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

Reviewer comments are underlined

Author comments are in plain text

ESurfD Manuscript text is in italics

changed Text is blue

Anonymous Referee #1

Remarks p2 line 11: sedimentation rates: this is not the same as accumulation rate or aggradation. The latter is the net elevation change (= sedimentation minus compaction or subsidence). These terms are mixed in the paper. E.g. in table 1, it is not clear if aggradation or sedimentation is shown. The results of this paper show aggradation data: change in elevation based on bathymetric surveys in the channels, both also sedimentation data based on cores on the flats. This difference is not properly discussed. This sedimentation rate might be higher than the elevation change due to subsidence. Table 1 show in the header "Turbidity", while often suspended matter concentrations are shown.

We agree with the reviewer that the sedimentation rates presented may also be affected by subsidence and compaction. The elevation change based on the bathymetric surveys includes both subsidence and compaction. According to Kooij et al., 1998 the rate of subsidence (deep vertical regional land movement) in the Biesbosch area is low and amounts to -0.25-0 mm year^{-1}, including compaction (-0.1-0 mm year^{-1}mm year^{-1}), isostasy (-0.1 mm year^{-1}), and tectonics (-0.03 mm year^{-1}). However, shallow surface compaction is likely considerable, but this has affected both the change in elevation based on the bathymetric surveys and the sedimentation data based on the cores on the flats. Therefore, we have decided to use the term net sedimentation for the rate of change in height based on the bathymetric data. This is explained in line 32 on p. 2. We use the terms sediment deposition or sedimentation for the average amount of sediment deposited annually derived from the cores on the flats.

Furthermore we have made the following changes in table 1:

- We have adapted the title of the second column from Accumulation [mm year-1] to net sedimentation [mm year-1] .
- We have changed the title of the third column from Accumulation to Deposition
- We have changed the title of the fourth column from Turbidity to SSC / Turbidity
- We have added a new column in between the former second and third columns. This column has the title Deposition [mm year-1]. When a source only gives the deposition in volume, the concomitant change in height, calculated using a sediment density of 1150 kg m^{-3}, is shown in italics
- The caption of the table has been adapted to “Net sedimentation and deposition in various types of delta compartments. When a source only gives the deposition in volume, the concomitant change in height, calculated using a sediment density of 1150 kg m^{-3}, is shown in italics”
- we have combined the studies of van Proosdij et al. 2006 and 2006a in Allen Creeck in one row.
- we have added the deposition rates for the Gleason and Walkerton marshes in the study of Darke and Megonigal 2003, for which only the accumulation rates were given in the first version of the manuscript
- we have added the deposition rates for the study of Bleuten et a. 2009

<u>p2 line 14: the authors describe that sedimentation is controlled by frequency and duration of inundation, SPM concentration in the feeding channel. However, none of these data are shown for the study site! The latter would be very interesting to show, especially because table 1 shows this for other sites.</u>

We have addressed this comment by an expansion of the description of the study site in section 2.1. The exact changes in this section will be illustrated in our reply to the next comment

<u>p3: description of the study site is not accurate enough. It is described as a tidal wetland. I interpret this as a wetland where water flows in and out, twice a day, based on the tidal cycle. The site has however an inlet upstream and an outlet downstream. Is there no change in current direction, causing inflow during flood at the downstream opening? In a tidal wetland, I would expect channels, bare flats and tidal marshes. Are there no marshes? The terrestrial zone is mowed to reduce hydraulic roughness: this indicated the area can be flooded. No information on this flooding (frequency, height, duration) is given.</u>

In section 2.1, we have added a short description of the water levels, discharge, and suspended sediment concentration in the channels of the study area. Furthermore, based on the digital elevation model and water level measurements by Rijkswaterstaat (available for the entire period since opening of the study area), we changed the subdivision of the study area from channels, tidal flats, and terrestrial zone to subtidal area (surface elevation <0.125 mNAP, always submerged) , flats (0.125 mNAP - mean sea level), low marshes (mean sea level - mean high water), high marshes (mean high water - extreme high water), and a terrestrial zone (> extreme high water). We have also added information on the flooding frequencies of these different areas.

To clarify both the morphology of the study area and the division of the study area in subtidal, flats, marshes and a terrestrial zone, we have added a new figure (Fig2), which includes a cross section of the study area. The location of this cross section is also indicated in Fig1.

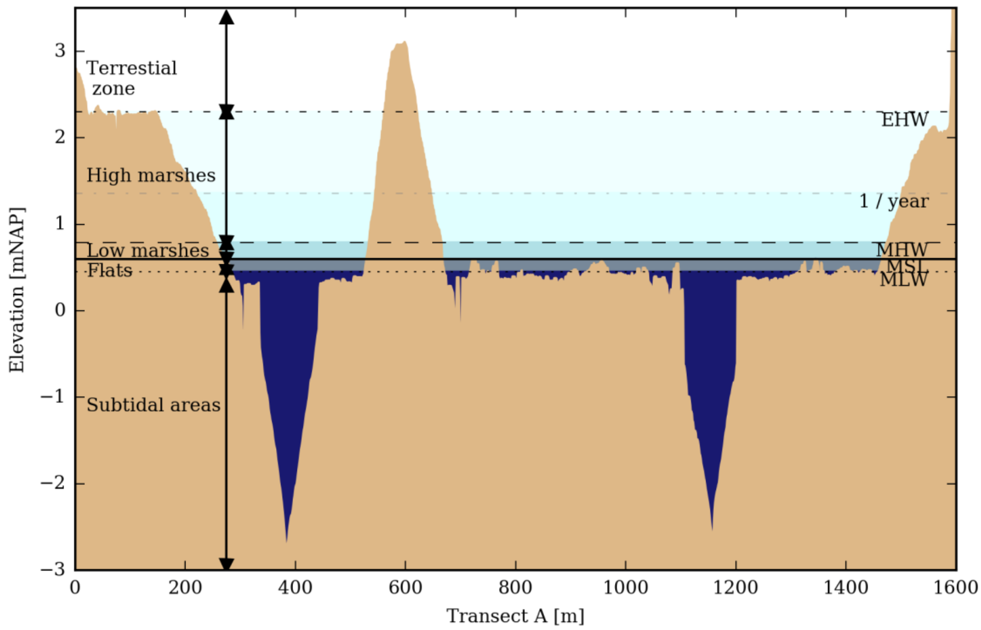


Figure 2. Elevation of Transect A (see Figure 1) with respect to the Dutch Ordnance Datum (m NAP) with subdivision of the area into subtidal areas, flats, low and high marshes, and terrestrial zone relative to mean low water (MLW), mean sea level (MSL), mean high water (MHW), the maximum observed water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

