 2014 – March 2015, to the entire study period to calculate the incoming sediment load. Especially given the major peak discharge in 2011. What was the effect of this for the study site? During this event, the total sediment load passing the border was as big as the load of an entire year!**

As mentioned above, given the issues and uncertainties of the calculation of the sediment trapping efficiency for the study area based on the measured long-term sedimentation and the data of discharge and suspended sediment at the upstream Lobith monitoring station, we have decided to remove this calculation from the manuscript (both from the methods and results section). We now only refer to the trapping efficiency of the study area as reported by Van der Deijl et al. (2017) (in the introduction and discussion sections).

# Establishing a sediment budget in the newly created ‘Kleine Noordwaard’ wetland area in the Rhine-Meuse delta

Eveline Christien van der Deijl<sup>1</sup>, Marcel van der Perk<sup>1</sup>, and Hans Middelkoop<sup>1</sup>

<sup>1</sup>Faculty of Geosciences, Universiteit Utrecht, The Netherlands.

*Correspondence to:* E. C. van der Deijl (E.C.vanderDeijl@uu.nl)

**Abstract.** Many deltas are threatened by accelerated soil subsidence, sea-level rise, increasing river discharge, and sediment starvation. Effective delta restoration and effective river management require a thorough understanding of the mechanisms of sediment deposition, erosion, and their controls. Sediment dynamics has been studied at floodplains and marshes, but little is known about the sediment dynamics and budget of newly created wetlands. Here we take advantage of a recently opened tidal freshwater system to study both the mechanisms and controls of sediment deposition and erosion in newly created wetlands. We quantified both the magnitude and spatial patterns of sedimentation and erosion in a former polder area in which water and sediment have been reintroduced since 2008. Based on terrestrial and bathymetric elevation data, supplemented with field observations of the location and height of cut banks and the thickness of the newly deposited layer of sediment, we determined the sediment budget of the study area for the period 2008-2015. Deposition primarily took place in channels in the central part of the former polder area, whereas channels near the inlet and outlet of the area experienced considerable erosion. In the intertidal area, sand deposition especially takes place at low lying locations close to the channels. Mud deposition typically occurs further away from the channels, but sediment is in general uniformly distributed over the intertidal area, due to the presence of topographic irregularities and micro topographic flow paths. Marsh erosion does not significantly contribute to the total sediment budget, because wind wave formation is limited by the length of the fetch. Consecutive measurements of channel bathymetry show a decrease in erosion and deposition rates over time, but the overall result of this study indicate that the area functions as a sediment trap. ~~On average, the area traps approximately 55 % of the sediment delivered to the study area, which is approximately 3 % of the sediment load of the River Rhine at the Dutch-German border.~~ The total sediment budget of the study area amounts to  $37.3 \cdot 10^3 \text{ m}^3 \text{ year}^{-1}$ , which corresponds to a net area-averaged deposition rate of  $6.4 \text{ mm year}^{-1}$ . This is enough to compensate for the actual rates of sea-level rise and soil subsidence in The Netherlands.

## 1 Introduction

Many deltas in the world cope with drowning and loss of delta land due to flood protected polders, dams, and embankments of channels, which result in accelerated soil subsidence and sediment starvation (Ibáñez et al., 1997; Syvitski and Saito, 2007; Ibáñez et al., 2014). The urgency of this problem is enhanced by sea-level rise (Syvitski, 2008) or increasing river discharge. Most deltas are valuable and densely populated, because of their ideal location for harbours, agriculture, aquaculture, and tourism (Kirwan and Megonigal, 2013; Ibáñez et al., 2014). Moreover, they encompass vast wetland areas of great ecological

value. Traditional approaches in river management aim at reducing flood risks by constructing dikes and dams. Although such constructions are often effective in reducing flood risks, they disrupt the morphodynamic processes and ecological functioning of the system, increase sediment starvation, and involve high costs for construction and maintenance (Hudson et al., 2008). Therefore, since recently, river delta management has been shifting from the implementation of these strong regulations towards the control of a more natural system where dynamic processes are restored and the system becomes multifunctional. Examples include the Tidal River Management project in Bangladesh (Khadim et al., 2013), the diversion projects in the Mississippi deltaic plain (DeLaune et al., 2003; Day et al., 2007; Paola et al., 2011), the Plan Integrale de Protección del Delta Ebro in the Ebro Delta (Calvo-Cubero et al., 2013) and the Room for the River initiative in the Netherlands (Rijke et al., 2012).

Paola et al. (2011) defined river delta restoration as diverting sediment and water from major channels into adjoining drowned areas, where the sediment can build new land and provide a platform for regenerating wetland ecosystems. Delta restoration is effective when sedimentation compensates for sea-level rise and soil subsidence. Table 1 summarizes sedimentation rates determined in various types of delta compartments representing different depositional environments. Sedimentation is variable and complex. This table suggests that sedimentation is positively related to the suspended sediment concentration. Furthermore, it is widely known from the literature that sedimentation is controlled by the frequency and duration of inundation (French and Spencer, 1993; Middelkoop and van der Perk, 1998; Reed et al., 1999; Temmerman et al., 2003; Thonon et al., 2007), the suspended sediment concentration in the feeding channel (Asselman and Middelkoop, 1998; French and Spencer, 1993), and the ability of sediment to settle, which is in turn controlled by vegetation (Darke and Megonigal, 2003; Temmerman et al., 2005b; Schile et al., 2014; Mitsch et al., 2014), the flow paths to or within the wetland/compartment (French and Spencer, 1993; Siobhan Fennessy et al., 1994; Reed et al., 1999; Davidson-Arnott et al., 2002; Temmerman et al., 2003; Anderson and Mitsch, 2007; Mitsch et al., 2014), and the residence time within the compartment (Asselman and Van Wijngaarden, 2002). Although considerable research has been devoted to sedimentation in wetlands in coastal deltas and river floodplains, remarkably few empirical field studies have been reported on the initial formation and evolution of newly created wetlands.

In the present study, we take advantage of a recently opened tidal freshwater system to study the sediment deposition or erosion in newly created tidal wetlands. In the framework of the Room for the River (RfR) initiative in the Netherlands, water and sediment have been reintroduced in previously embanked areas in the Biesbosch, a Tidal Freshwater Wetland (TFW) in the south-west of The Netherlands. This paper presents the first results of a larger field research project examining mechanisms and controls of sediment deposition and erosion in the Biesbosch tidal freshwater wetland.

The aim of this paper is to quantify both the magnitude and the spatial patterns of sediment deposition and erosion in one of the formerly embanked areas, 'Kleine Noordwaard'. For this, different sources of data were combined. Net sedimentation rates were determined from existing bathymetric data collected by a multibeam echosounder, existing LiDAR digital elevation models, supplemented by field observations of the thickness of the newly deposited sediment layer and field observations of the location and height of cut banks. From this we developed a medium-to-long term sediment budget for the Kleine Noordwaard. In this paper, we compare the rates and patterns of sedimentation and erosion in the study area to those in other wetlands, assess the relative contribution of geomorphological processes in the study area, and discuss practical implications for the management of newly created tidal freshwater wetlands.

## 2 Methods

### 2.1 Study area

The Biesbosch National Park is a 9000 ha freshwater tidal wetland in the lower Rhine and Meuse delta in the southwest of The Netherlands (see Fig. 1a and b). The area was reclaimed in medieval times, but it became completely inundated by the St. Elisabeth flood, which was a combination of two storm surges and two floods of the River Rhine between 1421 and 1424 (Zonneveld, 1959). In the subsequent two centuries, a deltaic splay developed of approximately 6 m thick (Kleinhans et al., 2010). The lower 4 m of this splay is sand, covered by 2 metres of clay (De Bont et al., 2000). In 1861 AD, the Nieuwe Merwede, an artificial branch of the River Rhine, was excavated through the area. As a consequence, water levels dropped and large parts of the wetland were embanked and reclaimed as polders for agriculture during the second half of the 19th century (De Bont et al., 2000; Bureau Noordwaard, 2006). However, since 2008, several of these polder areas have been re-opened for river water ('depoldered') to increase the discharge capacity of the River Rhine. The study area of the Kleine Noordwaard was among the first polder areas that have been depoldered.

The Kleine Noordwaard study area comprises the former Spiering, Oude Hardenhoek and Maltha polders (Fig. 1). Maps (c) and (d) represent the surface elevation before and after depoldering of the study area. In 2008, several channels with a width of 120 m, a maximum depth of 3 m and a side slope of 1:20 (Fig. 2) were dug throughout the area. The sandy material was used to create islands and extra protection along the embankments (Grontmij, 2002). The original clayey polder soil remained conserved, except in the former Spiering and Maltha polders, where the upper layer of clay had already been removed for reinforcement of embankments. On 7 May 2008, the embankments were opened and the channels were connected to the River Nieuwe Merwede in the north and to the Gat van de Noorderklip in the south. The major flow direction is from north to south, and water and sediment are supplied by the River Nieuwe Merwede, which is a branch of the River Waal, the major tributary of the River Rhine (Fig. 1). The River Rhine has an average discharge of  $2200 \text{ m}^3 \text{ s}^{-1}$  and an average suspended sediment concentration of  $15 \text{ mg l}^{-1}$  at the German-Dutch border located 85 km upstream from the Kleine Noordwaard. Peak discharges typically occur during the winter season and they range between  $5800$  (1-year-return) and  $9670 \text{ m}^3 \text{ s}^{-1}$  (10-year-return) with maximum concentrations between  $120$  and  $260 \text{ mg l}^{-1}$  (Rijkswaterstaat, 2016). ~~Field measurements of water levels, flow velocities, and turbidity, carried out in the period July 2014–March 2015 (van der Deijl et al., 2017)~~

~~Van der Deijl et al. (2017) have shown that water is in general imported in the north with an average discharge of . Their field measurements in the period between July 2014 and March 2015, indicated that the time-averaged inflow of water from the Nieuwe Merwede through the former Spiering polder into the Oude Hardenbroek polder amounted  $89 \text{ m}^3 \text{ s}^{-1}$  and an average concentration of  $26 \text{ mg l}^{-1}$ , with a maximum of  $191 \text{ m}^3 \text{ s}^{-1}$  and . The time-averaged suspended sediment concentrations amounted to  $26 \text{ mg l}^{-1}$  with a maximum of  $114 \text{ mg l}^{-1}$  during a raised discharge event ( $4500 \text{ m}^3 \text{ s}^{-1}$  at the German-Dutch border). In the south water is in general exported with an average discharge of  $86$  The water flow direction at the northern inlet of the Oude Hardenbroek polder reverses during short periods at the onset of ebb tide, which occurred only during 2.2% of the time. During this time, the outgoing average discharge was on average  $11 \text{ m}^3 \text{ s}^{-1}$  and an average concentration of  $19 \text{ mg l}^{-1}$ , with  $178 \text{ m}^3 \text{ s}^{-1}$  and  $62 \text{ mg l}^{-1}$  during In the south, water is generally exported, but under conditions of rapid rise of the raised~~

~~discharge event. Import, with a maximum of  $16 \text{ m}^3 \text{ s}^{-1}$ , only takes place when the~~ water level rises rapidly at the onset of flood tide~~-, the flow reverses. In the observed period this occurred only during 0.3% of the time with a maximum discharge of  $16 \text{ m}^3 \text{ s}^{-1}$ . Van der Deijl et al. (2017) determined the sediment trapping efficiency to be 0.29 during the above measurement period.~~

The water level is influenced by the tide, which is mixed semidiurnal with a range of approximately 0.2 to 0.4 m (Rijkswaterstaat, 2016), the wind direction and speed, the discharge of the River Rhine, and the artificially controlled discharge through the gates of the downstream Haringvliet barrier into the North Sea. Water levels are on average 0.63 m above Dutch Ordnance Datum (NAP), with a mean low water (MLW) of 0.45 m NAP and a mean high water (MHW) of 0.79 m NAP (Rijkswaterstaat, 2016). Approximately 29% of the area is comprised of subtidal area (surface elevation  $<0.125 \text{ m}$  NAP, always submerged), 36% of intertidal flats ( $0.125\text{-}0.63 \text{ m}$  NAP, submerged  $>44\%$  of the time), 6% of low marshes ( $0.63\text{-}0.79 \text{ m}$  NAP, submerged for 19 - 44% of the time), 22% of high marshes ( $0.79\text{-}2.3 \text{ m}$  NAP, whereby areas  $>1.1 \text{ m}$  NAP are only submerged for less than 5% of the time), and 7% of a terrestrial zone (see Fig. 2). In order to reduce the hydraulic roughness, the marshes and terrestrial zone are mown before the winter period, and most of the vegetation is effectively shortened through grazing by birds, horses, and cows. The vegetation can be classified as dry and wet grasslands with at the shoreline some *Mentha aquatica*, *Schoenoplectus triquetus* and *Bolboschoenus maritimus*. The mud flats are almost bare with some pioneer species such as *Hydrodictyon reticulatum*, *Limosella aquatica*, *Veronica anagallis-aquatica* and *Pulicaria vulgaris*. In the summer, grows locally some *Myriophyllum spicatum* in open water (De la Haye, 2011).

## 2.2 Field methods

The sediment budget of the study area is established from the average net sedimentation in navigable channels (approximately 25% of the study area), the average sedimentation in the subtidal area ( $<0.125 \text{ m}$  NAP, excluding channels), sedimentation in the intertidal area (flats and marshes), and the eroded volume of the marsh edge. We first determined the volumetric budgets, which were subsequently converted to mass budgets using sediment densities measured from field samples.

### 2.2.1 Channels

The change in surface elevation over multiple years was used to determine the sediment budget and the spatial pattern of sedimentation and erosion in the navigable channels. Surface elevation was measured by Rijkswaterstaat during consecutive bathymetric surveys in all channels in 2009, 2010, 2012 and 2015. In 2011, 2013 and 2014, additional channel sections were surveyed (see Fig. 1 d). The 2009 -2015 measurement period was hydrologically characterised by a major flood between 8 and 19 January 2011 with a peak river discharge of  $8315 \text{ m}^3 \text{ s}^{-1}$  and an elevated SSC of up to  $260 \text{ mg l}^{-1}$  at Lobith. Channel bed elevation was measured with a multi-beam Simrad EM3002d echosounder, combined with Netpos/LRK, and processed in QPS Quincy 8.0 (personal communication, Rijkswaterstaat). The total volumetric channel sediment budget was calculated from the difference in channel bed elevation between 2009 and 2015. Some channel sections were dredged in 2015 and were therefore excluded from the 2015 bathymetric map. The sediment budget was corrected for this exclusion by the linear relationship between the total channel sediment budget and the channel budget without the dredged area. To analyse rates of net sedimentation and erosion of sediment over time, we used only areas from which data were collected during all surveys

of 2009, 2010, 2012 and 2015. Survey data collected in the years of 2011, 2013 and 2014 were only used to assess whether changes in bed level had been consistent throughout the years.

### 2.2.2 Subtidal and intertidal area

We determined the sediment budget of both the subtidal and the intertidal area by measuring the sedimentation on top of the former polder soil during field campaigns in July and October 2014. The former polder soil consists of a compact non-erodible layer of clay, which was used as marker horizon, since its colour and density are clearly distinguishable from the recently deposited sediment (sand and mud). Transparent Perspex core samplers with a diameter of 59 mm and different lengths were used to collect 126 samples of the newly deposited sediment layer in 9 transects across the central part of the Kleine Noordwaard (pink aligned area in Fig. 1). The Spiering and Maltha polders were not sampled because the non-erodible layer of clay was removed before depoldering. The thickness of the newly deposited sediment layer was measured using a ruler. In the field the texture of the sediment was classified visually as clay, sandy clay, coarse sand, fine sand, silty sand, sandy silt, or silt. Based on these texture classes, the sediment layers were classified into former polder bed (clay, sandy clay), newly deposited sand (coarse sand, fine sand, silty sand) and newly deposited mud (sandy silt or silt). Since channels were dug and sand was replaced by depoldering of the area, we selected only samples with a base of former polder clay for further analysis. Furthermore, samples with sand on top of the base of former polder clay were corrected for the replacement of sand for depoldering. The elevation at the sample location was used to separate the samples in datasets for the subtidal and intertidal area. The total sediment budget of the subtidal area was calculated by multiplying the average thickness of the recently deposited sediment layer from samples located below 0.125 m NAP by the total subtidal area. The total sediment budget of the intertidal area was calculated using a negative exponential relation between sediment deposition and surface elevation.

### 2.2.3 Marsh erosion

To determine the contribution of marsh erosion to the budget of the channels and intertidal area, we measured the height and position of cut banks using a ruler and a Trimble R8 RTK GPS during field campaigns in July and October 2014. The current cut bank position and height were compared to the 2011 50 cm resolution digital elevation model of the Netherlands (AHN2), to calculate the volume of eroded land over the period 2011-2014.

### 2.2.4 Sediment budget and trapping efficiency

The total sediment budget of the study area was calculated by taking into account the different periods for which the individual budgets of the channels, the subtidal and intertidal area, and the eroded marshes were established. To obtain the total mass of the deposited sediment in the area, the volumetric sediment budget of the area was multiplied by the bulk density of the deposited sediment. Bulk density of sand, deposited in the channels, was determined gravimetrically by the weight of the terrestrial sediment in a pF-ring with volume of 98.125 cm<sup>3</sup>. To determine the bulk density of the mud, a 59 mm diameter



Transparent Perspex core sampler was used to collect a 7 cm core with 4 cm of organic rich mud and the underlying former polder clay at the intertidal flat, because a pF-ring could not be applied to mud. The core was subsampled at a 1 cm interval in the laboratory, and bulk density was determined by the weighted average sediment particle density and the volumetric moisture content of the samples. Moisture and organic matter content were determined from the difference in mass after oven drying at 105 °C and loss-on-ignition analysis at 550 °C, according to the standard techniques described by Heiri et al. (2001).

~~The trapping efficiency of the area was determined as the percentage of the sediment load supplied to the entrance of the study area. This sediment load was estimated using discharge and suspended sediment measurements at the entrance of the study area between July 2014 and March 2015 at a 10 minute interval (van der Deijl et al., 2017), which indicated that the area received approximately 5.8 % of the total sediment load of the River Rhine. The sediment load of the River Rhine was determined from discharge measurements (10 minute interval) and daily suspended sediment concentration (SSC) at the Rijkswaterstaat Lobith gauging station near the Dutch-German border (Rijkswaterstaat, 2016).~~

### 3 Results

#### 3.1 Bulk density

Sediment samples indicate a bulk density of 1.47 g cm<sup>-3</sup> for sand and a logarithmic increase with depth from 0.75 to 1.27 g cm<sup>-3</sup> for the 3 cm of mud at the intertidal flat. A maximum density of 1.5 g cm<sup>-3</sup> was found in the compacted former polder clay at the bottom of the core. To convert the sediment thickness to sediment mass per unit area bulk density values of 0.75, 0.94, 1.27, and 1.34 g cm<sup>-3</sup> were assigned to the respective 0-1, 1-2, 2-3, and > 3 cm depth intervals. For the sandy sediment deposited in channels or eroded from the island, we used a bulk density of 1.47 g cm<sup>-3</sup>. The organic matter content, varied between 3.9 and 4.3 % for the former polder clay and between 2.9 and 4.3 for the mud at the intertidal flats.

#### 3.2 Channels

Figure 3 shows the change in channel bed level and the yearly averaged cumulative change in channel bed volume in the central part of the area Kleine Noordwaard (pink and green areas in Fig. 1) from north to south both for the successive monitoring campaigns (a, b, c and d) and for the entire period (e). The northern part of the area (the inlet) is characterized by a negative sediment budget, due to the loss of sediment within the Spiering polders (purple in Fig. 1). Fig. 4a shows the bathymetric development of cross section 1, which represents the development of the channel near the inlet of the study area. The cross sectional area of the inlet has increased by bank erosion in the outer bend of the channel to the depth of the River Nieuwe Merwede. The maps in Fig. 3 show that outer bend erosion has occurred in the majority of the channels and that bars have developed at the end of these bends. The first outer bend of the single channel at the outlet of the study area has migrated by approximately 35-40 m in eastern direction. A steep cut bank has developed and concomitant sedimentation of a point bar occurred at the convex inner bend and at the end of the bend. Consequently, the second bend has migrated by approximately 20-30 m in western direction. Although the channel at the outlet of the study area has become 5-10 m wider, the width to depth

ratio decreased from 22.9 to 18.3 due to channel deepening. However, the channels are not able to migrate freely due to steep banks of dikes armoured by riprap, and the average width to depth ratio of the channel has decreased from 17.9 to 15.2.

Within 500 m from the inlet of the central part of the Kleine Noordwaard, the cumulative change in bed volume turns positive. Thus, the amount of sediment eroded in the Spiering polders and near the inlet of the central part of the Kleine Noordwaard is deposited in this area. Further downstream, the cumulative change in channel bed volume increases further reflecting the positive sediment budget of the Wassende Maan area (blue in Fig. 1). In contrast to the area near the inlet of the study area, the channels in the central part of the area have become shallower (see Fig. 4b) and width to depth ratios have increased from 20.3 to 21.9 for the through-flowing channels and from 6.4 to 6.8 for dead-ending channels.

