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

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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~~aggradation~~, 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~~aggradation~~ and erosion in newly created wetlands. We quantified both the magnitude and spatial patterns of sedimentimentation~~aggradation~~ 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~~aggradation~~ 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~~At the intertidal flats~~, sand deposition~~aggradation~~ especially takes place at low lying locations close to the channels. Mud deposition~~aggradation~~ 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~~Cut bank retreat~~ 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~~aggradation~~ 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~~46~~ % 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~~29.7~~ 10^3 m^3 year^{-1}, which corresponds to a net area-averaged deposition~~aggradation~~ rate of 6.4~~5.1~~ 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~~Sediment deposition~~ is variable and complex. This table suggests that sedimentation~~accumulation~~ is positively related to the suspended sediment concentration. Furthermore, it is widely known from the literature that sedimentation~~sediment deposition~~ 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~~sediment deposition~~ 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~~aggradation~~ 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~~aggradation~~ in the Biesbosch tidal freshwater wetland.

The aim of this paper is to quantify both the magnitude and the spatial patterns of sediment deposition~~aggradation~~ and erosion in one of the formerly embanked areas, 'Kleine Noordwaard'. For this, different sources of data were combined. Net sedimentation rates were~~Sediment accumulation was~~ 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. ~~Furthermore, we compared the rates and patterns to those in other wetlands and the sediment load of the River Rhine.~~

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. 1 (a) 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. ~~The channel in the Spiering polders in the north forms the inlet, while the channel in southern polder Maltha forms the outlet of the system.~~ On 7 May 2008, the embankments were opened and the channels were ~~inlet channel was~~ connected to the River Nieuwe Merwede in the north and ~~the outlet~~ 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 distributary of the River Rhine (Fig. 1). The River Rhine has an average discharge of 2200 m^3 s^{-1} and an average suspended sediment concentration of 15 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 m^3 s^{-1} (10-year-return) with maximum concentrations between 120 and 260 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) have shown that water is in general imported in the north with an average discharge of 89 m^3 s^{-1} and an average concentration of 26 mg l^{-1}, with 191 m^3 s^{-1} and 114 mg l^{-1} during a raised discharge event (4500 m^3 s^{-1} at the German-Dutch border). In the south water is in general exported with an average discharge of 86 m^3 s^{-1} and an average concentration of 19 mg l^{-1}, with 178 m^3 s^{-1} and 62 mg l^{-1} during the raised discharge event. Import, with a maximum of 16 m^3 s^{-1}, only takes place when the water level rises rapidly at the onset of flood tide. ~~Channels are always submerged, while the former polder bed comprises a system of mud flats, which are either submerged or dry, depending on the water level.~~

The water level is influenced by the tide, which is mixed semidiurnal with ~~has~~ a range of approximately 0.2 to 0.4 m (Rijkswaterstaat, 2016), the wind direction and speed,~~and~~ 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). ~~The area is composed of deep open water (18%), mud flats (31%), and a terrestrial zone (51%).~~ In order to reduce the hydraulic roughness, the marshes and terrestrial zone are mown~~is mowed~~ before the winter period, and most of the vegetation is effectively shortened through grazing by birds, horses, and cows. The vegetation ~~in the terrestrial zone~~ 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. ~~To establish a sediment budget of the study area, we determined separate sediment budgets for the channels (surface levels below 0 m above Dutch Ordnance Datum (NAP)), intertidal flats (surface levels between 0 and 0.5 m NAP), and the terrestrial zone (surface levels above 0.5 m NAP). For all subareas 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~~sediment accretion and loss~~ 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^3 s^{-1} and an elevated SSC of up to 260 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~~patterns in 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 ~~were~~had been consistent throughout the years.