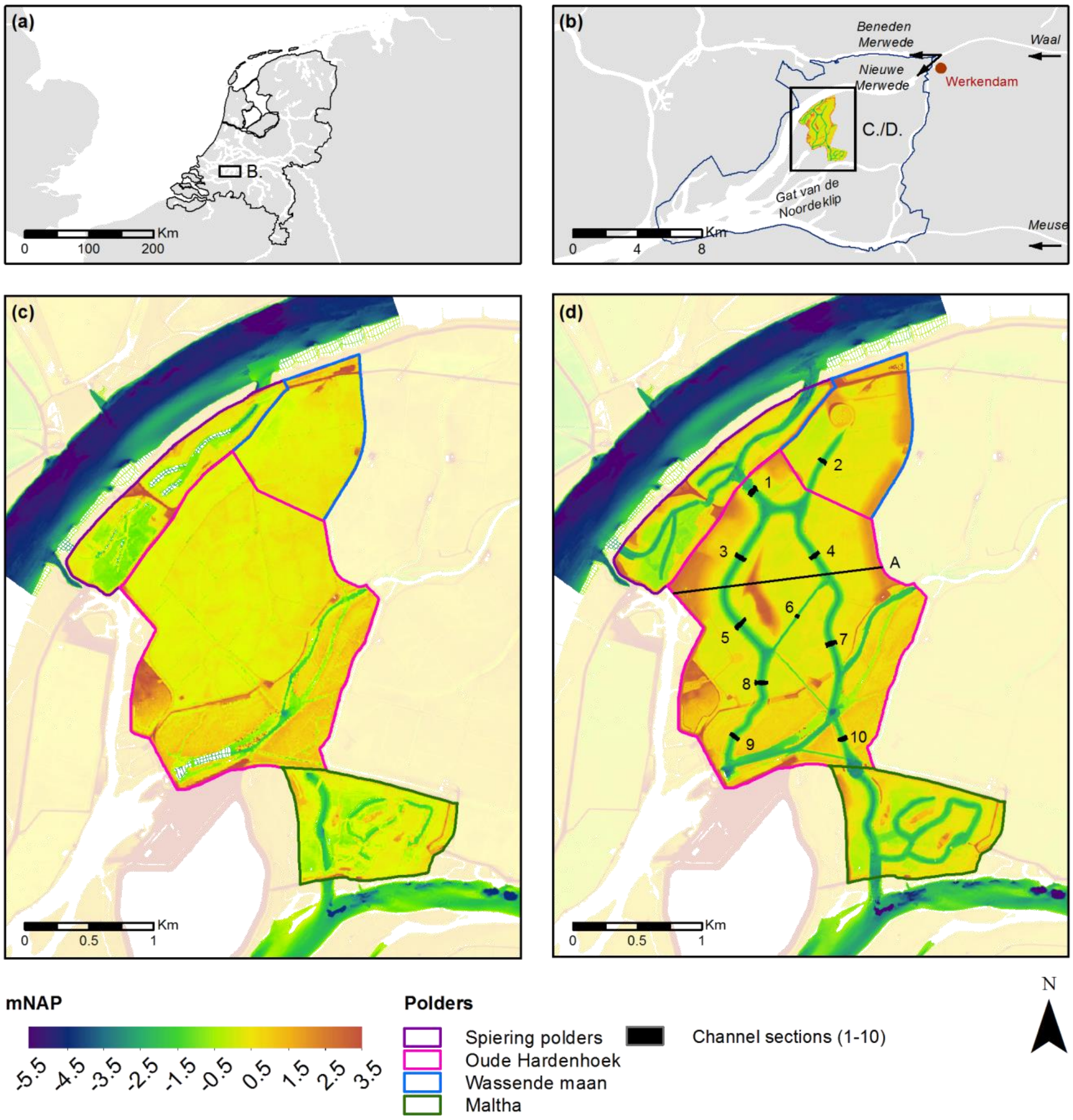


Figure 1. The study area Kleine Noordwaard, which is located within the Biesbosch Freshwater Tidal Wetland, in the lower Rhine and Meuse delta in the southwest of the Netherlands (a and b). Elevation is shown in meters, with respect to the Dutch Ordnance Datum (NAP) for the period before (c) and after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

We have also added a more detailed description of the discharge regime and suspended sediment concentrations of the River Rhine. Unfortunately, no measurements are available for the River Nieuwe Merwede, which is the feeding channel of the study area. The exact inflow of water and sediment from the Rhine into the Nieuwe Merwede is unknown, since it varies due to the tide, the river discharge of the River Rhine, and the artificially controlled discharge through the gates of the downstream located Haringvliet barrier into the North Sea.

The changes in the description of the study site can be found in the manuscript with track changes p4 line 28: there seems to be a big heterogeneity in the thickness of the deposited sediments. Using an average is probably very inaccurate to calculate the total sediment budget. Why not using a model, using elevation. The authors describe that sedimentation is significantly correlated with elevation.

We thank the reviewer for this suggestion. We now estimate the sediment budget using a model taking into account the surface elevation. For this, we divided the study area into navigable channels, subtidal area and intertidal area (flats, low and high marshes) and a terrestrial zone (not flooded during the study period). The sediment budget for the navigable channels was calculated from the bathymetric maps. For the subtidal area, the sediment budget was calculated using the average sedimentation in this area. The sediment budget for the intertidal area was calculated using a negative exponential relation between sediment deposition and elevation.

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), 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.~~*

2.3.2 Subtidal and intertidal area *~~Intertidal flats~~*

…… 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 open water and intertidal area. The total sediment budget of the open water 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 open water area. The total sediment budget of the intertidal area~~flats~~ was calculated using a negative exponential relation between sediment deposition and elevation. ~~multiplying the average thickness of the recently deposited sediment layer by the total area of the intertidal flats.~~

The exact changes in the description of the methods and results, can be found in the manuscript with track changes

p5: Terrestrial zone: only erosion is described here. But from the introduction, I derive that this part floods occasionally? Given the large surface of this part (>50% of the total area), even a very small sedimentation during winter can have a significant effect on the total budget.

In the new model-based estimation of the sediment budget (see reply to previous comment), we now include the entire intertidal area, which is flooded occasionally. The new net sedimentation rates, and trapping efficiency are indeed higher than the estimates in the previous version of the manuscript.