The temporal trend in annual average eroded and deposited sediment volumes is shown in Fig. 5 for the inlet (a), the centre (b), and the outlet (c) of the study area (represented by channel section 1; sections 2-9; and section 10 in Fig. 1). Both the annual amounts of erosion in the channels near the inlet and outlet, and the annual amounts of sedimentation in the centre of the area have decreased over time. This suggests that the channels tend to morphodynamic equilibrium. The decrease in the average net erosion at the inlet and outlet (black line in Fig. 5) is caused by the decrease in the average erosion rate (red in Fig. 5), since the average sedimentation rate (blue in Fig. 5) remains constant over time. The erosion rate has decreased over time because the channels reached the same depth as the River Nieuwe Merwede. The response time of the erosion (i.e. the time needed to reduce the net erosion rate by 63 %) is approximately 2.2 years for the entrance, and 3.3 years for the outlet. The response time of the net sedimentation for the central part of the system is 3.1 years. The response time for net sedimentation in the entire area is 6.5 years. This value is however less accurate as it is based on only three instead of six monitoring intervals.

Although the cumulative channel sediment budget decreases from north to south due to erosion at the outlet of the area, the total channel sediment budget is positive for most periods. The total yearly sediment budget was only negative for the period between the monitoring campaigns of September 2010 and March 2011. This monitoring period includes a discharge event that occurred between 8 and 19 January 2011 with a peak river discharge of  $8315 \text{ m}^3 \text{ s}^{-1}$  and an elevated SSC of up to  $260 \text{ mg l}^{-1}$  at Lobith. Apparently, this event triggered large changes in bed level during this monitoring period. The bathymetric maps in Fig. 3 and the bathymetric development in Fig. 4b show increased rates of sedimentation in the centre of the area during the discharge event. This increased sedimentation occurred at both the inner and outer bend of channels, while the bed level of the outer bend was eroded during other periods. The average change in bed level of the channels decreased from  $18.5 \text{ mm year}^{-1}$  to  $15.4 \text{ mm year}^{-1}$  and  $12.6 \text{ mm year}^{-1}$ , for the consecutive measurement intervals 2009-2010, 2010-2012 and 2012-2015. These changes in bed level correspond to a net sedimentation of  $21.7 \cdot 10^3 \text{ m}^3 \text{ year}^{-1}$ ,  $18 \cdot 10^3 \text{ m}^3 \text{ year}^{-1}$  and  $14.8 \cdot 10^3 \text{ m}^3 \text{ year}^{-1}$  and annual average sediment budgets of  $32.4 \text{ kton year}^{-1}$ ,  $26.9 \text{ kton year}^{-1}$  and  $22.1 \text{ kton year}^{-1}$ , respectively. The average channel sediment budget for the entire monitoring period (2009-2015) accounts for a net sedimentation of  $14 \text{ mm year}^{-1}$ , which corresponds to  $16.7 \cdot 10^3 \text{ m}^3 \text{ year}^{-1}$  and  $24.9 \text{ kton year}^{-1}$ .

### 3.3 Subtidal and intertidal area

Figure 6a shows the spatial variation of the measured sedimentation in the subtidal and intertidal area, and Fig. 7 shows the sedimentation for increasing distance to the inlet of the polder area (i.e. the source of the sediment) (graph a); distance

from the channel (graph b); and elevation (graph c). Although the highest sedimentation was measured along the channels, there is no significant relation between the total sedimentation and the distance to the channel. This is likely partly due to the relatively high sedimentation ( $>5$  cm) at the transition from the tidal flats to the marshes of the island in the centre of the area at a distance of approximately 240-270 m from the channel. These high sedimentation rates are probably caused by the redistribution of sediment eroded from the marshes of the island. Although there is no significant relation between the total sedimentation and the distance to the channel, field observations of the texture of the sediment layers indicated that the percentage of mud increases and the percentage of sand decreases with increasing distance to the channel. Furthermore, Fig. 7c. shows that the total sedimentation generally decreases with increasing height of the tidal area. This relation is significant but it explains only 9 % of the variation in sedimentation. However, local variation in sedimentation is large and is probably resulting from local topographic irregularities as mudflat runnels and old furrows, which are not accounted for in the digital elevation model of the area, which has a resolution of 1 m.

Between May 2008 and October 2014 an average of  $73 \pm 9.1$  mm (standard error of mean) of mud and sand, is deposited in the subtidal area. This corresponds to a sedimentation rate of  $11.3 \pm 1.4$  mm year<sup>-1</sup> and an annual average sediment budget of  $5.21 \cdot 10^3$  m<sup>3</sup> year<sup>-1</sup> and 6.24 kton year<sup>-1</sup>. The sediment budget of the intertidal area amounts  $15.7 \cdot 10^3$  m<sup>3</sup> year<sup>-1</sup> and 22.4 kton year<sup>-1</sup>.

### 3.4 Marsh erosion

Fig. 6b. shows all cut banks, observed in the study area in 2014. Cut banks are most abundant along the marshes of the island in the centre of the system. These cut banks are located in line to those channels with a relatively long fetch for waves formed by the abundant south-westerly winds. The only cut bank formed by channel migration due to outer bend erosion, is located along the channel in the Maltha polder. Comparison of the observed cut bank position and the 2011 digital elevation model of the area indicates that only 31 m<sup>3</sup> of the island eroded between 2011 and 2014. The eroded volume is  $-10.3$  m<sup>3</sup> year<sup>-1</sup>, which corresponds to an erosion of 15.4 ton year<sup>-1</sup>.

### 3.5 ~~Total sediment~~ Sediment budget ~~and trapping efficiency~~

Between 2008 and 2015, the total sediment budget for the 'Kleine Noordwaard' area amounted to  $37.3 \cdot 10^3$  m<sup>3</sup> year<sup>-1</sup>, which corresponds to a net area-averaged sedimentation rate of 6.4 mm year<sup>-1</sup> and an import of 46.8 kton year<sup>-1</sup> for the first 6.5 years after depoldering. Sedimentation of  $16.7 \cdot 10^3$  m<sup>3</sup> year<sup>-1</sup> in the channels accounts for approximately 44 percent of the total budget. The vast majority of the remaining 56 % comprises the annual sedimentation of  $5.2 \cdot 10^3$  m<sup>3</sup> year<sup>-1</sup> and  $15.8 \cdot 10^3$  m<sup>3</sup> year<sup>-1</sup> in the subtidal and intertidal area. Remobilization of sediment by erosion of marshes occurred at a negligible rate of about  $-10.3$  m<sup>3</sup> year<sup>-1</sup>. ~~During this period, the study area received an annual sediment load of approximately 85.6 kton year<sup>-1</sup>. This implies that approximately 55 % of the incoming sediment in the study area and approximately 3 % of the incoming sediment at Lobith (the Dutch-German border) was trapped by the area.~~ Consecutive measurements of channel bathymetry indicate that deposition has occurred in all years, but the actual channel deposition rate has decreased over the years (see Fig. 5). Assuming a constant deposition and erosion rate for the intertidal area, we have accounted for the decrease in net channel sedimentation

over the years by calculating the prospected sediment budget for the coming years using the bathymetric measurements of 2012 and 2015. The prospected sediment budget of the study area amounts to  $35.7 \cdot 10^3 \text{ m}^3 \text{ year}^{-1}$ , which corresponds to a net area-averaged sedimentation rate of  $6.2 \text{ mm year}^{-1}$ .

## 4 Discussion

### 5 4.1 Patterns in sedimentation

Most previous studies on patterns of sedimentation and erosion in tidal wetlands either focussed on marshes, tidal flats or tidal channels. The largest sedimentation rates in the Kleine Noordwaard were found in the channels. This is in agreement with the findings by Siobhan Fennessy et al. (1994); Anderson and Mitsch (2006); Mitsch et al. (2014) who showed that in deep open water areas, more sediment accumulates than in shallow open water areas that are more easily subjected to resuspension by wind-driven and biological sediment disturbances.

Consecutive bathymetric measurements showed that the channels tend towards morphodynamic equilibrium. Channel bed erosion and an associated decrease in width to depth ratio took mainly place near the inlet and outlet of the system, where only one channel is present. Sedimentation at the bed and an increase in the width to depth ratio occurred in the centre of the system, due to the increased cross-sectional area and associated decreased flow velocities. Application of the hydraulic geometry relations of Klaassen and Vermeer (1988) and the Engelund and Hansen predictor (1967) for the total sediment transport capacity in channels, as described by Marra et al. (2014), indicates that the transport capacity of the two main channels in the centre of the area is approximately 46 % of the capacity of the single channel near the inlet and outlet of the system. When it is assumed that both the inlet and centre of the system have reached their morphodynamic equilibrium, the negative sediment budget of the inlet for the period 2012-2015 can be seen as the total maximum transport capacity of this channel. The channels in the centre of the system have a relative transport capacity of only 46 %, so 54 % of the incoming material is deposited by the reduced transport capacity of the two parallel channel systems. However, the reduced transport capacity of the channels explains only 24 % of the positive sediment budget in the centre of the system, which indicates that not only the bifurcation, but also the presence of the wide and shallow intertidal area, results in enhanced sedimentation in the centre of the area.

Observations of freshly deposited material show a trend of declining sand deposition and increasing mud deposition away from the channels, which is in line with previous studies of Neubauer et al. (2002); Reed et al. (1999); Temmerman et al. (2003); French and Spencer (1993); Siobhan Fennessy et al. (1994) and Anderson and Mitsch (2007). Furthermore, a significant negative trend between sedimentation and the height of the location was found, which has also been reported by French and Spencer (1993); Middelkoop and van der Perk (1998); Reed et al. (1999); Temmerman et al. (2003); Thonon et al. (2007). Although the height and distance from the channel do control sedimentation, their influence is not as strong as observed in most marshes or river floodplains. There are three likely causes for the weak relations we found in the Kleine Noordwaard study area: 1) the small gradient in surface topography and a large variation in micro-relief by the presence of mudflat runnels, old furrows, and ditches (Whitehouse et al., 2000; Takekawa et al., 2010; Fagherazzi and Mariotti, 2012); 2) the absence of

vegetation (Neubauer et al., 2002; Darke and Megonigal, 2003; Vandenbruwaene et al., 2015), and 3) the small tidal range and water depths (Mariotti and Fagherazzi, 2013). These three factors result in an uniform sediment distribution by micro topographic flow paths during low water levels (Hupp et al., 2008; Temmerman et al., 2005a); sheet flow during high water levels (Vandenbruwaene et al., 2015; Temmerman et al., 2005a); or a relatively large impact of shear stress (Fagherazzi and Mariotti, 2012) of wind waves and currents, which hamper sediment settling and/or promote sediment redistribution across the tidal flats. However, it could also be argued that the absence of a clear relation between the total mud sedimentation and the distance to the channel is due to the fact that sedimentation is not limited by sediment depletion from the flow over the intertidal flats. This would imply that the water and sediment remain well-mixed across the intertidal flats or that the residence time of water above the flats is relatively short.

In contrast to studies of van de Koppel et al. (2005); Fagherazzi and Wiberg (2009); Tonelli et al. (2010); van Proosdij et al. (2006b), marsh erosion does not significantly contribute to the total sediment budget of the Kleine Noordwaard study area, where except for one cut bank that was formed by channel migration, all cut banks are formed by wind wave erosion. A fetch of 400 m and an average water depth of 0.2 m are typical for the study area. According to the approach of Fagherazzi and Wiberg (2009), which estimates the maximum wave height and accompanying bed shear stress, wind waves do not exceed a height of 8 cm for wind speeds up to  $15 \text{ m s}^{-1}$  under these conditions of water depth and fetch length. In accordance with Leonardi et al. (2016) who have shown that bank deterioration is linearly related to wave energy the low rate of cut bank retreat in the study area can be attributed to the low wave height. Higher wind waves and an inherent larger rate of cut bank retreat can only occur at the boundary of the terrestrial zone in the northeast of the area and at the southwest edge of the island. Both locations are exposed perpendicular to the southwest oriented channels, which are relatively deep and have a long fetch for the most abundant southwesterly winds. This demonstrates that a short wind fetch length effectively reduces cut bank erosion and the short fetch is probably the major reason for the low rates of marsh erosion in the majority of the study area.

In spite of their low height, wind waves cause erosion on tidal flats when the wave-generated shear stress exceeds the critical bed shear stress for erosion. A critical bed shear stress of  $0.35 \text{ N m}^{-2}$  (Mitchener and Torfs, 1996) for sand is only exceeded for typical conditions of fetch and water depth and very high wind speeds  $>13 \text{ m s}^{-1}$ . However, resuspension of unconsolidated mud with a critical shear stress of  $0.05 \text{ N m}^{-2}$  (Mitchener and Torfs, 1996), already takes place at a wind speed greater than  $5.5 \text{ m s}^{-1}$ , which was the case during approximately 20 % of the total study period. This suggests that resuspension of the newly deposited material at the intertidal flats takes place regularly.

## 4.2 Sediment budget

The results of this study indicate that the area Kleine Noordwaard functions as a sediment trap. Both the net area-averaged sedimentation of  $6.4 \text{ mm year}^{-1}$  for the period since the opening of the polder area and the estimated actual net area-averaged sedimentation rate of  $6.1 \text{ mm year}^{-1}$  are well within the reported ranges for net sedimentation on floodplains, wetlands, fresh- and salt-water marshes (see Table 1). Furthermore, the sedimentation in the Kleine Noordwaard is within the range of the mean overbank sedimentation rates over the last century ( $0.18\text{--}11.55 \text{ mm year}^{-1}$  with a mean of  $2.78 \text{ mm year}^{-1}$ ) on the upstream river floodplains along the River Waal as reconstructed by Middelkoop (1997) from heavy metal profiles in floodplain soils

of the River Rhine. However, the net sedimentation is larger than the 1-2 mm year<sup>-1</sup>, reported by Bleuten et al. (2009) for the Mariapolder, a re-opened polder area located north of the River Nieuwe Merwede, close to the Kleine Noordwaard. This is likely due to the fact that the Kleine Noordwaard study area receives a larger supply of water and sediment from the River Nieuwe Merwede than the Mariapolder that has only a single inlet/outlet and is only subject to tidal in- and outflow. This confirms the findings of van der Deijl et al. (2017) and Verschelling et al. (2017) that the supply of water and sediment is a major factor for the sediment budget of wetlands

The consecutive measurements of channel bathymetry indicate that net sedimentation is consistent, but that the actual sedimentation rate varies over the years. Although the largest rates of erosion and sedimentation occurred during the 2011 peak discharge event of the River Rhine, the total erosion and sedimentation rates have decreased to 37 % of their initial value within 2 to 3.5 years. This is confirmed by the slightly lower sedimentation of 4.2 mm year<sup>-1</sup>, for the period 2014-2015, as determined from the field measurements of water levels, flow velocities, and suspended sediment concentrations at both the in- and outlet of the study area (van der Deijl et al., 2017). The trend of a decrease in erosion and sedimentation in newly created wetlands was also found by Vandenbruwaene et al. (2012), who found in a newly created wetland a decrease in the net channel erosion and sedimentation rates towards zero after 4 years. These findings suggest a further decrease in the contribution of the sedimentation in the channels to the total sediment budget in the Kleine Noordwaard study area.

### 4.3 Implications for management

The findings of this study have a number of practical implications for future river delta restoration. The current net area-averaged sedimentation of 6.1 mm year<sup>-1</sup> is just enough to compensate the actual rate of sea-level rise and soil subsidence in the Netherlands, which are 2 mm year<sup>-1</sup> (Ligvoet et al., 2015) and 0-0.25 mm year<sup>-1</sup> respectively for the Biesbosch (Kooi et al., 1998). However, sedimentation in the area cannot compensate the high end scenarios for sea-level rise of 0.4 to 10.5 mm year<sup>-1</sup> as calculated for the Netherlands by Katsman et al. (2011), especially since freshly deposited sediment will compact over the years and thus result in a lower net sedimentation. ~~The area has only trapped approximately 55 % of the incoming sediment in the study area and 3 % of the incoming sediment at Lobith (the Dutch-German border).~~ According to van der Deijl et al. (2017), the trapping efficiency of the area amounted to 0.29 for the period July 2014 to March 2015. This low trapping efficiency well matches the purpose of opening the 'Kleine Noordwaard' polder, which was to function as an overflow area to divert floodwater from the River Nieuwe Merwede towards the south; a rapid silting up of the channel and tidal area is then undesired as it would reduce the flow capacity of the wetland. When the objective of opening the polder would shift to using natural sedimentation as a measure for compensating sea level rise, there is room to enhance the sediment trapping and increase the deposition rate of the area. This might be achieved in several ways: firstly, deposition in the study area could be enhanced by increasing the supply of water and sediment to the area, for example by modifying the inlet geometry. Secondly, lowering wave-generated shear stresses will reduce resuspension at the intertidal flats. This could be achieved by reducing the wind fetch length by the establishment of vegetation or by the construction of topographic irregularities. Finally, a large proportion of incoming sediment leaves the area without deposition via the channels through the downstream outlet. Reducing this direct pass-through transfer by increasing the residence time of the incoming water through adapting the channel course through the wetland, or

reducing the outlet size might also increase trapping efficiency and deposition. Such measures to increase the sediment trapping efficiency and sedimentation rates might also be considered for other wetlands, especially those where current sedimentation rates are not sufficient to compensate sea-level rise and soil subsidence. Overall, conversion of delta polders into wetlands may be an effective strategy of delta restoration, since sedimentation compensates at least partly for sea level rise and land subsidence.

## 5 Conclusions

Field measurements on water and sediment flow, topography and channel depth carried out over an 8-year period (2008-2015) allowed to quantify both the amount and the spatial patterns in deposition and erosion in the formerly embanked area Kleine Noordwaard in the lower Rhine-Meuse delta. The main conclusions of this study are:

1. During this period the total sediment budget of the ‘Kleine Noordwaard’ study area amounted to  $37.3 \cdot 10^3 \text{ m}^3 \text{ year}^{-1}$ , which corresponds to a net area-averaged sedimentation rate of  $6.4 \text{ mm year}^{-1}$  and an import of  $46.8 \text{ kton year}^{-1}$ .
2. Largest rates of sedimentation ( $14.3 \text{ mm year}^{-1}$ ) took place in the channels, and channel sedimentation contributed approximately 44% to the total sediment budget. Wide intertidal flats and oversized parallel channels resulted in enhanced sedimentation in the channels during the first years after opening. Over time, both channel deposition and erosion rates have decreased, resulting in a net sedimentation decreased from  $18.5 \text{ mm year}^{-1}$  to  $12.6 \text{ mm year}^{-1}$ , which implies that the filling-up of the channels tends towards morphodynamic equilibrium.
3. In the intertidal area sand deposition occurs primarily at low lying locations close to the channels, while mud deposition occurs primarily further away from the channels and inlet. Wind-driven resuspension of the newly deposited material at the intertidal flats takes place regularly due to small water depths and the absence of vegetation.
4. A short wind fetch length is probably the major reason for the low rates of marsh erosion in the majority of the study area.
5. The current net sedimentation is enough to compensate for the actual rate of sea-level rise and land subsidence, but not for the high end scenarios of sea-level rise. The net sedimentation in the Kleine Noordwaard study area - and wetlands in general - could be enhanced by altering the lay-out of the polder channels and the size of the upstream and downstream openings, increasing the supply of sediment into the area and the residence time within the polder.
6. The conversion of polders in delta areas into wetlands where renewed sediment deposition occurs may be an effective strategy of delta restoration, since sedimentation compensates at least partly for sea level rise and land subsidence.

*Data availability.* We will make the following data available via the Dryad repository (<http://datadryad.org/>):

1. Difference in channel bed level for each monitoring period (TIF) (Figure 3, Figure 4, Figure 5)

2. Initial Digital Elevation Model of the study area (TIF) (Figure 1, Figure 3, Figure 6)
3. Locations of inlet centre, and outlet (TIF)
4. Location of dredged area (TIF)
5. Total sedimentation at the intertidal flats (ascii xyz) (Figure 6a)
- 5 6. Location and height of the cutbanks (ascii xyz) (Figure 6b)

*Author contributions.* H. Middelkoop and M. van der Perk have designed the research proposal. E.C. van der Deijl collected and analysed the data. E.C. van der Deijl, M. van der Perk and H. Middelkoop interpreted the data and finally E.C. van der Deijl prepared the manuscript with the contributions, revisions and final approval from all co-authors.

*Competing interests.* The authors declare that they have no conflict of interest.

- 10 *Acknowledgements.* This project is financed by the Dutch Technology Foundation STW (project nr. 12431). We thank Staatsbosbeheer, Rijkswaterstaat, Dr. Hans de Boois, Eelco Verschelling, Dr. Wim Hoek, Renske Visser, Nanda Kik and Wouter Zonneveld for the provided data, assistance, logistic support and knowledge.