2.2.2 Subtidal and intertidal area~~Intertidal flats~~

We determined the sediment budget of both the subtidal and the intertidal area~~the intertidal flats~~ by measuring the sedimentation~~vertical accretion~~ 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 ~~newly deposited layers of~~ 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~~flats~~ was calculated using a negative exponential relation between sediment deposition and surface elevation.~~multiplying the average thickness of the recently deposited sediment layer by the total area of the intertidal flats.~~

2.2.3 Marsh erosion~~Terrestrial zone~~

To determine the contribution of marsh~~bank~~ erosion to the budget of the channels and intertidal area~~flats~~, 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~~intertidal flats~~, and the eroded marshes~~terrestrial zone~~ 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^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 °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 ~~(Van der Deijl et al [in prep])~~ indicated that the area received approximately 5.8 % of the total sediment load of the River Rhine. The sediment load ~~for the period between May 2008 and November 2015~~ 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^{-3} for sand and a logarithmic increase with depth from 0.75 to 1.27 g cm^{-3} for the 3 cm of mud at the intertidal flat. A maximum density of 1.5 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 g cm^{-3} were assigned to the respective 0-1, 1-2, 2-3, and $>$ 3 cm depth intervals. For the sandy sediment deposited~~ that accumulated~~ in channels or eroded from the island, we used a bulk density of 1.47 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), (d) 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. 4 a 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~~erosion~~ of the channel to the depth of the River Nieuwe Merwede. The maps in Fig. 5 show that outer bend erosion has occurred in the majority of the channels and that ~~Furthermore, outer bends have eroded and~~ 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~~with hard bank protection~~, 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.

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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~~attain an equilibrium state between their geometry and the flow conditions~~. 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 m^3 s^{-1} and an elevated SSC of up to 260 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. 4 b 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 mm $year^{-1}$ to 15.4 mm $year^{-1}$ and 12.6 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~~an accumulation~~ of 21.7 10^3 m^3 $year^{-1}$, 18 10^3 m^3 $year^{-1}$ and 14.8 10^3 m^3 $year^{-1}$ and annual average sediment budgets of 32.4 kton $year^{-1}$, 26.9 kton $year^{-1}$ and 22.1 kton $year^{-1}$, respectively. The average channel sediment budget for the entire monitoring period (2009-2015) accounts for a net sedimentation~~an accumulation~~ of 14 mm $year^{-1}$, which corresponds to 16.7 10^3 m^3 $year^{-1}$ and 24.9 kton $year^{-1}$.

3.3 Subtidal and intertidal area~~Intertidal flats~~

Figure 6 A shows the spatial variation of the measured sedimentation in the subtidal and intertidal area~~sediment accumulation on the intertidal flats~~, and Fig. 7 shows the sedimentation~~sediment accumulation~~ 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~~the height of the flats~~ (graph (c)). Although the highest sedimentation~~accumulation~~ was measured along the channels, there is no significant relation between the total sedimentation~~accumulation~~ and the distance to the channel. This is likely partly due to the relatively high sedimentation~~accumulation~~ (>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~~accumulation~~ 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~~accumulation~~ 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. 7 (c). shows that the total sedimentation~~accumulation~~ generally decreases with increasing height of the tidal area~~flat~~. This relation is significant but it explains only 9 % of the variation in sedimentation~~accumulation~~. However, local variation in sedimentation~~accumulation~~ 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~~accumulation~~ rate of 11.3 $\pm$ 1.4 mm $year^{-1}$ and an annual average sediment budget of 5.21 10^3 m^3 $year^{-1}$ and 6.24 kton $year^{-1}$. The sediment budget of the intertidal area amounts 15.7 10^3 m^3 $year^{-1}$ and 22.4 kton $year^{-1}$.~~Between May 2008 and October 2014 an average of 43 $\pm$ 3.55 mm (standard deviation) of mud and sand, accumulated in the intertidal area. This corresponds to a sedimentationaccumulation rate of 6.6 $\pm$ 1.0 mm $year^{-1}$ and an annual average sediment budget of 21.613 10^3 m^3 $year^{-1}$ and 24.414.6 kton $year^{-1}$.~~

3.4 Marsh erosion~~Terrestrial area~~

Fig. 6 B. 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^3 of the island eroded between 2011 and 2014. The eroded volume~~sediment budget of the terrestrial area~~ is -10.3 m^3 $year^{-1}$, which corresponds to an erosion of 15.4 ton $year^{-1}$.