The exact changes in the description of the methods and results, can be found in the manuscript with track changes p5 line 17. No information on how the incoming load was calculated, is given. This is however important information. For the River Rhine some info is given: 10 minute intervals for discharge, daily SSC concentrations, between 2008 and 2015. Is this done with the same accuracy for the inflow in the area? Is there no inflow at the downstream opening during flood (see previous remarks)? Measurements of SSC at inflow and outflow would be a good way to calculate a trapping efficiency. The paper often refers to the total load of the River Rhine at the German border. How relevant is this? It is so far away from the site, after many branches and tributary rivers. I am more interested in knowing the total load of the Nieuwe Merwede that feeds the site with water and sediments: SSC and discharge in this river and SSC and discharge entering the study site. Unfortunately this information is not given.

We have added a more detailed description of the discharge regime and suspended sediment concentrations of the River Rhine in the description of the study area. Unfortunately, there is no measurement station in the Nieuwe Merwede, which is the feeding channel of the study area. The exact division of water and sediment from the River Rhine towards the River Nieuwe Merwede is unknown, since it varies due to the tide, the river discharge of the River Rhine, and the artificially controlled discharge through the gates of the downstream located Haringvliet barrier into the North Sea. However, we measured water levels, flow velocities and suspended sediment concentrations at a 10 minute interval at the inflow and outflow of the study area between July 2014 and March 2015 (see van der Deijl et al., 2017). These measurements were used to estimate the fraction of sediment (5.8%) the study area has received from the total load of the River Rhine during this period. To calculate the total amount of sediment the study area has received since the opening of the study area, the fraction of 5.8% percent has been multiplied with the total load of the River Rhine, for which data is available for the entire period since the opening of the study area.

We have clarified the method of calculation of the sediment trapping efficiency in both the methods (Section 2.2.4) and the results (Section 3.5): the trapping efficiency was calculated based on the total sediment trapped in the area relative to the total amount of sediment the study area has received since the opening of the study area

P8 line 7: how is this 46% calculated?

We have clarified the method of calculation of the sediment trapping efficiency in both the methods (Section 2.2.4) and the results (Section 3.5): the trapping efficiency was calculated based on the total sediment trapped in the area relative to the total amount of sediment the study area has received since the opening of the study area

P10 line 22: is there seasonality in the sedimentation? What is the seasonality in discharge, in SSC, in tidal amplitude? How much do peak events contribute to the budget? The peak in 2011, was it only a peak in discharge or did this event also had higher SSC?

In section 2.1 we have added more detailed description of the discharge regime and suspended sediment concentrations of the River Rhine. We also describe that the tide is mixed semidiurnal with a tidal range of 0.2 to 0.4 m. In addition, in section 3.2, we added a sentence that describes the response of the SSC concentration during the 2011 discharge event.

Anonymous Referee #2

The authors present results of a comprehensive study on the morphological development of a recently opened wetland, based on an extensive data set.

First of all, I completely agree with the questions raised by Reviewer #1.

The text cites a paper as to be in preparation, by the authors, which is not in the list of references. That, and conference abstracts by the authors, suggest the availability of potentially more data on SSC and current velocities at the entrance to the wetland, which are, in here, deeply missed. I guess, there is a good reason for the suspected splitting of the data set.

The paper, which was cited as to be in preparation, has meanwhile been accepted and published. Therefore, we have changed all references to this paper in the text to *(van der Deijl et al., 2017)* and the paper has been added to the list of references.

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.

While this manuscript focuses on the medium-to-long term sediment budget since the opening of the study area , the above paper use 10-minute interval data on water level, flow velocity, and suspended sediment concentrations measured at the inlet and outlet of the study area to identify the controls on sediment trapping. The period for which these data is available only covers the period July 2014 - March 2015 and represents only a short period since the opening of the study area. This makes this detailed data less suitable for the purpose of this study Nevertheless, we use the data and refer to the above paper in a newly added description of the water levels, discharge, and suspended sediment concentration in the channels of the study area and the inundation frequency of the intertidal flats, marshes and terrestrial zone in the area description (Section 2.1). Furthermore, we used the data for estimating the proportion of the total sediment load of the River Rhine that enters the study area (Section 2.2.4).

So, since no more information is presented here on the forcing, tide-driven dynamics, etc., the focus should be on the analysis of geospatial information. In this, I think the data source is not (yet) presented to the reader in a proper way. From the suggested high quality of MBES and LIDAR data, I had expected simply better plots, e.g., from one flat in the center of the wetland and surrounding channels, showing more details of aggradation and erosion patters.

The color scale in Fig. 1 doesn't help. The interesting elevation range, -2 m to 1 m, is essentially not resolved.

Figure 1 was included in the manuscript to show both the location of the study area and the transformation of the study area as a result of depoldering, not to derive rates of deposition at the intertidal flats. Because of the regular submergence of the intertidal flats, a complete digital elevation model based on the Lidar data of the intertidal flats is only available before the depoldering of the study area. Therefore, it is not possible to determine rates of deposition at the intertidal flats from different LIDAR datasets..

To further clarify the initial morphology of the study area after depoldering, and the division of the study area in channels, flats, marshes and a terrestrial zone, we have added a new figure (Fig2). This figure is shown in the response to remark 3 by referee#1.

Furthermore, we added a new figure to the manuscript to further clarify the sedimentation and erosion patters in the channels (Figure 4 in the revised manuscript). This new figure shows the development of channel section 1 and 3 (for location of the transects see Figure 1 , shown in the response to remark 3 by referee#1.), which represent the morphological development of both the single channels near the inlet and outlet, and the perpendicular channels in the middle of the study area.