## References

- Anderson, C. J. and Mitsch, W. J.: Sediment, carbon, and nutrient accumulation at two 10-year-old created riverine marshes, *Wetlands*, 26, 779–792, 2006.
- Anderson, C. J. and Mitsch, W. J.: Erratum to: Sediment, carbon, and nutrient accumulations at two 10-year-old created riverine marshes, *Wetlands*, 27, 774–774, 2007.
- Asselman, N. E. M. and Middelkoop, H.: Temporal variability of contemporary floodplain sedimentation in the Rhine-Meuse Delta, the Netherlands, *Earth Surf Proc Land*, 23, 595–609, 1998.
- Asselman, N. E. M. and Van Wijngaarden, M.: Development and application of a 1D floodplain sedimentation model for the River Rhine in the Netherlands, *J Hydrol*, 268, 127–142, 2002.
- 10 Auerbach, L. W., Goodbred Jr, S. L., Mondal, D. R., Wilson, C. A., Ahmed, K. R., Roy, K., Steckler, M. S., Small, C., Gilligan, J. M., and Ackerly, B. A.: Flood risk of natural and embanked landscapes on the Ganges-Brahmaputra tidal delta plain, *Nature Climate Change*, 5, 153–157, 2015.
- Bleuten, W., Borren, W., Kleinveld, E., Oomes, L. B., and Timmermann, T.: Water and nutrient balances of the experimental site Mariapolder, The Netherlands, in: *Tidal Freshw Wetl*, edited by Barendrecht, A., Whigham, D. F., and Baldwin, A. H., chap. 18, pp. 167–206, Backhuys Publishers, Leiden, 2009.
- 15 Bureau Noordwaard: Ontwerpvisie ontpoldering noordwaard, Tech. rep., Rotterdam, 2006.
- Calvo-Cubero, J., Ibáñez, C., Rovira, A., Sharpe, P. J., and Reyes, E.: Mineral versus organic contribution to vertical accretion and elevation change in restored marshes (Ebro Delta, Spain), *Ecol Eng*, 61, 12–22, 2013.
- Craft, C. B. and Casey, W. P.: Sediment and nutrient accumulation in floodplain and depressional freshwater wetlands of Georgia, USA, *Wetlands*, 20, 323–332, 2000.
- 20 Darke, A. and Megonigal, J.: Control of sediment deposition rates in two mid-Atlantic Coast tidal freshwater wetlands, *Estuar Coast Shelf Sci*, 57, 255–268, 2003.
- Davidson-Arnott, R. G., van Proosdij, D., Ollerhead, J., and Schostak, L.: Hydrodynamics and sedimentation in salt marshes: examples from a macrotidal marsh, Bay of Fundy, *Geomorphology*, 48, 209–231, 2002.
- 25 Day, J., Cable, J., Lane, R., and Kemp, P.: Sediment Deposition at the Caernarvon Crevasse during the Great Mississippi Flood of 1927: Implications for Coastal Restoration, *Water*, 8, 38, 2016.
- Day, J. W., Boesch, D. F., Clairain, E. J., Kemp, G. P., Laska, S. B., Mitsch, W. J., Orth, K., Mashriqui, H., Reed, D. J., Shabman, L., Simenstad, C. A., Streever, B. J., Twilley, R. R., Watson, C. C., Wells, J. T., and Whigham, D. F.: Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita, *Science*, 315, 1679–1684, 2007.
- 30 De Bont, C., Dirks, G., Maas, G., Wolfert, H., Odé, O., and Polman, G.: Aardkundige en cultuurhistorische landschappen van de Biesbosch; Beschrijving en waardering als bouwstenen voor het landschapontwikkelingsconcept en de effectevaluatie voor rivierverruiming, Tech. rep., Alterra, Research Instituut voor de Groene Ruimte, Wageningen, doi:RIZA-rapport 2000.053, <http://edepot.wur.nl/119881>, 2000.
- De la Haye, M. A. A.: Jaarrapportage 2010 projectgebonden monitoring RWS Zuid-Holland, Noordwaard, Sliedrechtse Biesbosch, Oeverlanden Hollandsch Diep (APL-polder) en Het Gors en De Aanwas, Tech. rep., Grontmij, 2011.
- 35 DeLaune, R. D., Jugsujinda, A., Peterson, G. W., and Patrick, W. H.: Impact of Mississippi River freshwater reintroduction on enhancing marsh accretionary processes in a Louisiana estuary, *Estuar Coast Shelf Sci*, 58, 653–662, 2003.

- Fagherazzi, S. and Mariotti, G.: Mudflat runnels: Evidence and importance of very shallow flows in intertidal morphodynamics, *Geophys Res Lett*, 39, n/a–n/a, 2012.
- Fagherazzi, S. and Wiberg, P. L.: Importance of wind conditions, fetch, and water levels on wave-generated shear stresses in shallow intertidal basins, *J Geophys Res*, 114, 1–12, 2009.
- 5 French, J. R. and Spencer, T.: Dynamics of sedimentation in a tide-dominated backbarrier salt marsh, Norfolk, UK, *Mar Geol*, 110, 315–331, 1993.
- Gell, P., Fluin, J., Tibby, J., Hancock, G., Harrison, J., Zawadzki, A., Haynes, D., Khanum, S., Little, F., and Walsh, B.: Anthropogenic acceleration of sediment accretion in lowland floodplain wetlands, Murray–Darling Basin, Australia, *Geomorphology*, 108, 122–126, 2009.
- 10 Grontmij: Natuurontwikkeling Noordwaard - Inrichtingsplan, Tech. rep., Grontmij Advies & Techniek bv, eindhoven, 2002.
- Heiri, O., Lotter, A. F., and Lemcke, G.: Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results, *J Paleolimnol*, 25, 101–110, 2001.
- Hudson, P. F., Middelkoop, H., and Stouthamer, E.: Flood management along the Lower Mississippi and Rhine Rivers (The Netherlands) and the continuum of geomorphic adjustment, *Geomorphology*, 101, 209–236, 2008.
- 15 Hung, N. N., Delgado, J. M., Güntner, A., Merz, B., Bárdossy, A., and Apel, H.: Sedimentation in the floodplains of the Mekong Delta, Vietnam. Part I: Suspended sediment dynamics, *Hydrol Process*, 28, 3132–3144, 2014a.
- Hung, N. N., Delgado, J. M., Güntner, A., Merz, B., Bárdossy, A., and Apel, H.: Sedimentation in the floodplains of the Mekong Delta, Vietnam Part II: Deposition and erosion, *Hydrol Process*, 28, 3145–3160, 2014b.
- Hupp, C. R., Demas, C. R., Kroes, D. E., Day, R. H., and Doyle, T. W.: Recent sedimentation patterns within the central Atchafalaya Basin, Louisiana, *Wetlands*, 28, 125–140, 2008.
- 20 Ibáñez, C., Canicio, A., Day, J. W., and Curco, A.: Morphologic development, relative sea level rise and sustainable management of water and sediment in the Ebro Delta, Spain, *J Coast Conserv*, 3, 191–202, 1997.
- Ibáñez, C., Day, J. W., and Reyes, E.: The response of deltas to sea-level rise: Natural mechanisms and management options to adapt to high-end scenarios, *Ecol Eng*, 65, 122–130, 2014.
- 25 Islam, M. R., Begum, S. F., Yamaguchi, Y., and Ogawa, K.: The Ganges and Brahmaputra rivers in Bangladesh: basin denudation and sedimentation, *Hydrol Process*, 13, 2907–2923, 1999.
- Katsman, C. A., Sterl, A., Beersma, J. J., van den Brink, H. W., Church, J. A., Hazeleger, W., Kopp, R. E., Kroon, D., Kwadijk, J., Lammersen, R., Lowe, J., Oppenheimer, M., Plag, H. P., Ridley, J., von Storch, H., Vaughan, D. G., Vellinga, P., Vermeersen, L. L. A., van de Wal, R. S. W., and Weisse, R.: Exploring high-end scenarios for local sea level rise to develop flood protection strategies for a low-lying delta—the Netherlands as an example, *Climatic Change*, 109, 617–645, 2011.
- 30 Khadim, F. K., Kar, K. K., Halder, P. K., Rahman, M. A., and Morshed, A. M.: Integrated Water Resources Management (IWRM) impacts in south west coastal zone of Bangladesh and fact-finding on Tidal River Management (TRM), *J Water Resource Prot*, 05, 953–961, 2013.
- Kirwan, M. L. and Megonigal, J. P.: Tidal wetland stability in the face of human impacts and sea-level rise., *Nature*, 504, 53–60, 2013.
- Kleinmans, M. G., Weerts, H. J., and Cohen, K. M.: Avulsion in action: Reconstruction and modelling sedimentation pace and upstream flood water levels following a Medieval tidal-river diversion catastrophe (Biesbosch, The Netherlands, 1421–1750AD), *Geomorphology*, 118, 65–79, 2010.
- 35 Kooi, H., Johnston, P., Lambeck, K., and Smither, C.: Geological causes of recent (100 yr) vertical land movement in the Netherlands, *Tectonophysics*, 299, 297–316, 1998.

- Leonard, L. A.: Controls of sediment transport and deposition in an incised mainland marsh basin, southeastern North Carolina, *Wetlands*, 17, 263–274, 1997.
- Leonardi, N., Ganju, N. K., and Fagherazzi, S.: A linear relationship between wave power and erosion determines salt-marsh resilience to violent storms and hurricanes., *PNAS*, 113, 64–68, 2016.
- 5 Ligvoet, W., Bregman, B., Dorland, R., ten Brinke, W., de Vos, R., Petersen, A., and Visser, H.: Klimaatverandering. Samenvatting van het vijfde IPCC-assessment en een vertaling naar Nederland, [http://www.stowa.nl/Upload/nieuws/Klimaatverandering\[\\_\]SamenvattingvanhetvijfdeIPCC-assessmenteneenvertalingnaarNederland.pdf](http://www.stowa.nl/Upload/nieuws/Klimaatverandering[_]SamenvattingvanhetvijfdeIPCC-assessmenteneenvertalingnaarNederland.pdf), 2015.
- Mariotti, G. and Fagherazzi, S.: Wind waves on a mudflat: The influence of fetch and depth on bed shear stresses, *Cont Shelf Res*, 60, S99–S110, 2013.
- 10 Marra, W. A., Kleinhans, M. G., and Addink, E. A.: Network concepts to describe channel importance and change in multichannel systems: test results for the Jamuna River, Bangladesh, *Earth Surf Proc Land*, 39, 766–778, 2014.
- Middelkoop, H.: Embanked floodplains in the Netherlands. Geomorphological evolution over various time scales., Phd thesis, Utrecht University, The Netherlands, *Netherlands Geographical Studies* 224., 1997.
- Middelkoop, H. and Asselman, N. E. M.: Spatial variability of floodplain sedimentation at the event scale in the Rhine–Meuse delta, *The Netherlands, Earth Surf Proc Land*, 23, 561–573, 1998.
- 15 Middelkoop, H. and van der Perk, M.: Modelling spatial patterns of overbank sedimentation on embanked floodplains, *Geogr Ann*, 80A, 95–109, 1998.
- Mitchener, H. and Torfs, H.: Erosion of mud/sand mixtures, *Coastal Engineering*, 29, 1–25, 1996.
- Mitsch, W. J., Nedrich, S. M., Harter, S. K., Anderson, C., Nahlik, A. M., and Bernal, B.: Sedimentation in created freshwater riverine wetlands: 15 years of succession and contrast of methods, *Ecol Eng*, 72, 25–34, 2014.
- 20 Neubauer, S. C., Anderson, I. C., Constantine, J. A., and Kuehl, S. A.: Sediment Deposition and Accretion in a Mid-Atlantic (U.S.A.) Tidal Freshwater Marsh, *Estuar Coast Shelf Sci*, 54, 713–727, 2002.
- Paola, C., Twilley, R. R., Edmonds, D. A., Kim, W., Mohrig, D., Parker, G., Viparelli, E., and Voller, V. R.: Natural processes in delta restoration: application to the Mississippi Delta., *Annu Rev Mar Sci*, 3, 67–91, 2011.
- 25 Pasternack, G. and Brush, G.: Seasonal Variations in Sedimentation and Organic Content in Five Plant Associations on a Chesapeake Bay Tidal Freshwater Delta, *Estuar Coast Shelf Sci*, 53, 93–106, 2001.
- Pethick, J. S.: Long-term Accretion Rates on Tidal Salt Marshes, *J Sediment Res*, Vol. 51, 571–577, 1981.
- Reed, D. J., de Luca, N., and Foote, a. L.: Effect of hydrologic management on marsh surface sediment deposition in coastal Louisiana, *Estuaries*, 20, 301, 1997.
- 30 Reed, D. J., Spencer, T., Murray, A. L., French, J. R., and Leonard, L.: Marsh surface sediment deposition and the role of tidal creeks : Implications for created and managed coastal marshes, *J Coast Conserv*, 5, 81–90, 1999.
- Rijke, J., van Herk, S., Zevenbergen, C., and Ashley, R.: Room for the River: delivering integrated river basin management in the Netherlands, *International Journal of River Basin Management*, 10, 369–382, 2012.
- Rijkswaterstaat: Water data, <https://www.watergegevens.rws.nl/>, 2016.
- 35 Schile, L. M., Callaway, J. C., Morris, J. T., Stralberg, D., Thomas Parker, V., and Kelly, M.: Modeling tidal marsh distribution with sea-level rise: Evaluating the role of vegetation, sediment, and upland habitat in marsh resiliency, *PLoS One*, 9, 2014.
- Siobhan Fennessy, M., Brueske, C. C., and Mitsch, W. J.: Sediment deposition patterns in restored freshwater wetlands using sediment traps, *Ecol Eng*, 3, 409–428, 1994.

- Syvitski, J. P. M.: Deltas at risk, *Sustain Sci*, 3, 23–32, 2008.
- Syvitski, J. P. M. and Saito, Y.: Morphodynamics of deltas under the influence of humans, *Glob Planet Change*, 57, 261–282, 2007.
- Takekawa, J. Y., Woo, I., Athearn, N. D., Demers, S., Gardiner, R. J., Perry, W. M., Ganju, N. K., Shellenbarger, G. G., and Schoellhamer, D. H.: Measuring sediment accretion in early tidal marsh restoration, *Wetl Ecol Manag*, 18, 297–305, 2010.
- 5 Temmerman, S., Govers, G., Wartel, S., and Meire, P.: Spatial and temporal factors controlling short-term sedimentation in a salt and freshwater tidal marsh, scheldt estuary, Belgium, SW Netherlands, *Earth Surf Proc Land*, 28, 739–755, 2003.
- Temmerman, S., Bouma, T. J., Govers, G., and Lauwaet, D.: Flow paths of water and sediment in a tidal marsh: Relations with marsh developmental stage and tidal inundation height, *Estuaries*, 28, 338–352, 2005a.
- Temmerman, S., Bouma, T. J., Govers, G., Wang, Z. B., De Vries, M. B., and Herman, P. M. J.: Impact of vegetation on flow routing and sedimentation patterns: Three-dimensional modeling for a tidal marsh, *J Geophys Res*, 110, 1–18, 2005b.
- 10 Thonon, I., Middelkoop, H., and Perk, M. V. D.: The influence of floodplain morphology and river works on spatial patterns of overbank deposition, *Neth J Geosci*, 81, 63–75, 2007.
- Tonelli, M., Fagherazzi, S., and Petti, M.: Modeling wave impact on salt marsh boundaries, *J Geophys Res*, 115, 2010.
- van de Koppel, J., van der Wal, D., Bakker, J. P., and Herman, P. M. J.: Self-organization and vegetation collapse in salt marsh ecosystems., *The American Naturalist*, 165, E1–12, 2005.
- 15 van der Deijl, E. C., van der Perk, M., and Middelkoop, H.: Factors controlling sediment trapping in two freshwater tidal wetlands in the Biesbosch area, The Netherlands, *Journal of Soils and Sediments*, pp. 1–17, doi:10.1007/s11368-017-1729-x, <http://link.springer.com/10.1007/s11368-017-1729-x>, 2017.
- van Proosdij, D., Davidson-Arnott, R. G., and Ollerhead, J.: Controls on spatial patterns of sediment deposition across a macro-tidal salt marsh surface over single tidal cycles, *Estuar Coast Shelf Sci*, 69, 64–86, doi:10.1016/j.ecss.2006.04.022, <http://linkinghub.elsevier.com/retrieve/pii/S0272771406001375>, 2006a.
- 20 van Proosdij, D., Ollerhead, J., and Davidson-Arnott, R. G.: Seasonal and annual variations in the volumetric sediment balance of a macro-tidal salt marsh, *Mar Geol*, 225, 103–127, 2006b.
- van Wijnen, H. and Bakker, J.: Long-term Surface Elevation Change in Salt Marshes: a Prediction of Marsh Response to Future Sea-Level Rise, *Estuar Coast Shelf Sci*, 52, 381–390, 2001.
- 25 Vandenbruwaene, W., Meire, P., and Temmerman, S.: Formation and evolution of a tidal channel network within a constructed tidal marsh, *Geomorphology*, 151–152, 114–125, 2012.
- Vandenbruwaene, W., Schwarz, C., Bouma, T., Meire, P., and Temmerman, S.: Landscape-scale flow patterns over a vegetated tidal marsh and an unvegetated tidal flat: Implications for the landform properties of the intertidal floodplain, *Geomorphology*, 231, 40–52, 2015.
- 30 Verschelling, E., van der Deijl, E., van der Perk, M., Sloff, K., and Middelkoop, H.: Effects of discharge, wind, and tide on sedimentation in a recently restored tidal freshwater wetland, *Hydrological Processes*, 31, 2827–2841, doi:10.1002/hyp.11217, <http://doi.wiley.com/10.1002/hyp.11217>, 2017.
- Whitehouse, R., Bassoullet, P., Dyer, K., Mitchener, H., and Roberts, W.: The influence of bedforms on flow and sediment transport over intertidal mudflats, *Cont Shelf Res*, 20, 1099–1124, 2000.
- 35 Zonneveld, I.: De Brabantse Biesbosch : een studie van bodem en vegetatie van een zoetwatergetijdendelta bestaande uit de drie gedeelten A, B en C = a study of soil and vegetation of a freshwater tidal delta consisting of three volumes A, B and C, Ph.D. thesis, <http://library.wur.nl/WebQuery/wurpubs/487770>, 1959.