3.5 Total sediment budget and trapping efficiency

Between 2008 and 2015, the total sediment budget for the 'Kleine Noordwaard' area amounted to 37.3~~29.7~~ 10^3 m^3 $year^{-1}$, which corresponds to a net area-averaged sedimentation rate of 6.4~~5.1~~ mm $year^{-1}$ and an import of 46.8~~39.5~~ kton $year^{-1}$ for the first 6.5 years after depoldering. Sedimentation of 16.7 10^3 m^3 $year^{-1}$ in the channels accounts for approximately 44~~60~~ percent of the total budget. The vast majority of the remaining 56~~40~~ % comprises the annual sedimentation of 5.2 10^3 m^3 $year^{-1}$ and 15.8 10^3 m^3 $year^{-1}$ ~~13.0 10^3 m^3 $year^{-1}$~~ in the subtidal and intertidal area. Remobilization of sediment by erosion of marshes~~cut banks~~ occurred at a negligible rate of about -10.3 m^3 $year^{-1}$. During this period, the study area received an annual sediment load of approximately 85.6 kton $year^{-1}$. This implies that ~~the first 6.5 years after depoldering of the area~~ approximately 55~~46~~ % 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~~aggradation~~ has occurred in all years, but the actual channel deposition~~aggradation~~ rate has decreased over the years (see Fig. 5). Assuming a constant deposition~~accumulation~~ and erosion rate for the intertidal area~~- and terrestrial zone~~, we have accounted for the decrease in net channel sedimentation~~channel aggradation~~ 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~~25.5~~ 10^3 m^3 $year^{-1}$, which corresponds to a net area-averaged sedimentation rate of 6.2~~4.4~~ mm $year^{-1}$.

4 Discussion

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. ~~Yet the present study was designed to determine both the volume and the spatial patterns in sedimentation and erosion of the entire Kleine Noordwaard tidal freshwater wetland, which includes terrestrial area, tidal flats, and 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 ~~to attain an equilibrium state between their geometry and the flow conditions~~. 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~~Sediment accumulation~~ 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~~equilibrium state with the flow conditions~~, 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~~accumulation~~ and increasing mud deposition~~accumulation~~ 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~~accumulation~~ 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~~sediment accumulation~~, 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 ~~firstly,~~ micro topographic flow paths during low water levels (Hupp et al., 2008; Temmerman et al., 2005a); ~~secondly,~~ sheet flow during high water levels (Vandenbruwaene et al., 2015; Temmerman et al., 2005a); or ~~thirdly,~~ 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~~accumulation~~ 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~~cut bank retreat~~ 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. ~~Wind waves are generated by the transfer of energy from wind to the water surface. This transfer is determined by the length of the fetch (the unobstructed water surface over which the wind blows), and the mean water depth over this fetch (Fagherazzi and Wiberg, 2009).~~ 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 m s^{-1} under these conditions of water depth and fetch length. ~~This is probably the major reason for the low rates of cut bank retreat in the majority of the study area.~~ 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 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 m s^{-1}. However, resuspension of unconsolidated mud with a critical shear stress of 0.05 N m^{-2} (Mitchener and Torfs, 1996), already takes place at a wind speed greater than 5.5 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. ~~The results from this study do not allow drawing conclusions about the fate of the resuspended sediment, but possibly part of this sediment is exported from the study area during strong wind events or high river discharges.~~

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~~aggradation rate~~ of 6.4~~5.1~~ mm $year^{-1}$ for the period since the opening of the polder area and the estimated actual net area-averaged sedimentation~~aggradation~~ rate of 6.1~~4.4~~ mm $year^{-1}$ are well within the reported ranges for net sedimentation~~accumulation rates~~ on floodplains, wetlands, fresh- and salt-water marshes (see Table 1). Furthermore, the sedimentation~~aggradation rate~~ in the Kleine Noordwaard is within the range of the mean overbank sedimentation rates over the last century (0.18-11.55 mm $year^{-1}$ with a mean of 2.78 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~~aggradation rate~~ is larger than the 1-2 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~~aggradation~~ is consistent, but that the actual sedimentation~~aggradation~~ 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~~sediment aggradation rate~~ of 4.2 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., in prep.)~~ (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~~aggradation rate~~ of 6.1~~4.4~~ mm year^{-1} is just enough to compensate the actual rate of sea-level rise and soil subsidence in the Netherlands, which are 2 mm year^{-1} (Ligvoet et al., 2015) and 0-0.25 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 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~~accumulation~~. The area has only trapped approximately 55~~46~~ % of the incoming sediment in the study area and 3 % of the incoming sediment at Lobith (the Dutch-German border). 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.~~, which indicates that it is possible to optimise the sediment trapping efficiency and increase the aggradation rate of the study area. This might be achieved by reducing the resuspension at the intertidal flats by a decrease in the wave-generated shear stresses. This could be achieved by decreasing the fetch by the establishment of vegetation or by the construction of topographic irregularities. The aggradation rate 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. Such measures to increase the sediment trapping efficiency and aggradation rates can also be applied in other wetlands, especially those where current aggradation rates are not sufficient to compensate sea-level rise and soil 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:~~Existing data sets and field data were used to quantify both the amount and the spatial patterns in sediment accumulation and erosion in the formerly embanked area Kleine Noordwaard. The main conclusions of this study are:~~