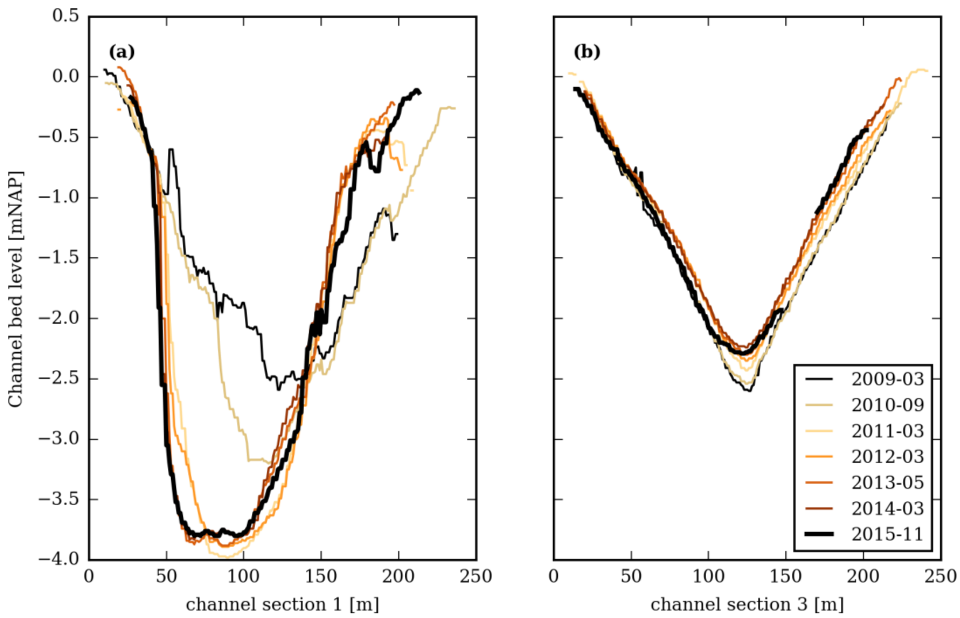
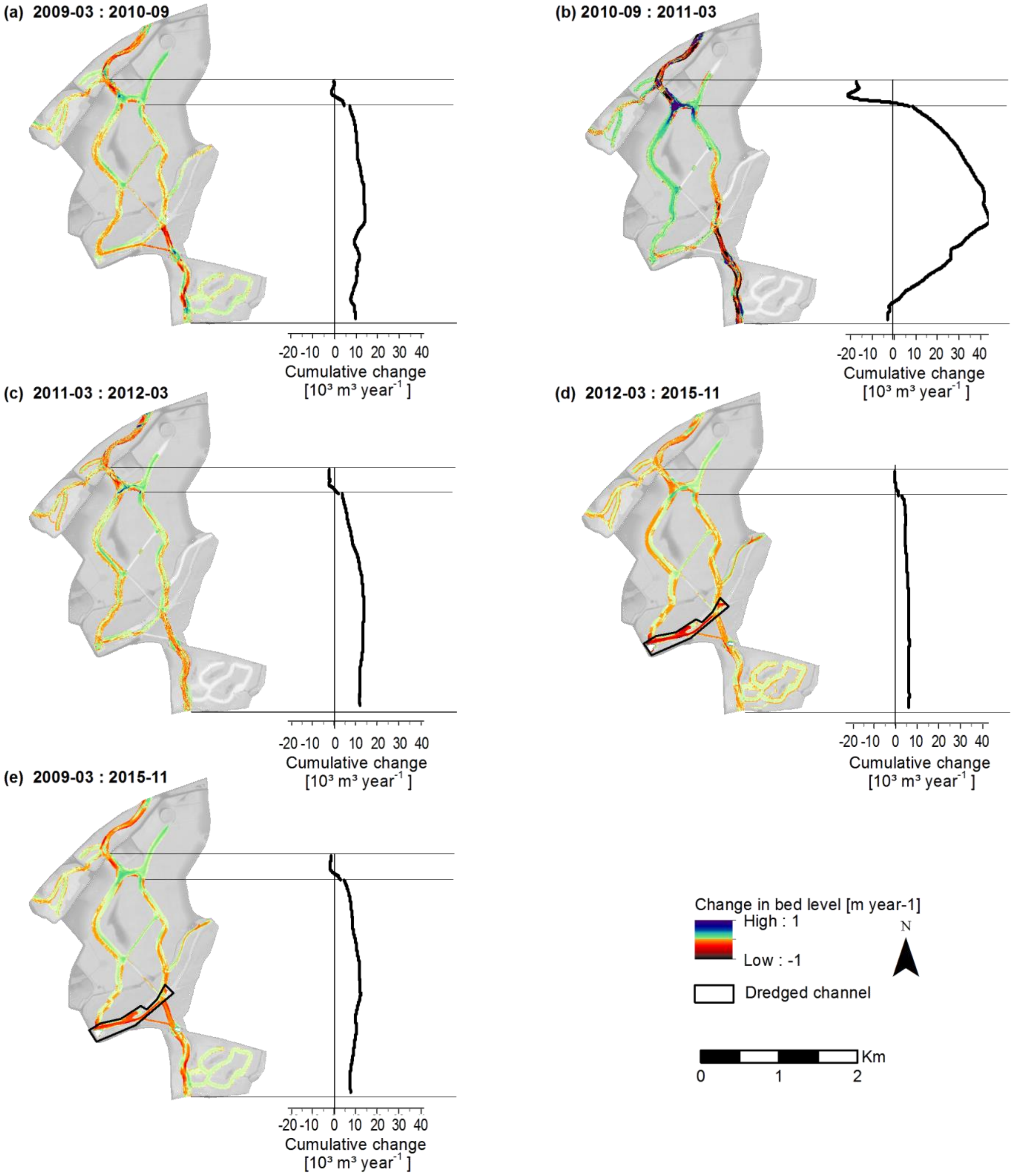


Figure 4. Bed level of channel section 1 (a) and 3 (b) for all monitoring campaigns. (see Figure 1 for the locations of the cross sections)

There are quite some simple methods around, based on gridded spatial data, e.g., the maximum bed elevation range to differentiate between more and less active regions, or, vertical dynamic trend analysis to show - what is already in the text - stagnation of morphological change with time at specific locations. The DEMs could have also been used to extract cross-sections of channels, or longitudinal transects from some channel thalweg, all means to give the reader a good impression of morphological changes. I'm just suggesting. How to proceed, and what to change, depends on the focus.

In our response to the former comment, we already mentioned that we added a new figure (now figure 4) to the manuscript to further clarify the aggradation and erosion patters in the channels by showing the morphological development of two channel cross-sections. Furthermore, we changed the data representation in figure 2 in the first version of the manuscript. The maps in this figure showed the spatial distribution of the total difference in channel bed level. This figure has become figure 3 in the revised manuscript and the maps now show the difference in channel bed level in m/year (the vertical dynamic trend) for each monitoring period.



Figure~~2~~ 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.

Tja, what is the actual focus? The determination of the budget? Analysis of transport both into inside the area? Geomorphological changes of flats, banks, channels? Analysis of the sedimentology, including transport of the coarse and cohesive fractions?

I find the focus unclear and the Introduction and Discussion symptomatically unspecific, e.g., page 9 line 24: "cut bank retreat does not significantly contribute to the total sediment budget". If the paper was about the budget, why is the statement, cut banks would not contribute to that budget, followed by a detailed comparison of cut bank dynamics with literature? That is a question of the focus. The same could be said regarding sand deposition in the deeper channels.