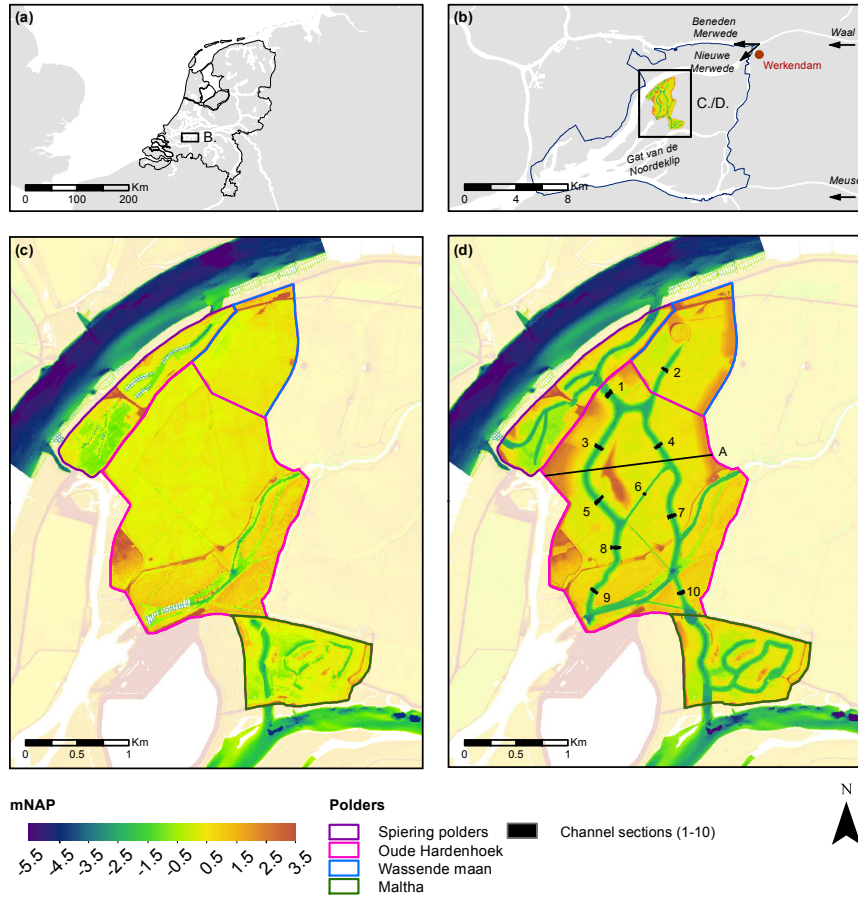
Table 1: Net sedimentation and deposition in various types of delta compartments. When a source only gives deposition in volume, the concomitant change in height is calculated using a sediment density of 1150 kg m<sup>-3</sup>

Type	Net sedimentation [mm year <sup>-1</sup> ]	Deposition [mm year <sup>-1</sup> ]	Deposition [mm year <sup>-1</sup> ]	SSC / Turbidity	Amplitude	Method	Source
Marshes	0.6				[m]		
Floodplains	1.1					Cores (137Cs , 210 Pb)	Craft and Casey (2000)
Wetland	1.2					Cores (137Cs , 210 Pb)	Craft and Casey (2000)
Wetland		1.5	1.1 - 8.4 g m <sup>-2</sup> day <sup>-1</sup>			Cores (137Cs , 210 Pb)	Craft and Casey (2000)
TFW		1.5	1.5-2.5 kg m <sup>-2</sup> year <sup>-1</sup>			Sediment traps (filters)	Reed et al. (1997)
					0.4 - 0.5	Waterlevels, watersamples	Bleuten et al. (2009)
Floodplains		2.2	2.56 kg m <sup>-2</sup> year <sup>-1</sup>	30 mg l <sup>-1</sup>		Sediment traps (artificial grass)	Middelkoop and Asselman (1998)
Floodplains		2.8		30 mg l <sup>-1</sup>		Cores	Middelkoop (1997)
Floodplains		2.5				Cores (137Cs , 210 Pb)	Gell et al. (2009)
Crevasse splay		2.5-3				Cores (137Cs , 210 Pb)	Day et al. (2016)
Salt Marshes	3.9			50-150 mg l <sup>-1</sup>	3.2 (nt) - 6.4 (st)	Marker horizons, sediment traps	French and Spencer (1993)
2 River Marshes		4.1	4.5-4.9 kg m <sup>-2</sup> year <sup>-1</sup>	17 - 35 NTU		Marker horizons	Anderson and Mitsch (2006)
TFW	4.3-5.5				0.7 (nt) - 0.9 (st)	Sediment traps (tiles), cores (Be7)	Neubauer et al. (2002)
3 Salt Marshes	0-11				1.3-2.3	Marker horizons, surface elevation, clay layer thickness	van Wijnen and Bakker (2001)
Floodplains		6	6.86 kg m <sup>-2</sup> year <sup>-1</sup>	90 (mean) - 400 mg l <sup>-1</sup> (flood)		Sediment traps and optical backscatter sensors	Hung et al. (2014a, b)
Salt Marshes	6			50 mg l <sup>-1</sup>	3.2 (nt) - 6.4 (st)	Sediment traps (filters)	French & Spencer, unpubl. in Reed et al. (1999)
Wetland Basin	5-10		5.9-12.8 kg m <sup>-2</sup> year <sup>-1</sup>			Sediment traps (bottles)	Siobhan Fennessy et al. (1994)

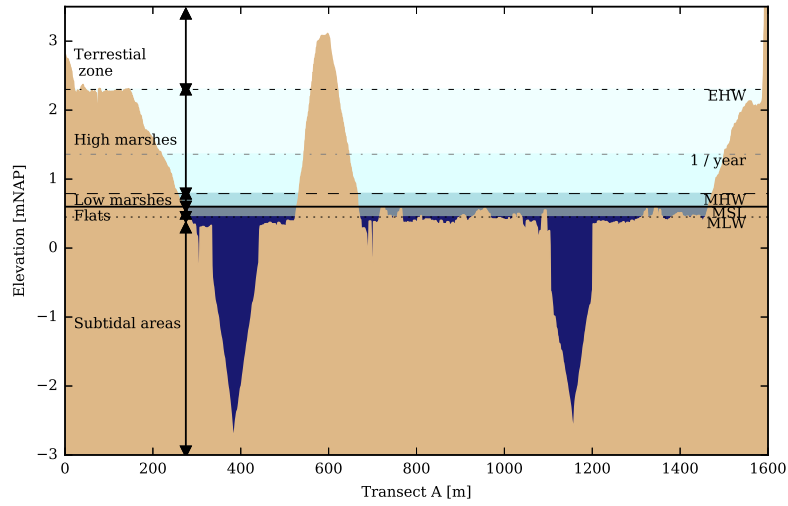
Continued on next page

Table 1 – continued from previous page

Type	Net sedimentation [mm year <sup>-1</sup> ]	Deposition [mm year <sup>-1</sup> ]	Deposition [mm year <sup>-1</sup> ]	SSC / Turbidity	Amplitude [m]	Method	Source
TFW		8.7	1 g cm <sup>-2</sup> year <sup>-1</sup>		3.2 (nt) - 6.4 (st)	Sediment traps (tiles)	Pasternack and Brush (2001)
Salt Marsh	8-14	21.3	0.2-67 g m <sup>-2</sup> tide <sup>-1</sup>	300 mg l <sup>-1</sup>	14	DEM, Sediment plates	van Proosdij et al. (2006a, b)
TFW	12		3.6 g m <sup>-2</sup> day <sup>-1</sup>	9 mg l <sup>-1</sup>	1.8 (st)	Sediment traps (tiles), Marker horizons	Darke and Megonigal (2003)
TFW	12			5 mg l <sup>-1</sup>		Marker horizons, Surface elevation tables	Calvo-Cubero et al. (2013)
Wetland	14 (13 years), 42 (1996), 55 (2009)					Sediment traps (bottles), Marker horizons	Mitsch et al. (2014)
TFW	15.5			27 mg l <sup>-1</sup>		Marker horizons, Surface elevation tables	Calvo-Cubero et al. (2013)
14 Salt Marshes	0.02-17				2-3 (nt) - 5-6 (st)	Model	Pethick (1981)
salt marsh		12.3	13.8-63.7 g m <sup>-2</sup> day <sup>-1</sup>	10-42 mg l <sup>-1</sup>	1.8 (st)	Sediment traps (filters)	Leonard (1997)
TFW	27		12.9 m <sup>-2</sup> day <sup>-1</sup>	19 mg l <sup>-1</sup>	1.8 (st)	Sediment traps (tiles), Marker horizons	Darke and Megonigal (2003)
River bed	39			1037 MT year <sup>-1</sup>		Gauging stations	Islam et al. (1999)
TFW	180					Fast static gps survey	Auerbach et al. (2015)

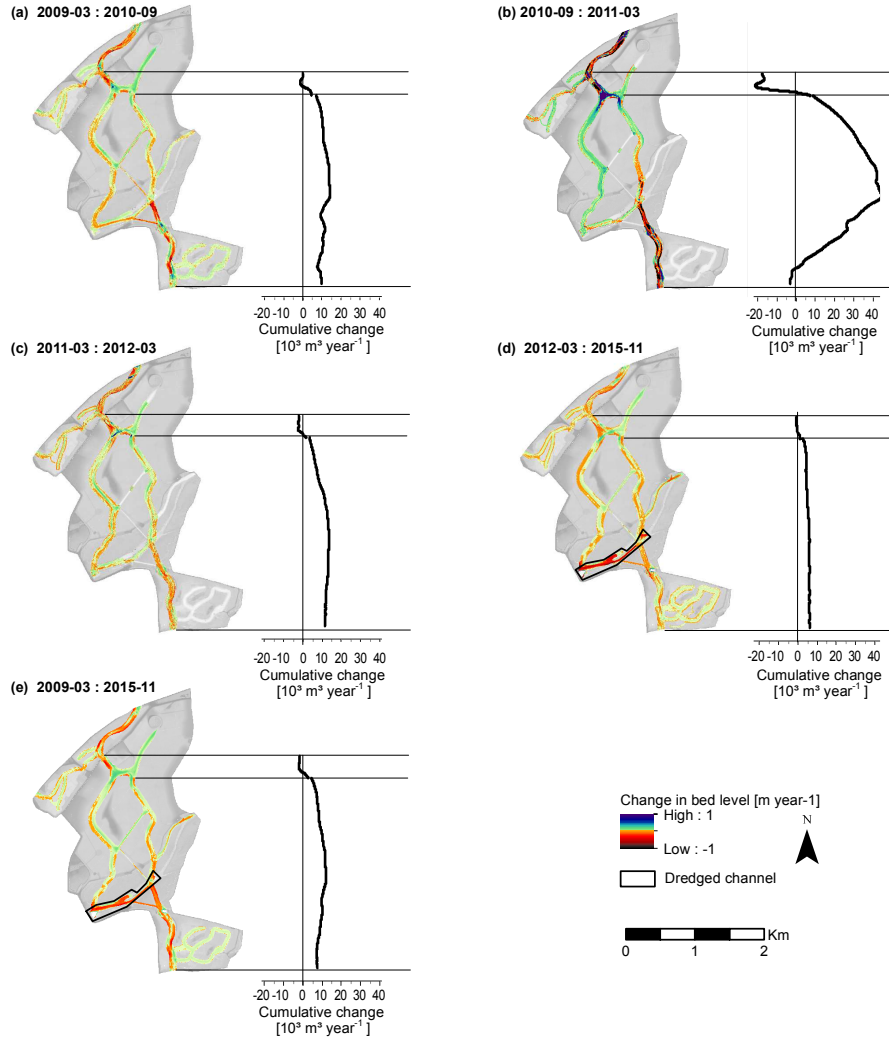


**Figure 1.** The study area Kleine Noordwaard, which is located within the Biesbosch Freshwater Tidal Wetland, in the lower Rhine and Meuse delta in the southwest of the Netherlands (a and b). Elevation is shown in meters, with respect to the Dutch Ordnance Datum (NAP) for the period before (c) and after depoldering (d).

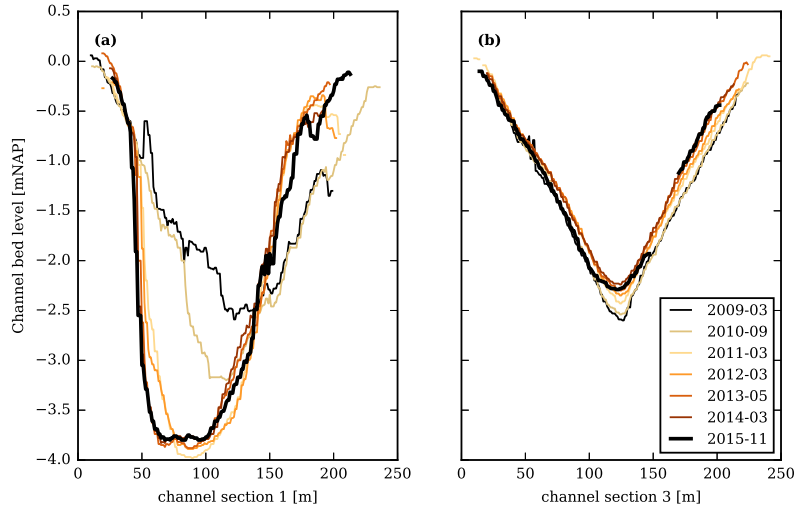


**Figure 2.** Elevation of Transect A (see Fig. 1) with respect to the Dutch Ordnance Datum (m NAP) with subdivision of the area into subtidal areas, flats, low and high marshes, and terrestrial zone relative to mean low water (MLW), mean sea level (MSL), mean high water (MHW), the maximum observed water level (EHW) and the water level for a peak discharge or storm with return period of 1 year, which were used to divide the study area in.

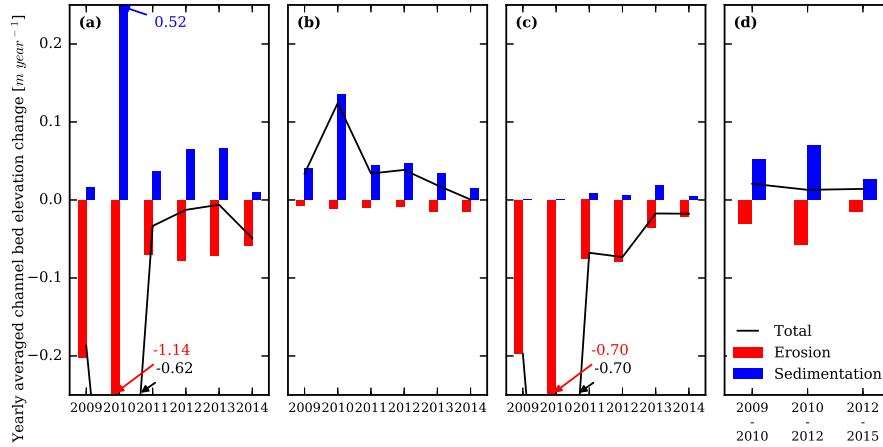




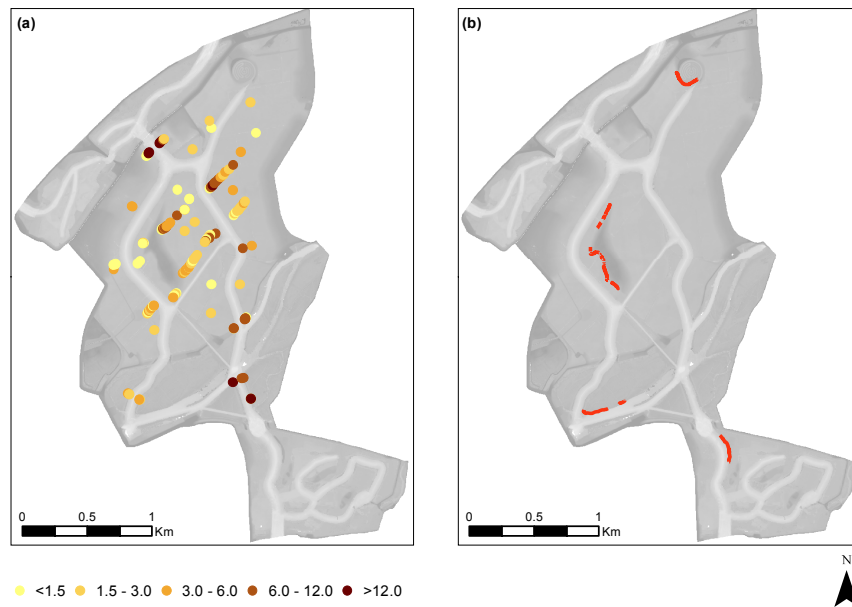
**Figure 3.** The difference in channel bed level and the cumulative channel bed volume for each monitoring period. The cumulative channel bed volume is shown along a N-S transect starting from the Spiering polders (purple in Fig. 1). The budget of the Wassende Maan (blue in Fig. 1) is added at once at the second black line. The channel in the southwest of the study area was dredged in the monitoring period 2012-2015. The dredged area is excluded in the analysis and not shown in the cumulative channel bed volume.



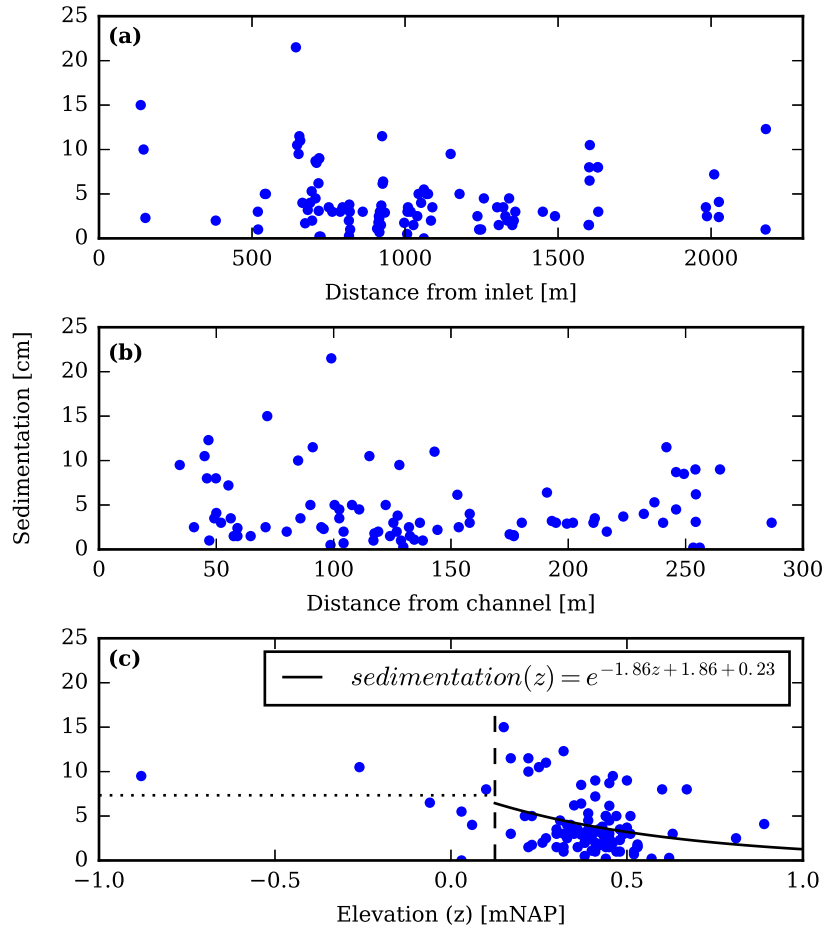
**Figure 4.** Bed level of channel section 1 (a) and 3 (b) for all monitoring campaigns. (see Fig. 1 for the locations of the cross sections)



**Figure 5.** The yearly averaged channel section sedimentation (blue bars), erosion (red bars) and total change in height (black lines) for the inlet (a), the centre (b), the outlet (c) and the entire study area (d), which was opened 7 May 2008 and experienced a peak discharge event from 8 to 19 January, 2011. Yearly averaged channel section sedimentation erosion and total change in height sedimentation rates for the entire area are only available for the periods 2009-2010, 2010-2012 and 2012-2015, since bathymetric measurements were only executed in all channels in 2009, 2010, 2012 and 2015; and in channel sections (see Fig. 1d) in 2011, 2013 and 2014.



**Figure 6.** The total sedimentation [cm] in the subtidal and intertidal area (a) and the location of the cutbanks (b) as measured during field campaigns of 2014



**Figure 7.** Total sedimentation during the period 2008-2014 in the subtidal and intertidal area, with respect to the distance from the inlet of the system (a), distance from the channel (b), and the elevation (c)

# Response to Reviewer #2, ESurf2017-22 revised version 2a - November 2011

We thank the reviewer for taking the time to read and review our manuscript. We address each specific comment below.

Reviewer comments are **bold**

Author comments are in plain text

The changes in the manuscript are shown in the manuscript with track changes

## **P4L28: Can you describe more thoroughly how this correction was calculated? Which data were used to calculate it?**

We have addressed this comment by adapting the method section. We now give a more detailed description of the method used for the correction of the sediment budget for the dredging in a part of the study area.

## **P5L16: This model needs to be explained more. It was not initially clear to me whether you were using a relationship from the literature or one fit to your data.**

We have further clarified the description of the model for the sedimentation in the intertidal area by adapting the method section. We have added the description of how the fit was determined, and we now explain that the second intercept in the fit represents the Ferguson bias correction factor.

## **I do agree with the first anonymous referee that the high heterogeneity of deposition needs to be accounted for in the estimate of the intertidal sediment budget, but I am concerned that the model does not have a lot of predictive power ( $R^2=0.09$ ), so I am not sure how much you gain from using this estimate versus just using the mean of the measurements. Can you quantify the uncertainty in the model prediction? How does that compare to the standard error of the mean of the measured sedimentation rate in the intertidal area?**

Even though the predictive power ( $R^2$ ) of the model for the intertidal area is only 0.103, the mean squared error of the fit (11.06) is smaller than the mean squared error of the measurements (12.33). Furthermore, the use of the regression model avoids the bias originating from the difference between the distribution of surface elevations of the sample locations and the distribution of the elevations of the entire intertidal area. Therefore, we prefer the use of the model over the use of the mean measured sedimentation.

## **P8L19: The value given for the intertidal sedimentation rate here does not match the one given above. It looks like a rounding error.**

We have adapted the intertidal sedimentation rate in this section. It was indeed a rounding error and the intertidal sedimentation should have been  $15.7 \cdot 10^3 \text{ m}^3 \text{ year}^{-1}$  ( $15.74 \cdot 10^3$ )

## **P8L22: Can you give more detail on how you calculate this future sediment budget? What time scale is this prediction relevant over?**

We have changed the text. In the new text, we do not make a future projection of the sediment budget, but we limit the description of the results to the calculation of the contemporary sediment budget.

**There is some additional analysis (transport capacity and wind wave/shear stress) in the Discussion. The details of the transport capacity calculations, in particular, could be moved to the Results section, while leaving the key conclusion -- "not only the bifurcation, but also the presence of the wide and shallow intertidal area, results in enhanced sedimentation in the centre of the area" -- in the discussion.**

We had added the analysis of the transport capacity of the channels to the discussion to indicate the implications for future river delta restoration of the 'designed' dimensions of the channels, and tidal area on both the sediment budget and the distribution of the sediment over the study area.