1. During this period ~~the period 2008-2015~~ the total sediment budget of the ‘Kleine Noordwaard’ study area amounted to 37.3~~29.7~~ 10^3 m^3 $year^{-1}$, which corresponds to a net area-averaged sedimentation~~aggradation~~ rate of 6.4~~5.1~~ mm $year^{-1}$ and an import of 46.8~~0.95~~ kton $year^{-1}$. The area has trapped approximately 55~~46~~ % of the sediment delivered to the study area, which is approximately 3 % of the incoming sediment at Lobith (Dutch-German border).

2. Largest rates of sedimentation (14.3 mm $year^{-1}$) took place in the channels, and channel sedimentation contributed approximatively 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 mm $year^{-1}$ to 12.6 mm $year^{-1}$, which implies that the filling-up of the channels tends towards morphodynamic equilibrium.~~Largest rates of net sedimentationaccumulation (14.3 mm $year^{-1}$) occurred in the channels, which accounts for approximately 60 percent of the total budget, the other 40 percent comprises sedimentation in the intertidal area at an average rate of 6.6 mm $year^{-1}$. Cut bank retreat does not significantly contribute to the total sediment budget.~~

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.~~At the intertidal flats sand aggradation occurs primarily at low lying locations close to the channels, while mud aggradation occurs primarily further away from the channels and inlet.~~

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~~aggradation rate~~ is enough to compensate for the actual rate of sea-level rise and land~~soil~~ subsidence, but not for the high end scenarios of sea-level rise. The net sedimentation in~~aggradation rate of~~ 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.~~ by optimizing the sediment trapping efficiency of the area or by increasing the supply of water and sediment to the area.~~

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.

7. ~~The rates of accumulation and erosion in the channels decrease over time, which imply the channels tend to equilibrium between the flow conditions and their geometry.~~

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~~accumulation~~ 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.

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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^{-3}

Type	Net sedimentation [mm $year^{-1}$]	Deposition [mm $year^{-1}$]	Deposition	SSC / Turbidity	Amplitude [m]	Method	Source
Marshes	0.6					Cores (137Cs , 210 Pb)	Craft and Casey (2000)
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^{-2} day^{-1}			Sediment traps (filters)	Reed et al. (1997)
TFW		1.5	1.5-2.5 kg m^{-2} $year^{-1}$		0.4 - 0.5	Waterlevels, watersamples	Bleuten et al. (2009)
Floodplains		*2.2*	2.56 kg m^{-2} $year^{-1}$	30 mg l^{-1}		Sediment traps (artificial grass)	Middelkoop and Asselman (1998)
Floodplains		2.8		30 mg l^{-1}		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^{-1}	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^{-2} $year^{-1}$	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^{-2} $year^{-1}$	90 (mean) - 400 mg l^{-1} (flood)		Sediment traps and optical backscatter sensors	Hung et al. (2014a, b)
Salt Marshes	6			50 mg l^{-1}	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^{-2} $year^{-1}$			Sediment traps (bottles)	Siobhan Fennessy et al. (1994)

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Table 1 – continued from previous page