The discussion essentially remains on the level of a comparison. In each part of the discussion, process based considerations are used to explain the situation at the specific location. Which is cool. But I asked myself at the end of each paragraph, what could be concluded from this discussion for similar geomorphological settings? I had the impression, and maybe I'm wrong, that the discussion did not lead to the conclusions.

As mentioned in the title of the manuscript, the focus of this paper is "Establishing a sediment budget in a newly opened wetland area". The rates and patterns of sedimentation and erosion are compared to those in other wetlands to discuss the relative contribution of geomorphological processes in the study area to the budget, and to derive practical implications for the management of newly created tidal freshwater wetlands.

We have made the following changes in the introduction to further clarify the focus of the manuscript:

1. Introduction

....

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 develop a medium-to-long term inorganic sediment budget for the Kleine Noordwaard. The rates and patterns of sedimentation and erosion are compared to those in other wetlands to discuss the relative contribution of geomorphological processes in the study area, and to derive 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.~~

In the discussion section, we compare the rates and patterns of sedimentation and erosion to those in other wetlands, and we use the process-based considerations to discuss the relative contribution of geomorphological processes to the sediment budget in our study area. To further clarify the implication of the processes to the sediment budget, each paragraph now ends with a concluding sentence. In sections 4.3 (Implications for management) and 5 (Conclusions) we refer to these conclusions to derive practical implications for the management of newly created tidal freshwater wetlands.

The exact changes in the discussion, can be found in the manuscript with track changes

The Conclusion is essentially a summary of Results. On one hand, it is said that the wetland is a trap for sediments. On the other hand, it is deduced at least for the channels that the domain is approaching some kind of equilibrium, which certainly didn't exist from the beginning. So, trapping occurs only because of the non-equilibrium state at the opening of the wetland? Which grain sizes could actually be trapped? Is it realistic that sand is transported into the wetland? If trapping was the goal (Paola et al., 2011, is cited in the Introduction), should we conclude that, to efficiently trap sediments, we would need to open new wetlands every once in a while? Ok, seriously, I find this important, as, e.g., around many estuaries we are having this discussion right now, everywhere in Europe.

We agree that this a topical and relevant discussion. We adapted section 4.3 (Implications for management) by adding reflection on current sedimentation rates and possible measures to enhance these. At the end of the section we state that conversion of polders into wetlands in deltas may be an effective strategy of delta restoration since sedimentation compensates at least partly for sea level rise and land subsidence. These management implications have also been added in the conclusions section.

So, in summary, I hope for a shorter text, with a clear focus. The plots should reflect the data quality. The Discussion should lead to the Conclusions.

To recap the response to the former comments: we have adapted and added figures, added concluding sentences in the discussion sections and we refer back to these conclusions in the conclusion.

Minor comments:

P6 L7 An interesting aspect is that "channels cannot migrate freely". Any ideas what this could mean for small-scale morphodynamics and the distribution of sediments? What is that "bank protection"?

The dikes along the channels near the inlet and outlet of the study area are protected by riprap to prevent erosion. Since the outer bends have reached the riprap, further erosion is prevented. As a result, there is less sediment available for further development of the point bars at the end of the bends and the channels will become fixed.

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.

P6 L23 Any particular reason, why the term "morphodynamic equilibrium" is persistently avoided, using "equilibrium state between their geometry and the flow conditions", instead?

We had no particular reason to avoid the term morphodynamic equilibrium, which is now used in the manuscript at P7 L26, P10 L1, P10 L9 and P13 L23

P4 L14 "whether changes . . . had been . . . years"

We have implemented this comment

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

P8 L17 "Yet . . . channels" example of many sentences which can simply be deleted without changing anything in the text

We have implemented this comment by deleting this sentence.

P9 L25 "Wind waves . . . fetch" common knowledge, not required

We have deleted this sentence from the manuscript

P10 L3 Entire paragraph: example for text with too many assumptions, for my taste, since in the end this does “not allow drawing conclusions”

> We have deleted the last sentence of the paragraph so we now end with the conclusion that resuspension of sediment takes place regularly.

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 ~~aggradation~~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 ~~aggradation~~ sediment deposition and erosion in newly created wetlands. We quantified both the magnitude and spatial patterns of ~~aggradation~~ 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. ~~Aggradation~~ 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. ~~At the intertidal flats, sand aggradation~~ In the intertidal area, sand deposition especially takes place at low lying locations close to the channels. Mud ~~aggradation~~ 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. ~~Cut bank retreat~~ 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 ~~aggradation~~ 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 ~~46~~ 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 ~~29.7~~ 37.3 10^3 m^3 $year^{-1}$, which corresponds to a net area-averaged ~~aggradation rate of 5.1~~ deposition rate of 6.4 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 (**???**). The urgency of this problem is enhanced by sea-level rise (**?**) or increasing river discharge. Most deltas are valuable and densely populated, because of their ideal location for harbours, agriculture, aquaculture, and tourism (**??**). 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 (**?**). 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 (**?**), the diversion projects in the Mississippi deltaic plain (**???**), the Plan Integrale de Protección del Delta Ebro in the Ebro Delta (**?**) and the Room for the River initiative in the Netherlands (**?**).

? 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. ~~Sediment deposition~~ Sedimentation is variable and complex. This table suggests that ~~accumulation~~ sedimentation is positively related to the suspended sediment concentration. Furthermore, it is widely known from the literature that ~~sediment deposition~~ sedimentation is controlled by the frequency and duration of inundation (**?????**), the suspended sediment concentration in the feeding channel (**??**), and the ability of sediment to settle, which is in turn controlled by vegetation (**????**), the flow paths to or within the wetland/compartment (**???????**), and the residence time within the compartment (**?**). Although considerable research has been devoted to ~~sediment deposition~~ 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 ~~aggradation~~ 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 ~~aggradation~~ 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 ~~aggradation~~ sediment deposition and erosion in one of the formerly embanked areas, 'Kleine Noordwaard'. For this, different sources of data were combined. ~~Sediment accumulation was~~ 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. ~~Furthermore, we compared~~ 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~~and the sediment load of the river Rhine~~, 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. 1~~(a) and (b)~~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 (**?**). In the subsequent two centuries, a deltaic splay developed of approximately 6 m thick (**?**). The lower 4 m of this splay is sand, covered by 2 metres of clay (**?**). 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 (**??**). 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 ”~~ 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 (**?**). 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 ~~inlet channel was~~ channels were connected to the River Nieuwe Merwede ~~and the outlet~~ 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 distributary of the River Rhine (Fig. 1). ~~Channels are always submerged, while the former polder bed comprises a system of mud flats, which are either submerged or dry, depending on~~ 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} (**?**) . Field measurements of water levels, flow velocities, and turbidity, carried out in the period July 2014–March 2015 (**?**) 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.