The inlet of the study area is a very small side channel of the River Nieuwe Merwede, so we had expected a very small transport capacity for this channel relative to the River Nieuwe Merwede, and therefore channel aggradation. However, the inlet channel shows erosion, which occurs when the supply of sediment is less than the transport capacity of the channel. Since the bed level of the inlet is higher than the bed level of the River, we assumed no bed load could enter the inlet of the study area, and that the (2012-2015) sediment budget of the inlet should represent the actual transport capacity, since the inlet channel tends to morphodynamic equilibrium (in – budget = out, where in = 0).

However, we now understand that these statements are not yet clear in the manuscript and after the reexamination of the development of the morphology of the inlet channel we have decided to remove this analysis, since we also state that the channel bed has eroded to the same depth as the River Nieuwe Merwede, and we see some sedimentation, just after the bifurcation with the River. Therefore, we have decided to remove the second part of the analysis of the total transport capacity from the discussion. It does not affect our overall observations or conclusion.

**The two following statements regarding the transport capacity are unclear to me:**

**P9L10: "the negative sediment budget of the inlet for the period 2012-2015 can be seen as the total maximum transport capacity of this channel." Why is this true? What is the value of the sediment budget/transport capacity?**

See our response to the previous comment

**P9L13: "the reduced transport capacity of the channels explains only 24% of the positive sediment budget in the centre of the system." I think this means that the reduced capacity of the central channels (54% of whatever the total capacity is) is only 24% of the total sediment budget of the centre of the system. What are these values?**

See our response to the previous comment

**Figure 5: The years on the x-axis are too closely spaced.**

We have implemented this comment by increasing the size between the years on the x-axis

**Figure 7: I don't understand why the model equation shows two intercept values. Perhaps this could be accounted for in a more detailed explanation of the model as suggested above.**

We have further clarified the description of the model for the sedimentation in the intertidal area by adapting the method section. We have added the description of how the fit was determined, and we now explain that the second intercept in the fit represents the Ferguson bias correction factor, which is now also mentioned in the caption of figure 7.

# Establishing a sediment budget in the newly created ‘Kleine Noordwaard’ wetland area in the Rhine-Meuse delta

Eveline Christien van der Deijl<sup>1</sup>, Marcel van der Perk<sup>1</sup>, and Hans Middelkoop<sup>1</sup>

<sup>1</sup>Faculty of Geosciences, Universiteit Utrecht, The Netherlands.

*Correspondence to:* E. C. van der Deijl (E.C.vanderDeijl@uu.nl)

**Abstract.** Many deltas are threatened by accelerated soil subsidence, sea-level rise, increasing river discharge, and sediment starvation. Effective delta restoration and effective river management require a thorough understanding of the mechanisms of sediment deposition, erosion, and their controls. Sediment dynamics has been studied at floodplains and marshes, but little is known about the sediment dynamics and budget of newly created wetlands. Here we take advantage of a recently opened tidal freshwater system to study both the mechanisms and controls of sediment deposition and erosion in newly created wetlands. We quantified both the magnitude and spatial patterns of sedimentation and erosion in a former polder area in which water and sediment have been reintroduced since 2008. Based on terrestrial and bathymetric elevation data, supplemented with field observations of the location and height of cut banks and the thickness of the newly deposited layer of sediment, we determined the sediment budget of the study area for the period 2008-2015. Deposition primarily took place in channels in the central part of the former polder area, whereas channels near the inlet and outlet of the area experienced considerable erosion. In the intertidal area, sand deposition especially takes place at low lying locations close to the channels. Mud deposition typically occurs further away from the channels, but sediment is in general uniformly distributed over the intertidal area, due to the presence of topographic irregularities and micro topographic flow paths. Marsh erosion does not significantly contribute to the total sediment budget, because wind wave formation is limited by the length of the fetch. Consecutive measurements of channel bathymetry show a decrease in erosion and deposition rates over time, but the overall result of this study indicate that the area functions as a sediment trap. The total contemporary sediment budget of the study area amounts to ~~37.3~~35.7 10<sup>3</sup> m<sup>3</sup> year<sup>-1</sup>, which corresponds to a net area-averaged deposition rate of ~~6.4~~6.1 mm year<sup>-1</sup>. This is enough to compensate for the actual rates of sea-level rise and soil subsidence in The Netherlands.

## 1 Introduction

Many deltas in the world cope with drowning and loss of delta land due to flood protected polders, dams, and embankments of channels, which result in accelerated soil subsidence and sediment starvation (Ibáñez et al., 1997; Syvitski and Saito, 2007; Ibáñez et al., 2014). The urgency of this problem is enhanced by sea-level rise (Syvitski, 2008) or increasing river discharge. Most deltas are valuable and densely populated, because of their ideal location for harbours, agriculture, aquaculture, and tourism (Kirwan and Megonigal, 2013; Ibáñez et al., 2014). Moreover, they encompass vast wetland areas of great ecological value. Traditional approaches in river management aim at reducing flood risks by constructing dikes and dams. Although such

constructions are often effective in reducing flood risks, they disrupt the morphodynamic processes and ecological functioning of the system, increase sediment starvation, and involve high costs for construction and maintenance (Hudson et al., 2008). Therefore, since recently, river delta management has been shifting from the implementation of these strong regulations towards the control of a more natural system where dynamic processes are restored and the system becomes multifunctional. Examples  
5 include the Tidal River Management project in Bangladesh (Khadim et al., 2013), the diversion projects in the Mississippi deltaic plain (DeLaune et al., 2003; Day et al., 2007; Paola et al., 2011), the Plan Integrale de Protección del Delta Ebro in the Ebro Delta (Calvo-Cubero et al., 2013) and the Room for the River initiative in the Netherlands (Rijke et al., 2012).

Paola et al. (2011) defined river delta restoration as diverting sediment and water from major channels into adjoining drowned areas, where the sediment can build new land and provide a platform for regenerating wetland ecosystems. Delta restoration  
10 is effective when sedimentation compensates for sea-level rise and soil subsidence. Table 1 summarizes sedimentation rates determined in various types of delta compartments representing different depositional environments. Sedimentation is variable and complex. This table suggests that sedimentation is positively related to the suspended sediment concentration. Furthermore, it is widely known from the literature that sedimentation is controlled by the frequency and duration of inundation (French and Spencer, 1993; Middelkoop and van der Perk, 1998; Reed et al., 1999; Temmerman et al., 2003; Thonon et al., 2007), the  
15 suspended sediment concentration in the feeding channel (Asselman and Middelkoop, 1998; French and Spencer, 1993), and the ability of sediment to settle, which is in turn controlled by vegetation (Darke and Megonigal, 2003; Temmerman et al., 2005b; Schile et al., 2014; Mitsch et al., 2014), the flow paths to or within the wetland/compartiment (French and Spencer, 1993; Siobhan Fennessy et al., 1994; Reed et al., 1999; Davidson-Arnott et al., 2002; Temmerman et al., 2003; Anderson and Mitsch, 2007; Mitsch et al., 2014), and the residence time within the compartment (Asselman and Van Wijngaarden,  
20 2002). Although considerable research has been devoted to sedimentation in wetlands in coastal deltas and river floodplains, remarkably few empirical field studies have been reported on the initial formation and evolution of newly created wetlands.

In the present study, we take advantage of a recently opened tidal freshwater system to study the sediment deposition or erosion in newly created tidal wetlands. In the framework of the Room for the River (RfR) initiative in the Netherlands, water and sediment have been reintroduced in previously embanked areas in the Biesbosch, a Tidal Freshwater Wetland (TFW) in  
25 the south-west of The Netherlands. This paper presents the first results of a larger field research project examining mechanisms and controls of sediment deposition and erosion in the Biesbosch tidal freshwater wetland.

The aim of this paper is to quantify both the magnitude and the spatial patterns of sediment deposition and erosion in one of the formerly embanked areas, 'Kleine Noordwaard'. For this, different sources of data were combined. Net sedimentation rates were determined from existing bathymetric data collected by a multibeam echosounder, existing LiDAR digital elevation  
30 models, supplemented by field observations of the thickness of the newly deposited sediment layer and field observations of the location and height of cut banks. From this we developed a medium-to-long term sediment budget for the Kleine Noordwaard. In this paper, we compare the rates and patterns of sedimentation and erosion in the study area to those in other wetlands, assess the relative contribution of geomorphological processes in the study area, and discuss practical implications for the management of newly created tidal freshwater wetlands.



## 2 Methods

### 2.1 Study area

The Biesbosch National Park is a 9000 ha freshwater tidal wetland in the lower Rhine and Meuse delta in the southwest of The Netherlands (see Fig. 1a and b). The area was reclaimed in medieval times, but it became completely inundated by the St. Elisabeth flood, which was a combination of two storm surges and two floods of the River Rhine between 1421 and 1424 (Zonneveld, 1959). In the subsequent two centuries, a deltaic splay developed of approximately 6 m thick (Kleinhans et al., 2010). The lower 4 m of this splay is sand, covered by 2 metres of clay (De Bont et al., 2000). In 1861 AD, the Nieuwe Merwede, an artificial branch of the River Rhine, was excavated through the area. As a consequence, water levels dropped and large parts of the wetland were embanked and reclaimed as polders for agriculture during the second half of the 19th century (De Bont et al., 2000; Bureau Noordwaard, 2006). However, since 2008, several of these polder areas have been re-opened for river water ('depoldered') to increase the discharge capacity of the River Rhine. The study area of the Kleine Noordwaard was among the first polder areas that have been depoldered.

The Kleine Noordwaard study area comprises the former Spiering, Oude Hardenhoek and Maltha polders (Fig. 1). Maps (c) and (d) represent the surface elevation before and after depoldering of the study area. In 2008, several channels with a width of 120 m, a maximum depth of 3 m and a side slope of 1:20 (Fig. 2) were dug throughout the area. The sandy material was used to create islands and extra protection along the embankments (Grontmij, 2002). The original clayey polder soil remained conserved, except in the former Spiering and Maltha polders, where the upper layer of clay had already been removed for reinforcement of embankments. On 7 May 2008, the embankments were opened and the channels were connected to the River Nieuwe Merwede in the north and to the Gat van de Noorderklip in the south. The major flow direction is from north to south, and water and sediment are supplied by the River Nieuwe Merwede, which is a branch of the River Waal, the major tributary of the River Rhine (Fig. 1). The River Rhine has an average discharge of  $2200 \text{ m}^3 \text{ s}^{-1}$  and an average suspended sediment concentration of  $15 \text{ mg l}^{-1}$  at the German-Dutch border located 85 km upstream from the Kleine Noordwaard. Peak discharges typically occur during the winter season and they range between  $5800$  (1-year-return) and  $9670 \text{ m}^3 \text{ s}^{-1}$  (10-year-return) with maximum concentrations between  $120$  and  $260 \text{ mg l}^{-1}$  (Rijkswaterstaat, 2016).

Van der Deijl et al. (2017) have shown that water is in general imported in the north. Their field measurements in the period between July 2014 and March 2015, indicated that the time-averaged inflow of water from the Nieuwe Merwede through the former Spiering polder into the Oude Hardenbroek polder amounted  $89 \text{ m}^3 \text{ s}^{-1}$  with a maximum of  $191 \text{ m}^3 \text{ s}^{-1}$ . The time-averaged suspended sediment concentrations amounted to  $26 \text{ mg l}^{-1}$  with a maximum of  $114 \text{ mg l}^{-1}$  during a raised discharge event ( $4500 \text{ m}^3 \text{ s}^{-1}$  at the German-Dutch border). The water flow direction at the northern inlet of the Oude Hardenbroek polder reverses during short periods at the onset of ebb tide, which occurred only during 2.2% of the time. During this time, the outgoing average discharge was on average  $11 \text{ m}^3 \text{ s}^{-1}$ . In the south, water is generally exported, but under conditions of rapid rise of the water level at the onset of flood tide, the flow reverses. In the observed period this occurred only during 0.3% of the time with a maximum discharge of  $16 \text{ m}^3 \text{ s}^{-1}$ . Van der Deijl et al. (2017) determined the sediment trapping efficiency to be 0.29 during the above measurement period.

The water level is influenced by the tide, which is mixed semidiurnal with a range of approximately 0.2 to 0.4 m (Rijkswaterstaat, 2016), the wind direction and speed, the discharge of the River Rhine, and the artificially controlled discharge through the gates of the downstream Haringvliet barrier into the North Sea. Water levels are on average 0.63 m above Dutch Ordnance Datum (NAP), with a mean low water (MLW) of 0.45 m NAP and a mean high water (MHW) of 0.79 m NAP (Rijkswaterstaat, 2016). Approximately 29% of the area is comprised of subtidal area (surface elevation <0.125 m NAP, always submerged), 36% of intertidal flats (0.125-0.63 m NAP, submerged >44% of the time), 6% of low marshes (0.63-0.79 m NAP, submerged for 19 - 44% of the time), 22% of high marshes (0.79-2.3 m NAP, whereby areas >1.1 m NAP are only submerged for less than 5% of the time), and 7% of a terrestrial zone (see Fig. 2). In order to reduce the hydraulic roughness, the marshes and terrestrial zone are mown before the winter period, and most of the vegetation is effectively shortened through grazing by birds, horses, and cows. The vegetation can be classified as dry and wet grasslands with at the shoreline some *Mentha aquatica*, *Schoenoplectus triqueter* and *Bolboschoenus maritimus*. The mud flats are almost bare with some pioneer species such as *Hydrodictyon reticulatum*, *Limosella aquatica*, *Veronica anagallis-aquatica* and *Pulicaria vulgaris*. In the summer, grows locally some *Myriophyllum spicatum* in open water (De la Haye, 2011).

## 2.2 Field methods

The sediment budget of the study area is established from the average net sedimentation in navigable channels (approximately 25% of the study area), the average sedimentation in the subtidal area (<0.125 m NAP, excluding channels), sedimentation in the intertidal area (flats and marshes), and the eroded volume of the marsh edge. We first determined the volumetric budgets, which were subsequently converted to mass budgets using sediment densities measured from field samples.

### 2.2.1 Channels

The change in surface elevation over multiple years was used to determine the sediment budget and the spatial pattern of sedimentation and erosion in the navigable channels. Surface elevation was measured by Rijkswaterstaat during consecutive bathymetric surveys in all channels in 2009, 2010, 2012 and 2015. In 2011, 2013 and 2014, additional channel sections were surveyed (see Fig. 1 d). The 2009 -2015 measurement period was hydrologically characterised by a major flood between 8 and 19 January 2011 with a peak river discharge of 8315 m<sup>3</sup> s<sup>-1</sup> and an elevated SSC of up to 260 mg l<sup>-1</sup> at Lobith. Channel bed elevation was measured with a multi-beam Simrad EM3002d echosounder, combined with Netpos/LRK, and processed in QPS Quincy 8.0 (personal communication, Rijkswaterstaat). The total volumetric channel sediment budget was calculated from the difference in channel bed elevation between 2009 and 2015. Some channel sections (approximately 14 % of the total channel area) were dredged in 2015 and were therefore excluded from the 2015 bathymetric map. The sediment budget for the monitoring intervals 2009-2015, and 2012-2015 was corrected for this exclusion by the linear relationship using a correction factor of 0.99. For this, a linear relationship without intercept was established between the total channel sediment budget, and the channel sediment budget without the dredged area-, for the monitoring intervals 2009-2010, 2010-2011 and 2011-2012.

To analyse rates of net sedimentation and erosion of sediment over time, we used only areas from which data were collected during all surveys of 2009, 2010, 2012 and 2015. Survey data collected in the years of 2011, 2013 and 2014 were only used to assess whether changes in bed level had been consistent throughout the years.

### 2.2.2 Subtidal and intertidal area

5 We determined the sediment budget of both the subtidal and the intertidal area by measuring the sedimentation on top of the former polder soil during field campaigns in July and October 2014. The former polder soil consists of a compact non-erodible layer of clay, which was used as marker horizon, since its colour and density are clearly distinguishable from the recently deposited sediment (sand and mud). Transparent Perspex core samplers with a diameter of 59 mm and different lengths were used to collect 126 samples of the newly deposited sediment layer in 9 transects across the central part of the  
10 Kleine Noordwaard (pink aligned area in Fig. 1). The Spiering and Maltha polders were not sampled because the non-erodible layer of clay was removed before depoldering. The thickness of the newly deposited sediment layer was measured using a ruler. In the field the texture of the sediment was classified visually as clay, sandy clay, coarse sand, fine sand, silty sand, sandy silt, or silt. Based on these texture classes, the sediment layers were classified into former polder bed (clay, sandy clay), newly deposited sand (coarse sand, fine sand, silty sand) and newly deposited mud (sandy silt or silt). Since channels were  
15 dug and sand was replaced by depoldering of the area, we selected only samples with a base of former polder clay for further analysis. Furthermore, samples with sand on top of the base of former polder clay were corrected for the replacement of sand for depoldering. The elevation at the sample location was used to separate the samples in datasets for the subtidal and intertidal area. The total sediment budget of the subtidal area was calculated by multiplying the average thickness of the recently deposited sediment layer from samples located below 0.125 m NAP by the total subtidal area. The total sediment budget of  
20 the intertidal area was calculated using a negative exponential relation between the measured sediment deposition and surface elevation, obtained from the AHN digital elevation model of the Netherlands (Actueel Hoogtebestand Nederland, 2017). For this, ordinary least-squares regression was performed between the logarithmic transformed measured sediment deposition and the surface elevation of the samples taken in the intertidal area. The back-transformed sediment deposition was bias-corrected using the Ferguson (1986) correction factor.

### 25 2.2.3 Marsh erosion

To determine the contribution of marsh erosion to the budget of the channels and intertidal area, we measured the height and position of cut banks using a ruler and a Trimble R8 RTK GPS during field campaigns in July and October 2014. The current cut bank position and height were compared to the 2011 50 cm resolution AHN2 digital elevation model of the Netherlands (AHN2)(Actueel Hoogtebestand Nederland, 2017), to calculate the volume of eroded land over the period 2011-2014.

## 2.2.4 Sediment budget

The total sediment budget of the study area was calculated by taking into account the different periods for which the individual budgets of the channels, the subtidal and intertidal area, and the eroded marshes were established. To obtain the total mass of the deposited sediment in the area, the volumetric sediment budget of the area was multiplied by the bulk density of the deposited sediment. Bulk density of sand, deposited in the channels, was determined gravimetrically by the weight of the terrestrial sediment in a pF-ring with volume of  $98.125 \text{ cm}^3$ . To determine the bulk density of the mud, a 59 mm diameter Transparent Perspex core sampler was used to collect a 7 cm core with 4 cm of organic rich mud and the underlying former polder clay at the intertidal flat, because a pF-ring could not be applied to mud. The core was subsampled at a 1 cm interval in the laboratory, and bulk density was determined by the weighted average sediment particle density and the volumetric moisture content of the samples. Moisture and organic matter content were determined from the difference in mass after oven drying at  $105^\circ\text{C}$  and loss-on-ignition analysis at  $550^\circ\text{C}$ , according to the standard techniques described by Heiri et al. (2001).

## 3 Results

### 3.1 Bulk density

Sediment samples indicate a bulk density of  $1.47 \text{ g cm}^{-3}$  for sand and a logarithmic increase with depth from 0.75 to  $1.27 \text{ g cm}^{-3}$  for the 3 cm of mud at the intertidal flat. A maximum density of  $1.5 \text{ g cm}^{-3}$  was found in the compacted former polder clay at the bottom of the core. To convert the sediment thickness to sediment mass per unit area bulk density values of 0.75, 0.94, 1.27, and  $1.34 \text{ g cm}^{-3}$  were assigned to the respective 0-1, 1-2, 2-3, and  $> 3 \text{ cm}$  depth intervals. For the sandy sediment deposited in channels or eroded from the island, we used a bulk density of  $1.47 \text{ g cm}^{-3}$ . The organic matter content, varied between 3.9 and 4.3 % for the former polder clay and between 2.9 and 4.3 for the mud at the intertidal flats.

### 3.2 Channels

Figure 3 shows the change in channel bed level and the yearly averaged cumulative change in channel bed volume in the central part of the area Kleine Noordwaard (pink and green areas in Fig. 1) from north to south both for the successive monitoring campaigns (a, b, c and d) and for the entire period (e). The northern part of the area (the inlet) is characterized by a negative sediment budget, due to the loss of sediment within the Spiering polders (purple in Fig. 1). Fig. 4a shows the bathymetric development of cross section 1, which represents the development of the channel near the inlet of the study area. The cross sectional area of the inlet has increased by bank erosion in the outer bend of the channel to the depth of the River Nieuwe Merwede. The maps in Fig. 3 show that outer bend erosion has occurred in the majority of the channels and that bars have developed at the end of these bends. The first outer bend of the single channel at the outlet of the study area has migrated by approximately 35-40 m in eastern direction. A steep cut bank has developed and concomitant sedimentation of a point bar occurred at the convex inner bend and at the end of the bend. Consequently, the second bend has migrated by approximately 20-30 m in western direction. Although the channel at the outlet of the study area has become 5-10 m wider, the width to depth

ratio decreased from 22.9 to 18.3 due to channel deepening. However, the channels are not able to migrate freely due to steep banks of dikes armoured by riprap, and the average width to depth ratio of the channel has decreased from 17.9 to 15.2.