Type	Net sedimentation [mm $year^{-1}$]	Deposition [mm $year^{-1}$]	Deposition	SSC / Turbidity	Amplitude [m]	Method	Source
TFW		*8.7*	1 g cm^{-2} $year^{-1}$		3.2 (nt) - 6.4 (st)	Sediment traps (tiles)	Pasternack and Brush (2001)
Salt Marsh	8-14	*21.3*	0.2-67 g m^{-2} $tide^{-1}$	300 mg l^{-1}	14	DEM, Sediment plates	van Proosdij et al. (2006a, b)
TFW	12		3.6 g m^{-2} day^{-1}	9 mg l^{-1}	1.8 (st)	Sediment traps (tiles), Marker horizons	Darke and Megonigal (2003)
TFW	12			5 mg l^{-1}		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^{-1}		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^{-2} day^{-1}	10-42 mg l^{-1}	1.8 (st)	Sediment traps (filters)	Leonard (1997)
TFW	27		12.9 m^{-2} day^{-1}	19 mg l^{-1}	1.8 (st)	Sediment traps (tiles), Marker horizons	Darke and Megonigal (2003)
River bed	39			1037 MT $year^{-1}$		Gauging stations	Islam et al. (1999)
TFW	180					Fast static gps survey	Auerbach et al. (2015)

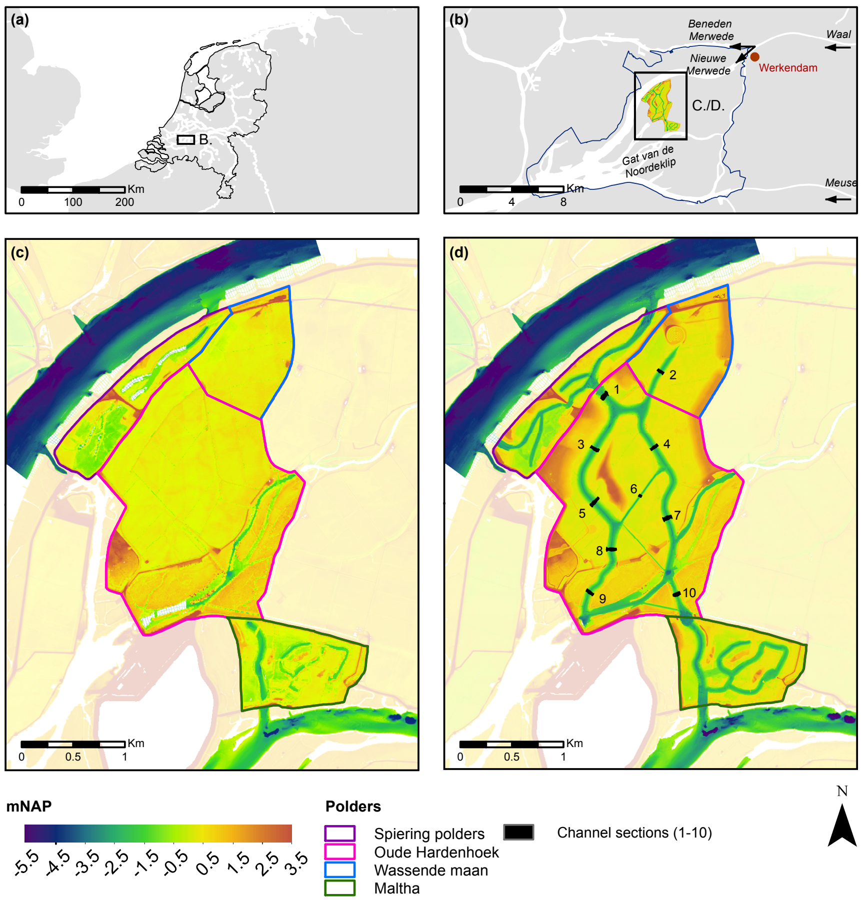

Figure 1. The study area Kleine Noordwaard, which is located within the Biesbosch Freshwater Tidal Wetland, in the lower Rhine and Meuse delta in the southwest of the Netherlands (a and b). Elevation is shown in meters, with respect to the Dutch Ordnance Datum (NAP) for the period before (c) and after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