The water level is influenced by the tide, which ~~has~~ is mixed semidiurnal with a range of approximately 0.2 to 0.4 m (**?**), the wind direction and speed, ~~and~~ the discharge of the River Rhine~~. The area is composed of deep open water (18%), mud flats (31%), and~~ , 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 (**?**). 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 (~~51%~~see Fig. 2). In order to reduce the hydraulic roughness, the ~~terrestrial zone is mowed~~ 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 ~~in the terrestrial zone~~ can be classified as dry and ~~damp~~ 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 (**?**).

2.2 Field methods

~~To establish a~~

The sediment budget of the study area ~~, we determined separate sediment budgets for the channels (surface levels below 0.1 m above Dutch Ordnance Datum (NAP)), intertidal flats (surface levels between 0.1 and 0.5~~ 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 ~~terrestrial zone (surface levels above 0.5 m NAP). For all subareas we~~ 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 ~~sediment accretion and loss in the~~ 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)).~~ 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 ~~patterns in~~ 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 ~~have~~ had been consistent throughout the years.

2.2.2 ~~Intertidal flats~~Subtidal and intertidal area

We determined the sediment budget of ~~the intertidal flats~~ both the subtidal and the intertidal area by measuring the ~~vertical accretion~~ 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~~ 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 ~~intertidal flats~~ 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 ~~area~~ subtidal area. The total sediment budget of the intertidal ~~flats~~area was calculated using a negative exponential relation between sediment deposition and surface elevation.

2.2.3 ~~Terrestrial zone~~Marsh erosion

To determine the contribution of ~~bank~~ marsh erosion to the ~~budgets~~ budget of the channels and intertidal ~~flats~~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, ~~intertidal flats~~the subtidal and intertidal area, and the ~~terrestrial zone~~ eroded marshes were established. To obtain the total mass of the ~~net~~ 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 **?**.

The trapping efficiency of the area was determined as the percentage of the sediment load supplied to the entrance of the study area. ~~Discharge~~ This sediment load was estimated using discharge and suspended sediment measurements at the entrance of the study area ~~(Van der Deijl et al in prep)~~ between July 2014 and March 2015 at a 10 minute interval (**?**), which indicated that the area ~~receives~~ 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 (**?**).

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 ~~that accumulated~~ deposited 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)~~ a, b, c and d) and for the entire period (~~(e)~~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 ~~erosion~~ bank erosion in the outer bend of the channel to the depth of the River Nieuwe Merwede. ~~Furthermore, outer bends have eroded and~~ 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 ~~with hard bank protection~~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 ~~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 deposition 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.~~

~~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 ~~attain an equilibriumstate between their geometry and the flow conditions~~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 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. 4b show increased rates of ~~deposition~~ sedimentation in the centre of the area during the discharge event. This increased ~~deposition~~ 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 ~~an accumulation~~ a net sedimentation of 21.7 10^3 m^3 year^{-1}, ~~18.0~~ 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 ~~an accumulation of 14.3~~ a net sedimentation of 14 mm year^{-1}, which corresponds to 16.7 10^{3} m^{3} year^{-1} and 24.9 kton year^{-1}.

3.3 ~~Intertidal flats~~Subtidal and intertidal area

Figure 6~~A~~ a shows the spatial variation of the measured ~~sediment accumulation on the intertidal flats~~sedimentation in the subtidal and intertidal area, and Fig. 7 shows the ~~sediment accumulation~~ sedimentation for increasing distance to the inlet of the polder area (i.e. the source of the sediment) (graph ~~(a)~~a); distance from the channel (graph ~~(b)); and the height of the flats (graph (d)~~b); and elevation (graph c). Although the highest ~~accumulation~~ sedimentation was measured along the channels, there is no significant relation between the total ~~accumulation~~ sedimentation and the distance to the channel. This is likely partly due to the relatively high ~~accumulation~~ 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 ~~accumulation~~ 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 ~~accumulation~~ 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. 7~~(c)~~c. shows that the total ~~accumulation~~ sedimentation generally decreases with increasing height of the tidal ~~flat~~area. This relation is significant but it explains only 9 % of the variation in ~~accumulation~~sedimentation. However, local variation in ~~accumulation~~ 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 ~~43~~ 73 ± ~~3.55~~ 9.1 mm (standard ~~deviation~~error of mean) of mud and sand, ~~accumulated in the intertidal~~ is deposited in the subtidal area. This corresponds to ~~an accumulation rate of 6.6~~ a sedimentation rate of 11.3 ± ~~1.0~~ 1.4 mm year^{-1} and an annual average sediment budget of ~~13~~ 5.21 10^{3} m^{3} year^{-1} and ~~14.6~~ 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}.