Within 500 m from the inlet of the central part of the Kleine Noordwaard, the cumulative change in bed volume turns positive. Thus, the amount of sediment eroded in the Spiering polders and near the inlet of the central part of the Kleine Noordwaard is deposited in this area. Further downstream, the cumulative change in channel bed volume increases further reflecting the positive sediment budget of the Wassende Maan area (blue in Fig. 1). In contrast to the area near the inlet of the study area, the channels in the central part of the area have become shallower (see Fig. 4b) and width to depth ratios have increased from 20.3 to 21.9 for the through-flowing channels and from 6.4 to 6.8 for dead-ending channels.

The temporal trend in annual average eroded and deposited sediment volumes is shown in Fig. 5 for the inlet (a), the centre (b), and the outlet (c) of the study area (represented by channel section 1; sections 2-9; and section 10 in Fig. 1). Both the annual amounts of erosion in the channels near the inlet and outlet, and the annual amounts of sedimentation in the centre of the area have decreased over time. This suggests that the channels tend to morphodynamic equilibrium. The decrease in the average net erosion at the inlet and outlet (black line in Fig. 5) is caused by the decrease in the average erosion rate (red in Fig. 5), since the average sedimentation rate (blue in Fig. 5) remains constant over time. The erosion rate has decreased over time because the channels reached the same depth as the River Nieuwe Merwede. The response time of the erosion (i.e. the time needed to reduce the net erosion rate by 63 %) is approximately 2.2 years for the entrance, and 3.3 years for the outlet. The response time of the net sedimentation for the central part of the system is 3.1 years. The response time for net sedimentation in the entire area is 6.5 years. This value is however less accurate as it is based on only three instead of six monitoring intervals.

Although the cumulative channel sediment budget decreases from north to south due to erosion at the outlet of the area, the total channel sediment budget is positive for most periods. The total yearly sediment budget was only negative for the period between the monitoring campaigns of September 2010 and March 2011. This monitoring period includes a discharge event that occurred between 8 and 19 January 2011 with a peak river discharge of  $8315 \text{ m}^3 \text{ s}^{-1}$  and an elevated SSC of up to  $260 \text{ mg l}^{-1}$  at Lobith. Apparently, this event triggered large changes in bed level during this monitoring period. The bathymetric maps in Fig. 3 and the bathymetric development in Fig. 4b show increased rates of sedimentation in the centre of the area during the discharge event. This increased sedimentation occurred at both the inner and outer bend of channels, while the bed level of the outer bend was eroded during other periods. The average change in bed level of the channels decreased from  $18.5 \text{ mm year}^{-1}$  to  $15.4 \text{ mm year}^{-1}$  and  $12.6 \text{ mm year}^{-1}$ , for the consecutive measurement intervals 2009-2010, 2010-2012 and 2012-2015. These changes in bed level correspond to a net sedimentation of  $21.7 \cdot 10^3 \text{ m}^3 \text{ year}^{-1}$ ,  $18 \cdot 10^3 \text{ m}^3 \text{ year}^{-1}$  and  $14.8 \cdot 10^3 \text{ m}^3 \text{ year}^{-1}$  and annual average sediment budgets of  $32.4 \text{ kton year}^{-1}$ ,  $26.9 \text{ kton year}^{-1}$  and  $22.1 \text{ kton year}^{-1}$ , respectively. The average channel sediment budget for the entire monitoring period (2009-2015) accounts for a net sedimentation of  $14 \text{ mm year}^{-1}$ , which corresponds to  $16.7 \cdot 10^3 \text{ m}^3 \text{ year}^{-1}$  and  $24.9 \text{ kton year}^{-1}$ .

### 3.3 Subtidal and intertidal area

Figure 6a shows the spatial variation of the measured sedimentation in the subtidal and intertidal area, and Fig. 7 shows the sedimentation for increasing distance to the inlet of the polder area (i.e. the source of the sediment) (graph a); distance

from the channel (graph b); and elevation (graph c). Although the highest sedimentation was measured along the channels, there is no significant relation between the total sedimentation and the distance to the channel. This is likely partly due to the relatively high sedimentation ( $>5$  cm) at the transition from the tidal flats to the marshes of the island in the centre of the area at a distance of approximately 240-270 m from the channel. These high sedimentation rates are probably caused by the redistribution of sediment eroded from the marshes of the island. Although there is no significant relation between the total sedimentation and the distance to the channel, field observations of the texture of the sediment layers indicated that the percentage of mud increases and the percentage of sand decreases with increasing distance to the channel. Furthermore, Fig. 7c. shows that the total sedimentation generally decreases with increasing height of the tidal area. This relation is significant but it explains only 9 % of the variation in sedimentation. However, local variation in sedimentation is large and is probably resulting from local topographic irregularities as mudflat runnels and old furrows, which are not accounted for in the digital elevation model of the area, which has a resolution of 1 m.

Between May 2008 and October 2014 an average of  $73 \pm 9.1$  mm (standard error of mean) of mud and sand, is deposited in the subtidal area. This corresponds to a sedimentation rate of  $11.3 \pm 1.4$  mm year<sup>-1</sup> and an annual average sediment budget of  $5.21 \cdot 10^3$  m<sup>3</sup> year<sup>-1</sup> and 6.24 kton year<sup>-1</sup>. The sediment budget of the intertidal area amounts  $15.7 \cdot 10^3$  m<sup>3</sup> year<sup>-1</sup> and 22.4 kton year<sup>-1</sup>.

### 3.4 Marsh erosion

Fig. 6b. shows all cut banks, observed in the study area in 2014. Cut banks are most abundant along the marshes of the island in the centre of the system. These cut banks are located in line to those channels with a relatively long fetch for waves formed by the abundant south-westerly winds. The only cut bank formed by channel migration due to outer bend erosion, is located along the channel in the Maltha polder. Comparison of the observed cut bank position and the 2011 digital elevation model of the area indicates that only 31 m<sup>3</sup> of the island eroded between 2011 and 2014. The eroded volume is  $-10.3$  m<sup>3</sup> year<sup>-1</sup>, which corresponds to an erosion of 15.4 ton year<sup>-1</sup>.

### 3.5 Sediment budget

Between 2008 and 2015, the total sediment budget for the 'Kleine Noordwaard' area amounted to  $37.3 \cdot 10^3$  m<sup>3</sup> year<sup>-1</sup>, which corresponds to a net area-averaged sedimentation rate of 6.4 mm year<sup>-1</sup> and an import of 46.8 kton year<sup>-1</sup> for the first 6.5 years after depoldering. Sedimentation of  $16.7 \cdot 10^3$  m<sup>3</sup> year<sup>-1</sup> in the channels accounts for approximately 44 percent of the total budget. The vast majority of the remaining 56 % comprises the annual sedimentation of  $5.2 \cdot 10^3$  m<sup>3</sup> year<sup>-1</sup> and  $15.8$   $15.7 \cdot 10^3$  m<sup>3</sup> year<sup>-1</sup> in the subtidal and intertidal area. Remobilization of sediment by erosion of marshes occurred at a negligible rate of about  $-10.3$  m<sup>3</sup> year<sup>-1</sup>. Consecutive measurements of channel bathymetry indicate that deposition has occurred in all years, but the actual channel deposition rate has decreased over the years, and the channels have almost reached morphodynamic equilibrium (see Fig. 5). ~~Assuming a constant deposition and erosion rate for the intertidal area, we have accounted for the decrease in net channel sedimentation over the years by calculating the prospected sediment budget for the coming years using the bathymetric measurements of 2012 and 2015. The prospected sediment budget of the study area~~ The contemporary sediment

budget calculated for the 2012-2015 period amounts to  $35.7 \cdot 10^3 \text{ m}^3 \text{ year}^{-1}$ , ~~which~~. This corresponds to a net area-averaged sedimentation rate of ~~6.2~~6.1  $\text{mm year}^{-1}$ .

## 4 Discussion

### 4.1 Patterns in sedimentation

- 5 Most previous studies on patterns of sedimentation and erosion in tidal wetlands either focussed on marshes, tidal flats or tidal channels. The largest sedimentation rates in the Kleine Noordwaard were found in the channels. This is in agreement with the findings by Siobhan Fennessy et al. (1994); Anderson and Mitsch (2006); Mitsch et al. (2014) who showed that in deep open water areas, more sediment accumulates than in shallow open water areas that are more easily subjected to resuspension by wind-driven and biological sediment disturbances.
- 10 Consecutive bathymetric measurements showed that the channels tend towards morphodynamic equilibrium. Channel bed erosion and an associated decrease in width to depth ratio took mainly place near the inlet and outlet of the system, where only one channel is present. Sedimentation at the bed and an increase in the width to depth ratio occurred in the centre of the system, due to the increased cross-sectional area and associated decreased flow velocities. ~~Application~~, since application of the hydraulic geometry relations of Klaassen and Vermeer (1988) and the Engelund and Hansen predictor (1967) for the total
- 15 sediment transport capacity in channels, as described by Marra et al. (2014), indicates that the transport capacity of the two main channels in the centre of the area is approximately 46 % of the capacity of the single channel near the inlet and outlet of the system. ~~When it is assumed that both the inlet and centre of the system have reached their morphodynamic equilibrium, the negative sediment budget of the inlet for the period 2012-2015 can be seen as the total maximum transport capacity of this channel. The channels in the centre of the system have a relative transport capacity of only 46 %, so 54 % of the incoming~~
- 20 ~~material is deposited by the reduced transport capacity of the two parallel channel systems. However, the reduced transport capacity of the channels explains only 24 % of the positive sediment budget in the centre of the system, which indicates that not only the bifurcation, but also the presence of the wide and shallow intertidal area, results in enhanced sedimentation in the centre of the area.~~

- Observations of freshly deposited material show a trend of declining sand deposition and increasing mud deposition away
- 25 from the channels, which is in line with previous studies of Neubauer et al. (2002); Reed et al. (1999); Temmerman et al. (2003); French and Spencer (1993); Siobhan Fennessy et al. (1994) and Anderson and Mitsch (2007). Furthermore, a significant negative trend between sedimentation and the height of the location was found, which has also been reported by French and Spencer (1993); Middelkoop and van der Perk (1998); Reed et al. (1999); Temmerman et al. (2003); Thonon et al. (2007). Although the height and distance from the channel do control sedimentation, their influence is not as strong as observed in
- 30 most marshes or river floodplains. There are three likely causes for the weak relations we found in the Kleine Noordwaard study area: 1) the small gradient in surface topography and a large variation in micro-relief by the presence of mudflat runnels, old furrows, and ditches (Whitehouse et al., 2000; Takekawa et al., 2010; Fagherazzi and Mariotti, 2012); 2) the absence of vegetation (Neubauer et al., 2002; Darke and Megonigal, 2003; Vandenbruwaene et al., 2015), and 3) the small tidal range

and water depths (Mariotti and Fagherazzi, 2013). These three factors result in an uniform sediment distribution by micro topographic flow paths during low water levels (Hupp et al., 2008; Temmerman et al., 2005a); sheet flow during high water levels (Vandenbruwaene et al., 2015; Temmerman et al., 2005a); or a relatively large impact of shear stress (Fagherazzi and Mariotti, 2012) of wind waves and currents, which hamper sediment settling and/or promote sediment redistribution across the tidal flats. However, it could also be argued that the absence of a clear relation between the total mud sedimentation and the distance to the channel is due to the fact that sedimentation is not limited by sediment depletion from the flow over the intertidal flats. This would imply that the water and sediment remain well-mixed across the intertidal flats or that the residence time of water above the flats is relatively short.

In contrast to studies of van de Koppel et al. (2005); Fagherazzi and Wiberg (2009); Tonelli et al. (2010); van Proosdij et al. (2006b), marsh erosion does not significantly contribute to the total sediment budget of the Kleine Noordwaard study area, where except for one cut bank that was formed by channel migration, all cut banks are formed by wind wave erosion. A fetch of 400 m and an average water depth of 0.2 m are typical for the study area. According to the approach of Fagherazzi and Wiberg (2009), which estimates the maximum wave height and accompanying bed shear stress, wind waves do not exceed a height of 8 cm for wind speeds up to  $15 \text{ m s}^{-1}$  under these conditions of water depth and fetch length. In accordance with Leonardi et al. (2016) who have shown that bank deterioration is linearly related to wave energy the low rate of cut bank retreat in the study area can be attributed to the low wave height. Higher wind waves and an inherent larger rate of cut bank retreat can only occur at the boundary of the terrestrial zone in the northeast of the area and at the southwest edge of the island. Both locations are exposed perpendicular to the southwest oriented channels, which are relatively deep and have a long fetch for the most abundant southwesterly winds. This demonstrates that a short wind fetch length effectively reduces cut bank erosion and the short fetch is probably the major reason for the low rates of marsh erosion in the majority of the study area.

In spite of their low height, wind waves cause erosion on tidal flats when the wave-generated shear stress exceeds the critical bed shear stress for erosion. A critical bed shear stress of  $0.35 \text{ N m}^{-2}$  (Mitchener and Torfs, 1996) for sand is only exceeded for typical conditions of fetch and water depth and very high wind speeds  $>13 \text{ m s}^{-1}$ . However, resuspension of unconsolidated mud with a critical shear stress of  $0.05 \text{ N m}^{-2}$  (Mitchener and Torfs, 1996), already takes place at a wind speed greater than  $5.5 \text{ m s}^{-1}$ , which was the case during approximately 20 % of the total study period. This suggests that resuspension of the newly deposited material at the intertidal flats takes place regularly.

## 4.2 Sediment budget

The results of this study indicate that the area Kleine Noordwaard functions as a sediment trap. Both the net area-averaged sedimentation of  $6.4 \text{ mm year}^{-1}$  for the period since the opening of the polder area and the estimated actual net area-averaged sedimentation rate of  $6.1 \text{ mm year}^{-1}$  are well within the reported ranges for net sedimentation on floodplains, wetlands, fresh- and salt-water marshes (see Table 1). Furthermore, the sedimentation in the Kleine Noordwaard is within the range of the mean overbank sedimentation rates over the last century ( $0.18\text{-}11.55 \text{ mm year}^{-1}$  with a mean of  $2.78 \text{ mm year}^{-1}$ ) on the upstream river floodplains along the River Waal as reconstructed by Middelkoop (1997) from heavy metal profiles in floodplain soils of the River Rhine. However, the net sedimentation is larger than the  $1\text{-}2 \text{ mm year}^{-1}$ , reported by Bleuten et al. (2009) for the



Mariapolder, a re-opened polder area located north of the River Nieuwe Merwede, close to the Kleine Noordwaard. This is likely due to the fact that the Kleine Noordwaard study area receives a larger supply of water and sediment from the River Nieuwe Merwede than the Mariapolder that has only a single inlet/outlet and is only subject to tidal in- and outflow. This confirms the findings of van der Deijl et al. (2017) and Verschelling et al. (2017) that the supply of water and sediment is a major factor for the sediment budget of wetlands

The consecutive measurements of channel bathymetry indicate that net sedimentation is consistent, but that the actual sedimentation rate varies over the years. Although the largest rates of erosion and sedimentation occurred during the 2011 peak discharge event of the River Rhine, the total erosion and sedimentation rates have decreased to 37 % of their initial value within 2 to 3.5 years. This is confirmed by the slightly lower sedimentation of  $4.2 \text{ mm year}^{-1}$ , for the period 2014-2015, as determined from the field measurements of water levels, flow velocities, and suspended sediment concentrations at both the in- and outlet of the study area (van der Deijl et al., 2017). The trend of a decrease in erosion and sedimentation in newly created wetlands was also found by Vandenbruwaene et al. (2012), who found in a newly created wetland a decrease in the net channel erosion and sedimentation rates towards zero after 4 years. These findings suggest a further decrease in the contribution of the sedimentation in the channels to the total sediment budget in the Kleine Noordwaard study area.

### 4.3 Implications for management

The findings of this study have a number of practical implications for future river delta restoration. The current net area-averaged sedimentation of  $6.1 \text{ mm year}^{-1}$  is just enough to compensate the actual rate of sea-level rise and soil subsidence in the Netherlands, which are  $2 \text{ mm year}^{-1}$  (Ligvoet et al., 2015) and  $0\text{-}0.25 \text{ mm year}^{-1}$  respectively for the Biesbosch (Kooi et al., 1998). However, sedimentation in the area cannot compensate the high end scenarios for sea-level rise of  $0.4$  to  $10.5 \text{ mm year}^{-1}$  as calculated for the Netherlands by Katsman et al. (2011), especially since freshly deposited sediment will compact over the years and thus result in a lower net sedimentation. According to van der Deijl et al. (2017), the trapping efficiency of the area amounted to 0.29 for the period July 2014 to March 2015. This low trapping efficiency well matches the purpose of opening the 'Kleine Noordwaard' polder, which was to function as an overflow area to divert floodwater from the River Nieuwe Merwede towards the south; a rapid silting up of the channel and tidal area is then undesired as it would reduce the flow capacity of the wetland. When the objective of opening the polder would shift to using natural sedimentation as a measure for compensating sea level rise, there is room to enhance the sediment trapping and increase the deposition rate of the area. This might be achieved in several ways: firstly, deposition in the study area could be enhanced by increasing the supply of water and sediment to the area, for example by modifying the inlet geometry. Secondly, lowering wave-generated shear stresses will reduce resuspension at the intertidal flats. This could be achieved by reducing the wind fetch length by the establishment of vegetation or by the construction of topographic irregularities. Finally, a large proportion of incoming sediment leaves the area without deposition via the channels through the downstream outlet. Reducing this direct pass-through transfer by increasing the residence time of the incoming water through adapting the channel course through the wetland, or reducing the outlet size might also increase trapping efficiency and deposition. Such measures to increase the sediment trapping efficiency and sedimentation rates might also be considered for other wetlands, especially those where current sedimentation rates are not sufficient to compensate

sea-level rise and soil subsidence. Overall, conversion of delta polders into wetlands may be an effective strategy of delta restoration, since sedimentation compensates at least partly for sea level rise and land subsidence.

## 5 Conclusions

Field measurements on water and sediment flow, topography and channel depth carried out over an 8-year period (2008-2015) allowed to quantify both the amount and the spatial patterns in deposition and erosion in the formerly embanked area Kleine Noordwaard in the lower Rhine-Meuse delta. The main conclusions of this study are:

1. During this period the total sediment budget of the ‘Kleine Noordwaard’ study area amounted to  $37.3 \cdot 10^3 \text{ m}^3 \text{ year}^{-1}$ , which corresponds to a net area-averaged sedimentation rate of  $6.4 \text{ mm year}^{-1}$  and an import of  $46.8 \text{ kton year}^{-1}$ .
2. Largest rates of sedimentation ( $14.3 \text{ mm year}^{-1}$ ) took place in the channels, and channel sedimentation contributed approximately 44% to the total sediment budget. Wide intertidal flats and oversized parallel channels resulted in enhanced sedimentation in the channels during the first years after opening. Over time, both channel deposition and erosion rates have decreased, resulting in a net sedimentation decreased from  $18.5 \text{ mm year}^{-1}$  to  $12.6 \text{ mm year}^{-1}$ , which implies that the filling-up of the channels tends towards morphodynamic equilibrium.
3. In the intertidal area sand deposition occurs primarily at low lying locations close to the channels, while mud deposition occurs primarily further away from the channels and inlet. Wind-driven resuspension of the newly deposited material at the intertidal flats takes place regularly due to small water depths and the absence of vegetation.
4. A short wind fetch length is probably the major reason for the low rates of marsh erosion in the majority of the study area.
5. The current net sedimentation is enough to compensate for the actual rate of sea-level rise and land subsidence, but not for the high end scenarios of sea-level rise. The net sedimentation in the Kleine Noordwaard study area - and wetlands in general - could be enhanced by altering the lay-out of the polder channels and the size of the upstream and downstream openings, increasing the supply of sediment into the area and the residence time within the polder.
6. The conversion of polders in delta areas into wetlands where renewed sediment deposition occurs may be an effective strategy of delta restoration, since sedimentation compensates at least partly for sea level rise and land subsidence.

**25** *Data availability.* We will make the following data available via the Dryad repository (<http://datadryad.org/>):

1. Difference in channel bed level for each monitoring period (TIF) (Figure 3, Figure 4, Figure 5)
2. Initial Digital Elevation Model of the study area (TIF) (Figure 1, Figure 3, Figure 6)
3. Locations of inlet centre, and outlet (TIF)

4. Location of dredged area (TIF)
5. Total sedimentation at the intertidal flats (ascii xyz) (Figure 6a)
6. Location and height of the cutbanks (ascii xyz) (Figure 6b)

*Author contributions.* H. Middelkoop and M. van der Perk have designed the research proposal. E.C. van der Deijl collected and analysed the data. E.C. van der Deijl, M. van der Perk and H. Middelkoop interpreted the data and finally E.C. van der Deijl prepared the manuscript with the contributions, revisions and final approval from all co-authors.