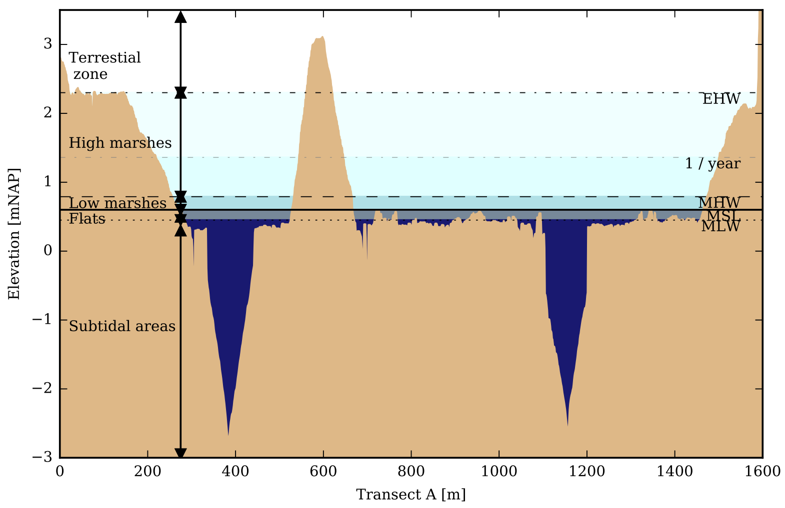

Figure 2. Elevation of Transect A (see Fig. 1) with respect to the Dutch Ordnance Datum (m NAP) with subdivision of the area into subtidal areas, flats, low and high marshes, and terrestrial zone relative to mean low water (MLW), mean sea level (MSL), mean high water (MHW), the maximum observed water 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.

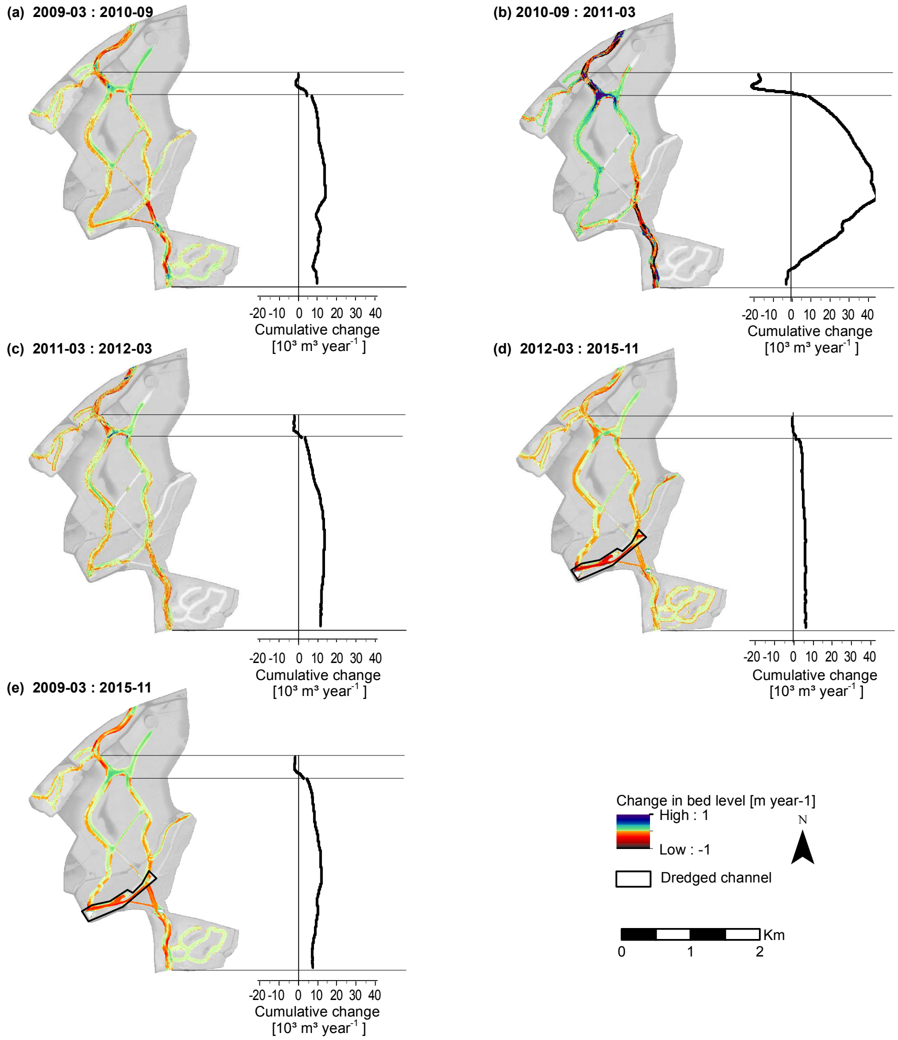

Figure 3. The difference in channel bed level and the cumulative channel bed volume for each monitoring period. The cumulative channel bed volume is shown along a N-S transect starting from the Spiering polders (purple in Fig. 1). The budget of the Wassende Maan (blue in Fig. 1) is added at once at the 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.