3.4 ~~Terrestrial area~~Marsh erosion

Fig. 6~~B~~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 ~~sediment budget of the terrestrial area~~ eroded volume 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 ~~29.7~~ 37.3 10^3 m^3 year^{-1}, which corresponds to a net area-averaged sedimentation rate of ~~5.1~~ 6.4 mm year^{-1} and an import of ~~39.5~~ 46.8 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 ~~60~~ 44 percent of the total budget. The vast majority of the remaining ~~40~~ 56 % comprises the annual sedimentation of ~~13.0~~ 5.2 10^3 m~~^{3} year^{-1} in the~~ ^{3} year^{-1} and 15.8 10^3 m^3 year^{-1} in the subtidal and intertidal area. Remobilization of sediment by erosion of ~~cut banks~~ marshes occurred at a negligible rate of about -10.3 m^3 year^{-1}. During ~~the first 6.5 years after depoldering of the area approximately 46~~ this period, the study area received an annual sediment load of approximately 85.6 kton year^{-1}. 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 ~~aggradation~~ deposition has occurred in all years, but the actual channel ~~aggradation~~ deposition rate has decreased over the years (see Fig. 5). Assuming a constant ~~accumulation~~ deposition and erosion rate for the ~~intertidal- and terrestrial zone~~intertidal area, we have accounted for the decrease in ~~channel aggradation~~ 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 ~~25.5~~ to 35.7 10^3 m^3 year^{-1}, which corresponds to a net area-averaged sedimentation rate of ~~4.4~~ 6.2 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 **???** 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 ~~to attain an equilibriumstate between their geometry and the flow conditions~~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. ~~Sediment accumulation~~ 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 **?**, 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 ~~equilibrium state with the flow conditions~~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 ~~accumulation~~ deposition and increasing mud ~~accumulation~~ deposition away from the channels, which is in line with previous studies of **?????** and **?**. Furthermore, a significant negative trend between ~~accumulation~~ sedimentation and the height of the location was found, which has also been reported by **?????**. Although the height and distance from the channel do control ~~sediment accumulation~~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 (**???**); 2) the absence of vegetation (**???**), and 3) the small tidal range and water depths (**?**). These three factors result in an uniform sediment distribution by ~~firstly,~~ micro topographic flow paths during low water levels (**??**); ~~secondly,~~ sheet flow during high water levels (**??**); or ~~thirdly,~~ a relatively large impact of shear stress (**?**) 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 ~~accumulation~~ 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 **????**, ~~cut bank retreat~~ 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. ~~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 (?).~~ 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 **?**, 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 **?** 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} (**?**) 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} (**?**), 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 ~~aggradation rate of 5.1~~ sedimentation of 6.4 mm year^{-1} for the period since the opening of the polder area and the estimated actual net area-averaged ~~aggradation rate of 4.4~~ sedimentation rate of 6.1 mm year^{-1} are well within the reported ranges for ~~accumulation rates~~ net sedimentation on floodplains, wetlands, fresh- and salt-water marshes (see Table 1). Furthermore, the ~~aggradation rate~~ sedimentation 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 **?** from heavy metal profiles in floodplain soils of the River Rhine. However, the ~~aggradation~~ net sedimentation is larger than the 1-2 mm year^{-1}, reported by **?** 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 **?** and **?** 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 ~~aggradation~~ net sedimentation is consistent, but that the actual ~~aggradation~~ sedimentation rate varies over the years. Although the largest rates of erosion and sedimentation occurred during the 2011 peak discharge event of the ~~river~~ 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 ~~net sediment accumulation rate~~ sedimentation 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.).~~ (**?**). The trend of a decrease in erosion and sedimentation ~~rates~~ in newly created wetlands was also found by **?**, 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 ~~aggradation rate of 4.4~~ sedimentation of 6.1 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} (**?**) and ~~0.5-2.5~~ 0-0.25 mm year^{-1} respectively for the Biesbosch (**?**). However, sedimentation in the area ~~can not~~ 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 **?**, especially since freshly deposited sediment will compact over the years and thus result in a lower net ~~accumulation~~sedimentation. The area has only trapped approximately ~~46~~ 55 % of the incoming sediment in the study area and ~~approximately~~ 3 % of the incoming sediment at Lobith (the Dutch-German border)~~, which indicates that it is possible to optimise~~ . 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 ~~efficiency~~ and increase the ~~aggradation~~ deposition rate of the ~~study~~ area. This might be achieved ~~by reducing the resuspension at the intertidal flats by a decrease in the~~ 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 ~~decreasing the fetch~~ reducing the wind fetch length by the establishment of vegetation or by the construction of topographic irregularities. ~~The aggradation rate in the study area could be enhanced~~ 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 ~~supply of water and sediment to the area, for example by modifying the inlet geometry~~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 ~~aggradation rates can also be applied in~~ sedimentation rates might also be considered for other wetlands, especially those where current ~~aggradation~~ 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

~~Existing data sets and field data were used~~ 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 ~~sediment accumulation~~ 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 10^3 m^3 year^{-1}, which corresponds to a net area-averaged sedimentation rate of 6.4 mm year^{-1} and an import of 46.8 kton year^{-1}. The area has trapped approximately 55 % 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.

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)
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.

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~~s~~ Net sedimentation and deposition in various types of delta compartments. When a source only gives deposition in
nge in height is calculated using a sediment density of 1150 kg m^{-3}

Type	~~Accumulation~~Net sedimentation [mm $year^{-1}$]	~~Accumulation~~ [mm $year^{-1}$]	Deposition	SSC / Turbidity	Amplitude [m]	Method	Source
Marshes	0.6					Cores (137Cs , 210 Pb)	**?**
Floodplains	1.1					Cores (137Cs , 210 Pb)	**?**
Wetland	1.2					Cores (137Cs , 210 Pb)	**?**
Wetland		*1.5*	1.1 - 8.4 g m^{-2} day^{-1}			Sediment traps (filters)	**?**
TFW ~~1.5~~		1.5	1.5-2.5 kg m^{-2} $year^{-1}$		0.4 - 0.5	Waterlevels, watersamples	**?**
Floodplains		*2.2*	2.56 kg m^{-2} $year^{-1}$	30 mg l^{-1}		Sediment traps (artificial grass)	**?**
Floodplains		2.8		30 mg l^{-1}		Cores	**?**
Floodplains		2.5				Cores (137Cs , 210 Pb)	**?**
Crevasse splay		2.5-3				Cores (137Cs , 210 Pb)	**?**
Salt Marshes	3.9			50-150 mg l^{-1}	3.2 (nt) - 6.4 (st)	Marker horizons, sediment traps	**?**
2 River Marshes		*4.1*	~~4. - 4.9~~ 4.5-4.9 kg m^{-2} $year^{-1}$	17 - 35 NTU		Marker horizons	**?**
TFW	~~4.9~~ 4.3-5.5				0.7 (nt) - 0.9 (st)	Sediment traps (tiles), cores (Be7)	**?**
3 Salt Marshes	~~0 - 11~~ 0-11				1.3~~- 2.3~~ -2.3	Marker horizons, surface elevation, clay layer thickness	**?**
Floodplains		6	6.86 kg m^{-2} $year^{-1}$	90 (mean) - 400 mg l^{-1} (flood)		Sediment traps and optical backscatter sensors	**??**
Salt Marshes	6			50 mg l^{-1}	3.2 (nt) - 6.4 (st)	Sediment traps (filters)	French & Spencer, unpubl. in **?**