*Competing interests.* The authors declare that they have no conflict of interest.

*Acknowledgements.* This project is financed by the Dutch Technology Foundation STW (project nr. 12431). We thank Staatsbosbeheer, Rijkswaterstaat, Dr. Hans de Boois, Eelco Verschelling, Dr. Wim Hoek, Renske Visser, Nanda Kik and Wouter Zonneveld for the provided data, assistance, logistic support and knowledge.

## References

- Actueel Hoogtebestand Nederland: Actueel Hoogtebestand Nederland, <https://www.ahn.nl/>, 2017.
- Anderson, C. J. and Mitsch, W. J.: Sediment, carbon, and nutrient accumulation at two 10-year-old created riverine marshes, *Wetlands*, 26, 779–792, 2006.
- 5 Anderson, C. J. and Mitsch, W. J.: Erratum to: Sediment, carbon, and nutrient accumulations at two 10-year-old created riverine marshes, *Wetlands*, 27, 774–774, 2007.
- Asselman, N. E. M. and Middelkoop, H.: Temporal variability of contemporary floodplain sedimentation in the Rhine-Meuse Delta, the Netherlands, *Earth Surf Proc Land*, 23, 595–609, 1998.
- Asselman, N. E. M. and Van Wijngaarden, M.: Development and application of a 1D floodplain sedimentation model for the River Rhine in  
10 the Netherlands, *J Hydrol*, 268, 127–142, 2002.
- Auerbach, L. W., Goodbred Jr, S. L., Mondal, D. R., Wilson, C. A., Ahmed, K. R., Roy, K., Steckler, M. S., Small, C., Gilligan, J. M., and Ackerly, B. A.: Flood risk of natural and embanked landscapes on the Ganges-Brahmaputra tidal delta plain, *Nature Climate Change*, 5, 153–157, 2015.
- Bleuten, W., Borren, W., Kleinveld, E., Oomes, L. B., and Timmermann, T.: Water and nutrient balances of the experimental site Mariapolder, The Netherlands, in: *Tidal Freshw Wetl*, edited by Barendrecht, A., Whigham, D. F., and Baldwin, A. H., chap. 18, pp. 167–206, Backhuys Publishers, Leiden, 2009.
- 15 Bureau Noordwaard: Ontwerpvisie ontpoldering noordwaard, Tech. rep., Rotterdam, 2006.
- Calvo-Cubero, J., Ibáñez, C., Rovira, A., Sharpe, P. J., and Reyes, E.: Mineral versus organic contribution to vertical accretion and elevation change in restored marshes (Ebro Delta, Spain), *Ecol Eng*, 61, 12–22, 2013.
- 20 Craft, C. B. and Casey, W. P.: Sediment and nutrient accumulation in floodplain and depressional freshwater wetlands of Georgia, USA, *Wetlands*, 20, 323–332, 2000.
- Darke, A. and Megonigal, J.: Control of sediment deposition rates in two mid-Atlantic Coast tidal freshwater wetlands, *Estuar Coast Shelf Sci*, 57, 255–268, 2003.
- Davidson-Arnott, R. G., van Proosdij, D., Ollerhead, J., and Schostak, L.: Hydrodynamics and sedimentation in salt marshes: examples from  
25 a macrotidal marsh, Bay of Fundy, *Geomorphology*, 48, 209–231, 2002.
- Day, J., Cable, J., Lane, R., and Kemp, P.: Sediment Deposition at the Caernarvon Crevasse during the Great Mississippi Flood of 1927: Implications for Coastal Restoration, *Water*, 8, 38, 2016.
- Day, J. W., Boesch, D. F., Clairain, E. J., Kemp, G. P., Laska, S. B., Mitsch, W. J., Orth, K., Mashriqui, H., Reed, D. J., Shabman, L., Simenstad, C. A., Streever, B. J., Twilley, R. R., Watson, C. C., Wells, J. T., and Whigham, D. F.: Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita, *Science*, 315, 1679–1684, 2007.
- 30 De Bont, C., Dirksen, G., Maas, G., Wolfert, H., Odé, O., and Polman, G.: Aardkundige en cultuurhistorische landschappen van de Biesbosch; Beschrijving en waardering als bouwstenen voor het landschapontwikkelingsconcept en de effectevaluatie voor rivierverruiming, Tech. rep., Alterra, Research Instituut voor de Groene Ruimte, Wageningen, doi:RIZA-rapport 2000.053, <http://edepot.wur.nl/119881>, 2000.
- De la Haye, M. A. A.: Jaarrapportage 2010 projectgebonden monitoring RWS Zuid-Holland, Noordwaard, Sliedrechtse Biesbosch, Oever-  
35 landen Hollandsch Diep (APL-polder) en Het Gors en De Aanwas, Tech. rep., Grontmij, 2011.
- DeLaune, R. D., Jugsujinda, A., Peterson, G. W., and Patrick, W. H.: Impact of Mississippi River freshwater reintroduction on enhancing marsh accretionary processes in a Louisiana estuary, *Estuar Coast Shelf Sci*, 58, 653–662, 2003.

- Fagherazzi, S. and Mariotti, G.: Mudflat runnels: Evidence and importance of very shallow flows in intertidal morphodynamics, *Geophys Res Lett*, 39, n/a–n/a, 2012.
- Fagherazzi, S. and Wiberg, P. L.: Importance of wind conditions, fetch, and water levels on wave-generated shear stresses in shallow intertidal basins, *J Geophys Res*, 114, 1–12, 2009.
- 5 Ferguson, R. I.: River Loads Underestimated by Rating Curves, *Water Resources Research*, 22, 74–76, doi:10.1029/WR022i001p00074, <http://doi.wiley.com/10.1029/WR022i001p00074>, 1986.
- French, J. R. and Spencer, T.: Dynamics of sedimentation in a tide-dominated backbarrier salt marsh, Norfolk, UK, *Mar Geol*, 110, 315–331, 1993.
- Gell, P., Fluin, J., Tibby, J., Hancock, G., Harrison, J., Zawadzki, A., Haynes, D., Khanum, S., Little, F., and Walsh, B.: Anthropogenic  
10 acceleration of sediment accretion in lowland floodplain wetlands, Murray–Darling Basin, Australia, *Geomorphology*, 108, 122–126, 2009.
- Grontmij: Natuurontwikkeling Noordwaard - Inrichtingsplan, Tech. rep., Grontmij Advies & Techniek bv, eindhoven, 2002.
- Heiri, O., Lotter, A. F., and Lemcke, G.: Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results, *J Paleolimnol*, 25, 101–110, 2001.
- 15 Hudson, P. F., Middelkoop, H., and Stouthamer, E.: Flood management along the Lower Mississippi and Rhine Rivers (The Netherlands) and the continuum of geomorphic adjustment, *Geomorphology*, 101, 209–236, 2008.
- Hung, N. N., Delgado, J. M., Güntner, A., Merz, B., Bárdossy, A., and Apel, H.: Sedimentation in the floodplains of the Mekong Delta, Vietnam. Part I: Suspended sediment dynamics, *Hydrol Process*, 28, 3132–3144, 2014a.
- Hung, N. N., Delgado, J. M., Güntner, A., Merz, B., Bárdossy, A., and Apel, H.: Sedimentation in the floodplains of the Mekong Delta,  
20 Vietnam Part II: Deposition and erosion, *Hydrol Process*, 28, 3145–3160, 2014b.
- Hupp, C. R., Demas, C. R., Kroes, D. E., Day, R. H., and Doyle, T. W.: Recent sedimentation patterns within the central Atchafalaya Basin, Louisiana, *Wetlands*, 28, 125–140, 2008.
- Ibáñez, C., Canicio, A., Day, J. W., and Curco, A.: Morphologic development, relative sea level rise and sustainable management of water and sediment in the Ebro Delta, Spain, *J Coast Conserv*, 3, 191–202, 1997.
- 25 Ibáñez, C., Day, J. W., and Reyes, E.: The response of deltas to sea-level rise: Natural mechanisms and management options to adapt to high-end scenarios, *Ecol Eng*, 65, 122–130, 2014.
- Islam, M. R., Begum, S. F., Yamaguchi, Y., and Ogawa, K.: The Ganges and Brahmaputra rivers in Bangladesh: basin denudation and sedimentation, *Hydrol Process*, 13, 2907–2923, 1999.
- Katsman, C. A., Sterl, A., Beersma, J. J., van den Brink, H. W., Church, J. A., Hazeleger, W., Kopp, R. E., Kroon, D., Kwadijk, J., Lammersen,  
30 R., Lowe, J., Oppenheimer, M., Plag, H. P., Ridley, J., von Storch, H., Vaughan, D. G., Vellinga, P., Vermeersen, L. L. A., van de Wal, R. S. W., and Weisse, R.: Exploring high-end scenarios for local sea level rise to develop flood protection strategies for a low-lying delta—the Netherlands as an example, *Climatic Change*, 109, 617–645, 2011.
- Khadim, F. K., Kar, K. K., Halder, P. K., Rahman, M. A., and Morshed, A. M.: Integrated Water Resources Management (IWRM) impacts in south west coastal zone of Bangladesh and fact-finding on Tidal River Management (TRM), *J Water Resource Prot*, 05, 953–961, 2013.
- 35 Kirwan, M. L. and Megonigal, J. P.: Tidal wetland stability in the face of human impacts and sea-level rise., *Nature*, 504, 53–60, 2013.
- Kleinhans, M. G., Weerts, H. J., and Cohen, K. M.: Avulsion in action: Reconstruction and modelling sedimentation pace and upstream flood water levels following a Medieval tidal-river diversion catastrophe (Biesbosch, The Netherlands, 1421–1750AD), *Geomorphology*, 118, 65–79, 2010.

- Kooi, H., Johnston, P., Lambeck, K., and Smither, C.: Geological causes of recent (100 yr) vertical land movement in the Netherlands, *Tectonophysics*, 299, 297–316, 1998.
- Leonard, L. A.: Controls of sediment transport and deposition in an incised mainland marsh basin, southeastern North Carolina, *Wetlands*, 17, 263–274, 1997.
- 5 Leonardi, N., Ganju, N. K., and Fagherazzi, S.: A linear relationship between wave power and erosion determines salt-marsh resilience to violent storms and hurricanes., *PNAS*, 113, 64–68, 2016.
- Ligvoet, W., Bregman, B., Dorland, R., ten Brinke, W., de Vos, R., Petersen, A., and Visser, H.: Klimaatverandering. Samenvatting van het vijfde IPCC-assessment en een vertaling naar Nederland, [http://www.stowa.nl/Upload/nieuws/Klimaatverandering\[\\_\]SamenvattingvanhetvijfdeIPCC-assessmenteneenvertalingnaarNederland.pdf](http://www.stowa.nl/Upload/nieuws/Klimaatverandering[_]SamenvattingvanhetvijfdeIPCC-assessmenteneenvertalingnaarNederland.pdf), 2015.
- 10 Mariotti, G. and Fagherazzi, S.: Wind waves on a mudflat: The influence of fetch and depth on bed shear stresses, *Cont Shelf Res*, 60, S99–S110, 2013.
- Marra, W. A., Kleinhans, M. G., and Addink, E. A.: Network concepts to describe channel importance and change in multichannel systems: test results for the Jamuna River, Bangladesh, *Earth Surf Proc Land*, 39, 766–778, 2014.
- Middelkoop, H.: Embanked floodplains in the Netherlands. Geomorphological evolution over various time scales., Phd thesis, Utrecht University, The Netherlands, *Netherlands Geographical Studies* 224., 1997.
- 15 Middelkoop, H. and Asselman, N. E. M.: Spatial variability of floodplain sedimentation at the event scale in the Rhine–Meuse delta, The Netherlands, *Earth Surf Proc Land*, 23, 561–573, 1998.
- Middelkoop, H. and van der Perk, M.: Modelling spatial patterns of overbank sedimentation on embanked floodplains, *Geogr Ann*, 80A, 95–109, 1998.
- 20 Mitchener, H. and Torfs, H.: Erosion of mud/sand mixtures, *Coastal Engineering*, 29, 1–25, 1996.
- Mitsch, W. J., Nedrich, S. M., Harter, S. K., Anderson, C., Nahlik, A. M., and Bernal, B.: Sedimentation in created freshwater riverine wetlands: 15 years of succession and contrast of methods, *Ecol Eng*, 72, 25–34, 2014.
- Neubauer, S. C., Anderson, I. C., Constantine, J. A., and Kuehl, S. A.: Sediment Deposition and Accretion in a Mid-Atlantic (U.S.A.) Tidal Freshwater Marsh, *Estuar Coast Shelf Sci*, 54, 713–727, 2002.
- 25 Paola, C., Twilley, R. R., Edmonds, D. A., Kim, W., Mohrig, D., Parker, G., Viparelli, E., and Voller, V. R.: Natural processes in delta restoration: application to the Mississippi Delta., *Annu Rev Mar Sci*, 3, 67–91, 2011.
- Pasternack, G. and Brush, G.: Seasonal Variations in Sedimentation and Organic Content in Five Plant Associations on a Chesapeake Bay Tidal Freshwater Delta, *Estuar Coast Shelf Sci*, 53, 93–106, 2001.
- Pethick, J. S.: Long-term Accretion Rates on Tidal Salt Marshes, *J Sediment Res*, Vol. 51, 571–577, 1981.
- 30 Reed, D. J., de Luca, N., and Foote, a. L.: Effect of hydrologic management on marsh surface sediment deposition in coastal Louisiana, *Estuaries*, 20, 301, 1997.
- Reed, D. J., Spencer, T., Murray, A. L., French, J. R., and Leonard, L.: Marsh surface sediment deposition and the role of tidal creeks : Implications for created and managed coastal marshes, *J Coast Conserv*, 5, 81–90, 1999.
- Rijke, J., van Herk, S., Zevenbergen, C., and Ashley, R.: Room for the River: delivering integrated river basin management in the Netherlands, *International Journal of River Basin Management*, 10, 369–382, 2012.
- 35 Rijkswaterstaat: Water data, <https://www.watergegevens.rws.nl/>, 2016.
- Schile, L. M., Callaway, J. C., Morris, J. T., Stralberg, D., Thomas Parker, V., and Kelly, M.: Modeling tidal marsh distribution with sea-level rise: Evaluating the role of vegetation, sediment, and upland habitat in marsh resiliency, *PLoS One*, 9, 2014.

- Siobhan Fennessy, M., Brueske, C. C., and Mitsch, W. J.: Sediment deposition patterns in restored freshwater wetlands using sediment traps, *Ecol Eng*, 3, 409–428, 1994.
- Syvitski, J. P. M.: Deltas at risk, *Sustain Sci*, 3, 23–32, 2008.
- Syvitski, J. P. M. and Saito, Y.: Morphodynamics of deltas under the influence of humans, *Glob Planet Change*, 57, 261–282, 2007.
- 5 Takekawa, J. Y., Woo, I., Athearn, N. D., Demers, S., Gardiner, R. J., Perry, W. M., Ganju, N. K., Shellenbarger, G. G., and Schoellhamer, D. H.: Measuring sediment accretion in early tidal marsh restoration, *Wetl Ecol Manag*, 18, 297–305, 2010.
- Temmerman, S., Govers, G., Wartel, S., and Meire, P.: Spatial and temporal factors controlling short-term sedimentation in a salt and freshwater tidal marsh, scheldt estuary, Belgium, SW Netherlands, *Earth Surf Proc Land*, 28, 739–755, 2003.
- Temmerman, S., Bouma, T. J., Govers, G., and Lauwaet, D.: Flow paths of water and sediment in a tidal marsh: Relations with marsh  
10 developmental stage and tidal inundation height, *Estuaries*, 28, 338–352, 2005a.
- Temmerman, S., Bouma, T. J., Govers, G., Wang, Z. B., De Vries, M. B., and Herman, P. M. J.: Impact of vegetation on flow routing and sedimentation patterns: Three-dimensional modeling for a tidal marsh, *J Geophys Res*, 110, 1–18, 2005b.
- Thonon, I., Middelkoop, H., and Perk, M. V. D.: The influence of floodplain morphology and river works on spatial patterns of overbank deposition, *Neth J Geosci*, 81, 63–75, 2007.
- 15 Tonelli, M., Fagherazzi, S., and Petti, M.: Modeling wave impact on salt marsh boundaries, *J Geophys Res*, 115, 2010.
- van de Koppel, J., van der Wal, D., Bakker, J. P., and Herman, P. M. J.: Self-organization and vegetation collapse in salt marsh ecosystems., *The American Naturalist*, 165, E1–12, 2005.
- van der Deijl, E. C., van der Perk, M., and Middelkoop, H.: Factors controlling sediment trapping in two freshwater tidal wetlands in the Biesbosch area, The Netherlands, *Journal of Soils and Sediments*, pp. 1–17, doi:10.1007/s11368-017-1729-x, <http://link.springer.com/10.1007/s11368-017-1729-x>,  
20 1007/s11368-017-1729-x, 2017.
- van Proosdij, D., Davidson-Arnott, R. G., and Ollerhead, J.: Controls on spatial patterns of sediment deposition across a macro-tidal salt marsh surface over single tidal cycles, *Estuar Coast Shelf Sci*, 69, 64–86, doi:10.1016/j.ecss.2006.04.022, <http://linkinghub.elsevier.com/retrieve/pii/S0272771406001375>, 2006a.
- van Proosdij, D., Ollerhead, J., and Davidson-Arnott, R. G.: Seasonal and annual variations in the volumetric sediment balance of a macro-  
25 tidal salt marsh, *Mar Geol*, 225, 103–127, 2006b.
- van Wijnen, H. and Bakker, J.: Long-term Surface Elevation Change in Salt Marshes: a Prediction of Marsh Response to Future Sea-Level Rise, *Estuar Coast Shelf Sci*, 52, 381–390, 2001.
- Vandenbruwaene, W., Meire, P., and Temmerman, S.: Formation and evolution of a tidal channel network within a constructed tidal marsh, *Geomorphology*, 151-152, 114–125, 2012.
- 30 Vandenbruwaene, W., Schwarz, C., Bouma, T., Meire, P., and Temmerman, S.: Landscape-scale flow patterns over a vegetated tidal marsh and an unvegetated tidal flat: Implications for the landform properties of the intertidal floodplain, *Geomorphology*, 231, 40–52, 2015.
- Verschelling, E., van der Deijl, E., van der Perk, M., Sloff, K., and Middelkoop, H.: Effects of discharge, wind, and tide on sedimentation in a recently restored tidal freshwater wetland, *Hydrological Processes*, 31, 2827–2841, doi:10.1002/hyp.11217, <http://doi.wiley.com/10.1002/hyp.11217>, 2017.
- 35 Whitehouse, R., Bassoullet, P., Dyer, K., Mitchener, H., and Roberts, W.: The influence of bedforms on flow and sediment transport over intertidal mudflats, *Cont Shelf Res*, 20, 1099–1124, 2000.

Zonneveld, I.: De Brabantse Biesbosch : een studie van bodem en vegetatie van een zoetwatergetijdendelta bestaande uit de drie gedeelten A, B en C = a study of soil and vegetation of a freshwater tidal delta consisting of three volumes A, B and C, Ph.D. thesis, <http://library.wur.nl/WebQuery/wurpubs/487770>, 1959.