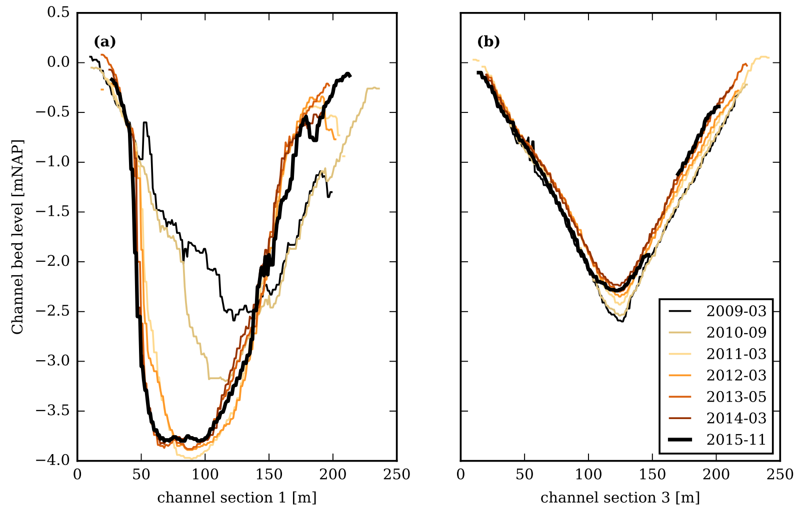

Figure 4. Bed level of channel section 1 (a) and 3 (b) for all monitoring campaigns. (see Fig. 1 for the locations of the cross sections)

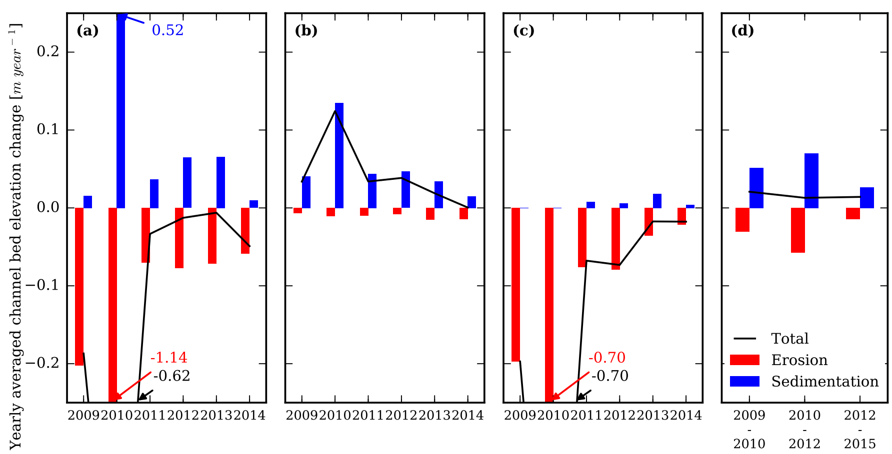

Figure 5. The yearly averaged channel section sedimentation (blue bars), erosion (red bars) and total change in height (black lines) for the inlet (a), the centre (b), the outlet (c) and the entire study area (d), which was opened 7 May 2008 and experienced a peak discharge event from 8 to 19 January, 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. 1 (d)) in 2011, 2013 and 2014.