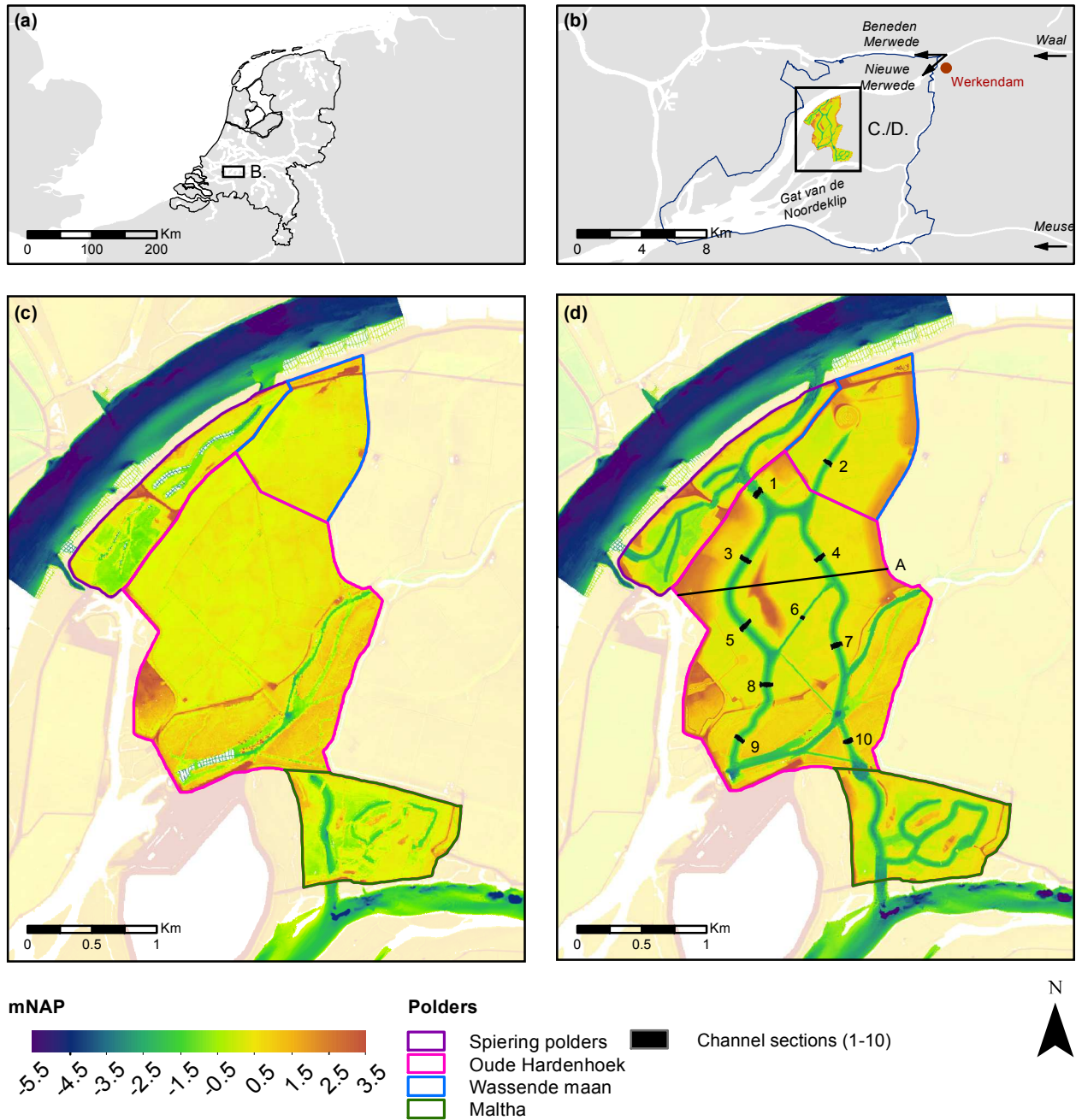
Table 1: Net sedimentation and deposition in various types of delta compartments. When a source only gives deposition in volume, the concomitant change in height is calculated using a sediment density of 1150 kg m<sup>-3</sup>

Type	Net sedimentation [mm year <sup>-1</sup> ]	Deposition [mm year <sup>-1</sup> ]	Deposition [mm year <sup>-1</sup> ]	SSC / Turbidity	Amplitude	Method	Source
Marshes	0.6						
Floodplains	1.1					Cores (137Cs , 210 Pb)	Craft and Casey (2000)
Wetland	1.2					Cores (137Cs , 210 Pb)	Craft and Casey (2000)
Wetland		1.5	1.1 - 8.4 g m <sup>-2</sup> day <sup>-1</sup>			Cores (137Cs , 210 Pb)	Craft and Casey (2000)
TFW		1.5	1.5-2.5 kg m <sup>-2</sup> year <sup>-1</sup>			Sediment traps (filters)	Reed et al. (1997)
					0.4 - 0.5	Waterlevels, watersamples	Bleuten et al. (2009)
Floodplains		2.2	2.56 kg m <sup>-2</sup> year <sup>-1</sup>	30 mg l <sup>-1</sup>		Sediment traps (artificial grass)	Middelkoop and Asselman (1998)
Floodplains		2.8		30 mg l <sup>-1</sup>		Cores	Middelkoop (1997)
Floodplains		2.5				Cores (137Cs , 210 Pb)	Gell et al. (2009)
Crevasse splay		2.5-3				Cores (137Cs , 210 Pb)	Day et al. (2016)
Salt Marshes	3.9			50-150 mg l <sup>-1</sup>	3.2 (nt) - 6.4 (st)	Marker horizons, sediment traps	French and Spencer (1993)
2 River Marshes		4.1	4.5-4.9 kg m <sup>-2</sup> year <sup>-1</sup>	17 - 35 NTU		Marker horizons	Anderson and Mitsch (2006)
TFW	4.3-5.5				0.7 (nt) - 0.9 (st)	Sediment traps (tiles), cores (Be7)	Neubauer et al. (2002)
3 Salt Marshes	0-11				1.3-2.3	Marker horizons, surface elevation, clay layer thickness	van Wijnen and Bakker (2001)
Floodplains		6	6.86 kg m <sup>-2</sup> year <sup>-1</sup>	90 (mean) - 400 mg l <sup>-1</sup> (flood)		Sediment traps and optical backscatter sensors	Hung et al. (2014a, b)
Salt Marshes	6			50 mg l <sup>-1</sup>	3.2 (nt) - 6.4 (st)	Sediment traps (filters)	French & Spencer, unpubl. in Reed et al. (1999)
Wetland Basin	5-10		5.9-12.8 kg m <sup>-2</sup> year <sup>-1</sup>			Sediment traps (bottles)	Siobhan Fennessy et al. (1994)

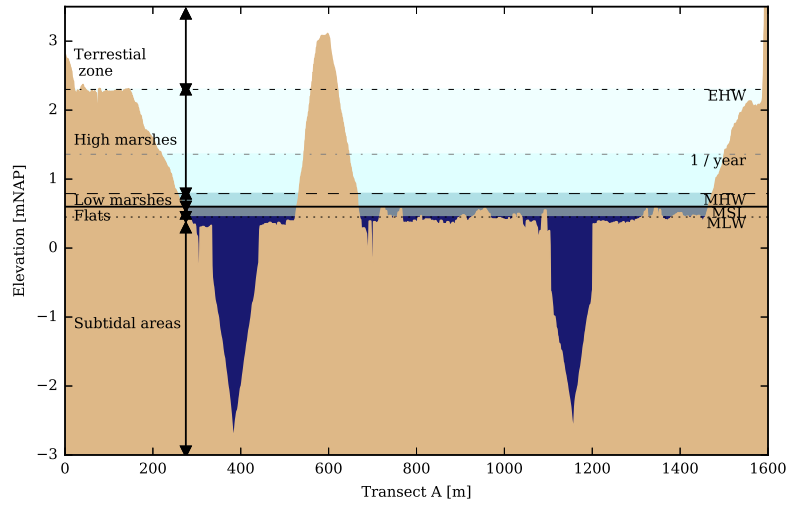
Continued on next page

Table 1 – continued from previous page

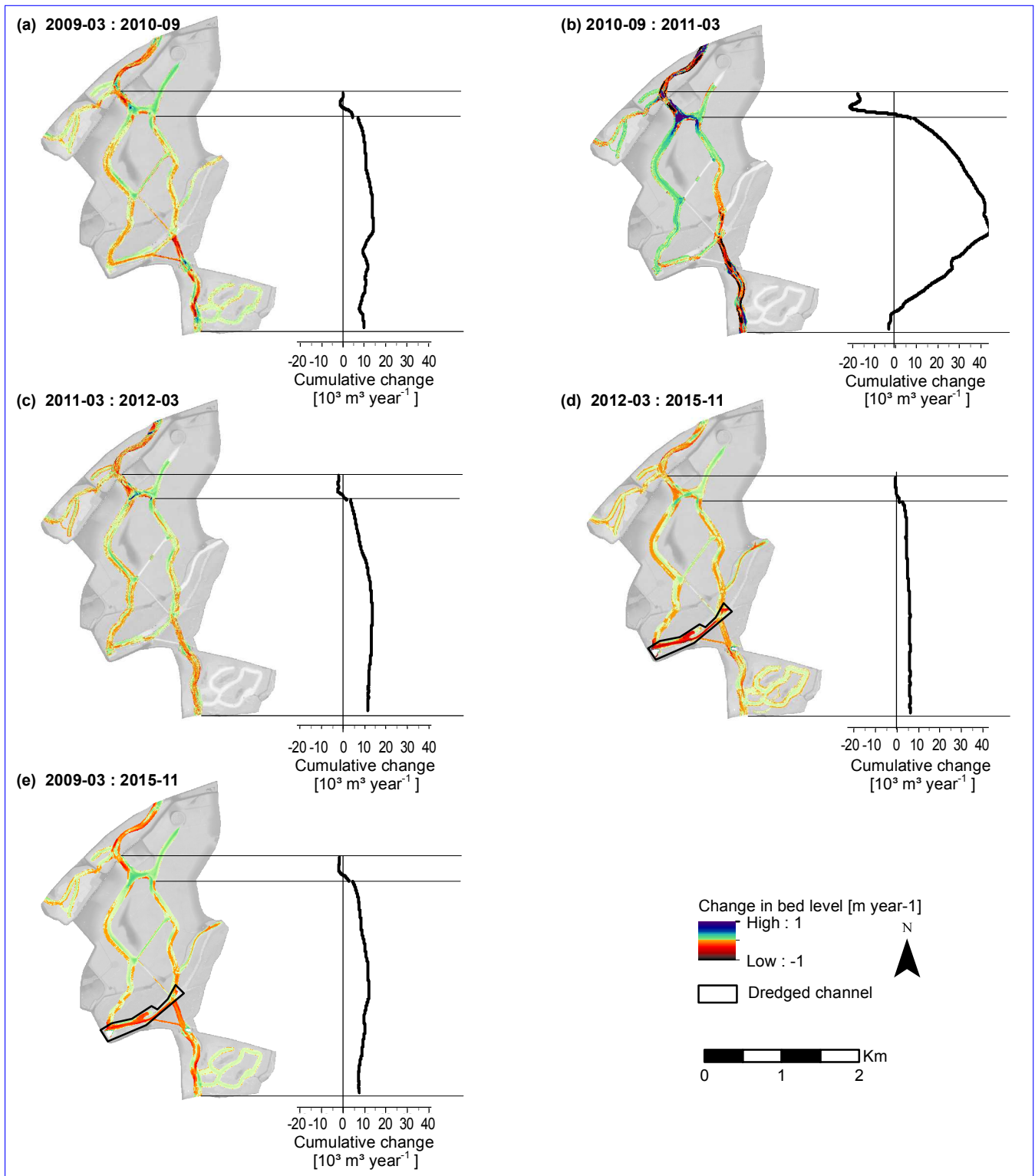
Type	Net sedimentation [mm year <sup>-1</sup> ]	Deposition [mm year <sup>-1</sup> ]	Deposition [mm year <sup>-1</sup> ]	SSC / Turbidity	Amplitude [m]	Method	Source
TFW		8.7	1 g cm <sup>-2</sup> year <sup>-1</sup>		3.2 (nt) - 6.4 (st)	Sediment traps (tiles)	Pasternack and Brush (2001)
Salt Marsh	8-14	21.3	0.2-67 g m <sup>-2</sup> tide <sup>-1</sup>	300 mg l <sup>-1</sup>	14	DEM, Sediment plates	van Proosdij et al. (2006a, b)
TFW	12		3.6 g m <sup>-2</sup> day <sup>-1</sup>	9 mg l <sup>-1</sup>	1.8 (st)	Sediment traps (tiles), Marker horizons	Darke and Megonigal (2003)
TFW	12			5 mg l <sup>-1</sup>		Marker horizons, Surface elevation tables	Calvo-Cubero et al. (2013)
Wetland	14 (13 years), 42 (1996), 55 (2009)					Sediment traps (bottles), Marker horizons	Mitsch et al. (2014)
TFW	15.5			27 mg l <sup>-1</sup>		Marker horizons, Surface elevation tables	Calvo-Cubero et al. (2013)
14 Salt Marshes	0.02-17				2-3 (nt) - 5-6 (st)	Model	Pethick (1981)
salt marsh		12.3	13.8-63.7 g m <sup>-2</sup> day <sup>-1</sup>	10-42 mg l <sup>-1</sup>	1.8 (st)	Sediment traps (filters)	Leonard (1997)
TFW	27		12.9 m <sup>-2</sup> day <sup>-1</sup>	19 mg l <sup>-1</sup>	1.8 (st)	Sediment traps (tiles), Marker horizons	Darke and Megonigal (2003)
River bed	39			1037 MT year <sup>-1</sup>		Gauging stations	Islam et al. (1999)
TFW	180					Fast static gps survey	Auerbach et al. (2015)



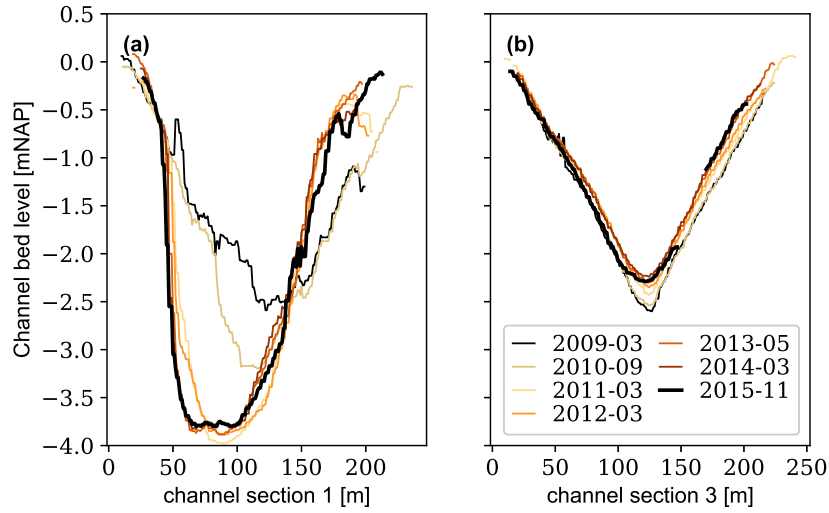
**Figure 1.** The study area Kleine Noordwaard, which is located within the Biesbosch Freshwater Tidal Wetland, in the lower Rhine and Meuse delta in the southwest of the Netherlands (a and b). Elevation is shown in meters, with respect to the Dutch Ordnance Datum (NAP) for the period before (c) and after depoldering (d).



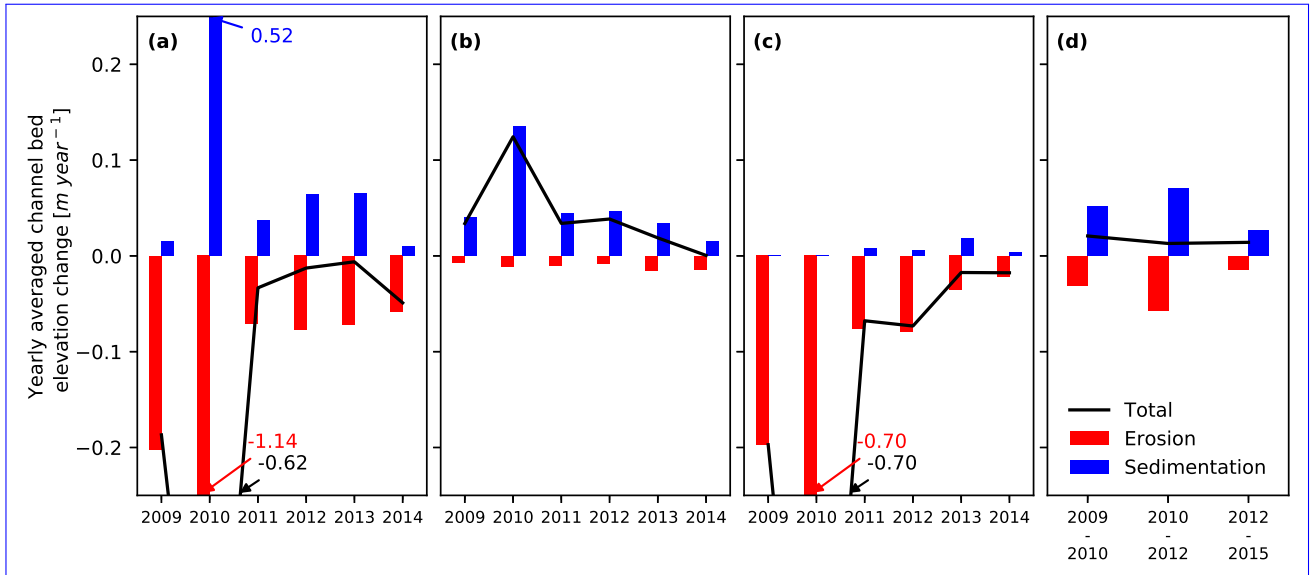
**Figure 2.** Elevation of Transect A (see Fig. 1) with respect to the Dutch Ordnance Datum (m NAP) with subdivision of the area into subtidal areas, flats, low and high marshes, and terrestrial zone relative to mean low water (MLW), mean sea level (MSL), mean high water (MHW), the maximum observed water level (EHW) and the water level for a peak discharge or storm with return period of 1 year, which were used to divide the study area in.



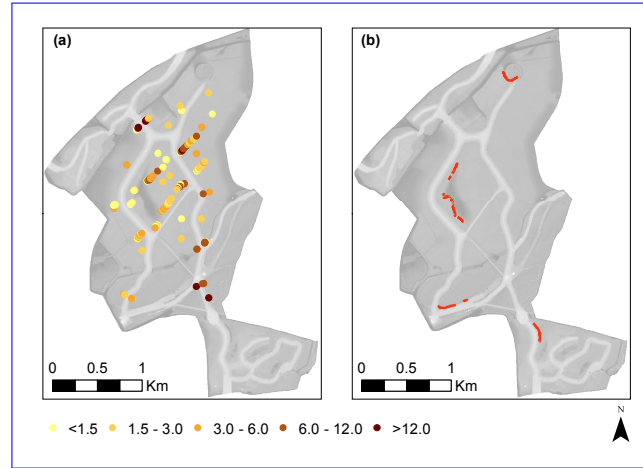
**Figure 3.** The difference in channel bed level and the cumulative channel bed volume for each monitoring period. The cumulative channel bed volume is shown along a N-S transect starting from the Spieringpolders (purple in Fig. 1). The budget of the Wassende Maan (blue in Fig. 1) is added at once at the second black line. The channel in the southwest of the study area was dredged in the monitoring period 2012-2015. The dredged area is excluded in the analysis and not shown in the cumulative channel bed volume.



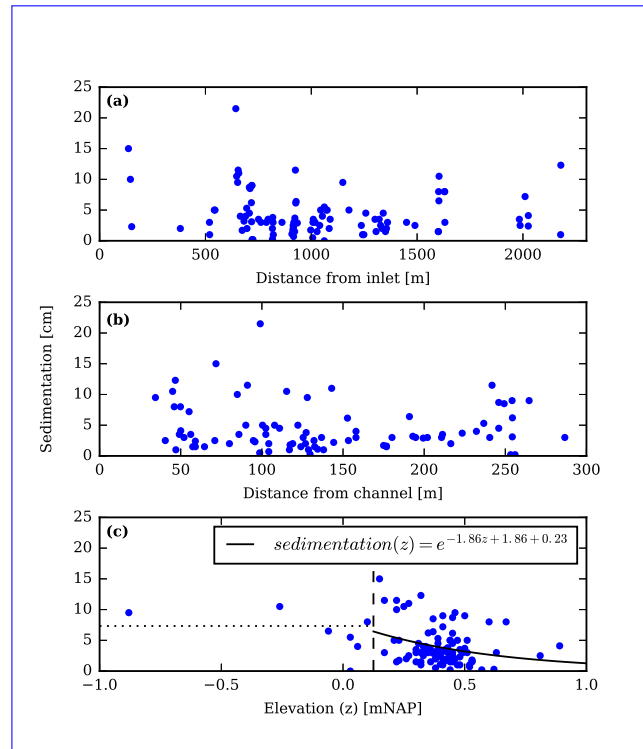
**Figure 4.** Bed level of channel section 1 (a) and 3 (b) for all monitoring campaigns. (see Fig. 1 for the locations of the cross sections)



**Figure 5.** The yearly averaged channel section sedimentation (blue bars), erosion (red bars) and total change in height (black lines) for the inlet (a), the centre (b), the outlet (c) and the entire study area (d), which was opened 7 May 2008 and experienced a peak discharge event from 8 to 19 January, 2011. Yearly averaged channel section sedimentation erosion and total change in height sedimentation rates for the entire area are only available for the periods 2009-2010, 2010-2012 and 2012-2015, since bathymetric measurements were only executed in all channels in 2009, 2010, 2012 and 2015; and in channel sections (see Fig. 1d) in 2011, 2013 and 2014.



**Figure 6.** The total sedimentation [cm] in the subtidal and intertidal area (a) and the location of the cutbanks (b) as measured during field campaigns of 2014



**Figure 7.** Total sedimentation during the period 2008-2014 in the subtidal and intertidal area, with respect to the distance from the inlet of the system (a), distance from the channel (b), and the elevation (c). The dotted and thick lines show the models for sedimentation in the subtidal and intertidal area. The second intercept represents the bias correction factor of Ferguson (1986).