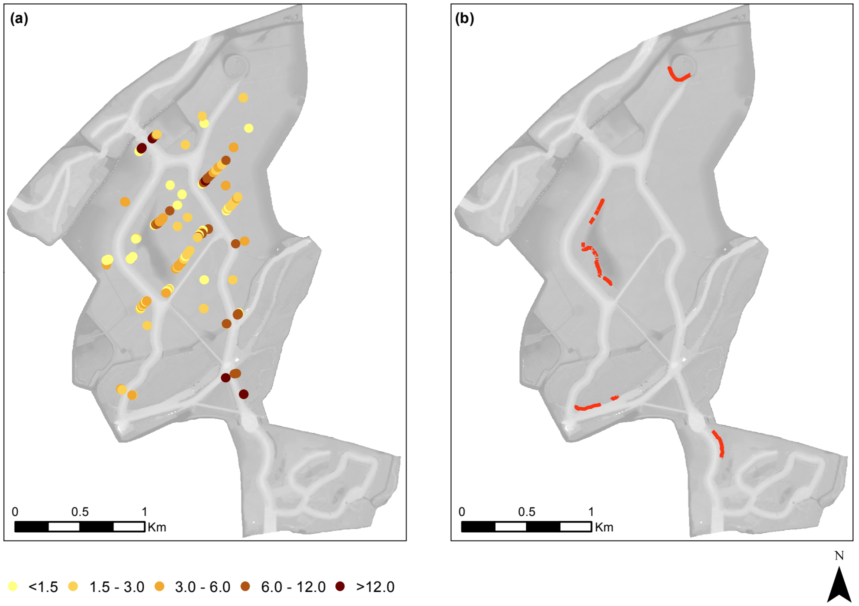

Figure 6. The total sedimentation~~accumulation~~ [cm] in the open water and intertidal area~~at the intertidal flats~~ (a) and the location of the cutbanks (b) as measured during field campaigns of 2014

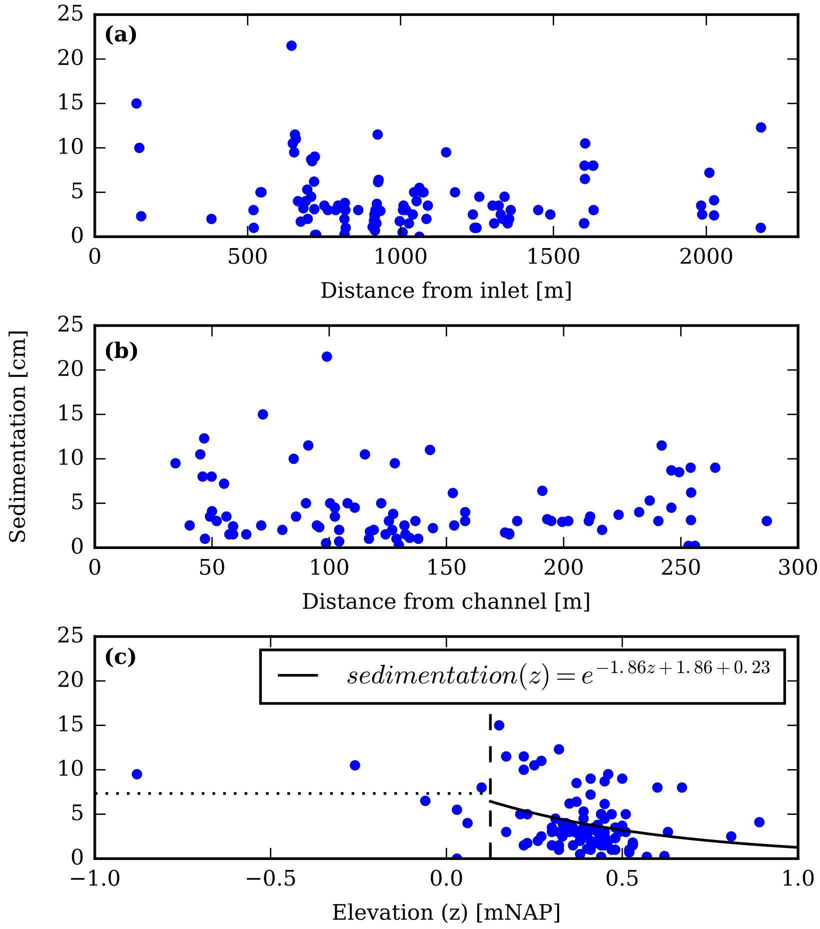

Figure 7. Total sedimentation~~accumulation~~ during the period 2008-2014 in the open water and intertidal area~~at the intertidal flats~~, with respect to the distance from the inlet of the system (a), distance from the channel (b), and the elevation ~~of the flats~~ (c)