Continued on next page

Table 1 – continued from previous page

Type	~~Accumulation~~Net sedimentation [mm $year^{-1}$]	~~Accumulation~~ [mm $year^{-1}$]	Deposition	SSC / Turbidity	Amplitude [m]	Method	Source
Wetland Basin	~~5 - 10~~ 5-10		5.9-12.8 kg m^{-2} $year^{-1}$			Sediment traps (bottles)	**?**
TFW		*8.7*	1 g cm^{-2} $year^{-1}$		3.2 (nt) - 6.4 (st)	Sediment traps (tiles)	**?**
Salt Marsh	~~8 - 14~~8-14	*21.3*	0.2-67 g m^{-2} $tide^{-1}$	300 mg l^{-1}	14	DEM, Sediment plates	~~?~~**??**
TFW	12		3.6 g m^{-2} day^{-1}	9 mg l^{-1}	1.8 (st)	Sediment traps (tiles), Marker horizons	**?**
TFW	12			5 mg l^{-1}		Marker horizons, Surface elevation tables	**?**
Wetland	14 (13 years), 42 (1996), 55 (2009)					Sediment traps (bottles), Marker horizons	**?**
TFW	~~16~~ 15.5			27 mg l^{-1}		Marker horizons, Surface elevation tables	**?**
14 Salt Marshes	0.02~~ - 17 for marshes of 500 - 10 years old~~ -17				2-3 (nt) - 5-6 (st)	Model	**?**
salt marsh		*12.3*	13.8~~ - 63.7~~ -63.7 g m^{-2} day^{-1}	10-42 mg l^{-1}	1.8 (st)	Sediment traps (filters)	**?**

Continued on next page

Table 1 – continued from previous page

Type	~~Accumulation~~Net sedimentation [mm year^{-1}]	~~Accumulation~~Deposition [mm year^{-1}]	SSC / Turbidity	Amplitude [m]	Method	Source
~~Salt marsh~~ TFW	~~*21.3*~~ 27	~~0.2 - 67 g~~ 12.9 m^{-2} ~~tide~~day^{-1}	~~300~~ 19 mg l^{-1}	~~14 Sediment traps (filters) ?Salt Marsh 22-130 mg l^{-1} 11 Sediment traps, geotracer gps van Proosdij et al, 1999 in ?TFW 27-21 mg l^{-1}~~ 1.8 (st)	Sediment traps (tiles), Marker horizons	**?**
River ~~channel~~ bed	39		1037 ~~million tonnes~~ MT year^{-1}		Gauging stations	**?**
TFW	180				Fast static gps survey	**?**

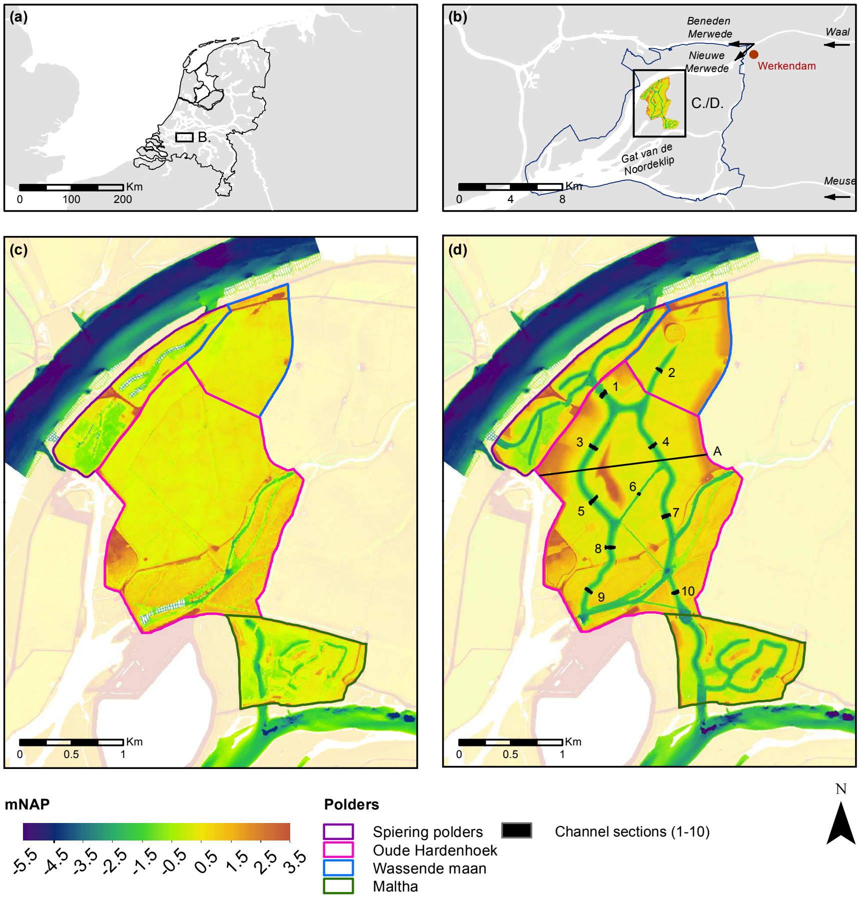


Figure 1. The study area Kleine Noordwaard, which is located within the Biesbosch Freshwater Tidal Wetland, in the lower Rhine and Meuse delta in the southwest of the Netherlands (a and b). Elevation is shown in meters, with respect to the Dutch Ordnance Datum (NAP) for the period before (c) and after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

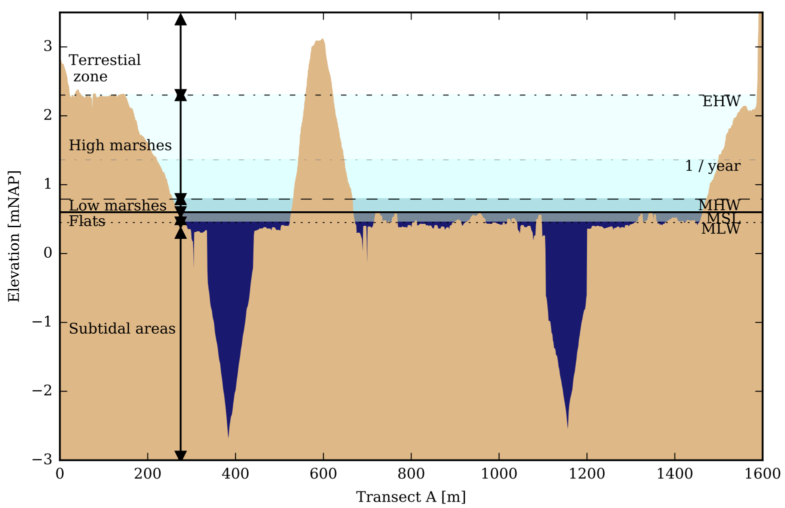


Figure 2. Elevation of Transect A (see Fig. 1) with respect to the Dutch Ordnance Datum (m NAP) with subdivision of the area into subtidal areas, flats, low and high marshes, and terrestrial zone relative to mean low water (MLW), mean sea level (MSL), mean high water (MHW), the maximum observed water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

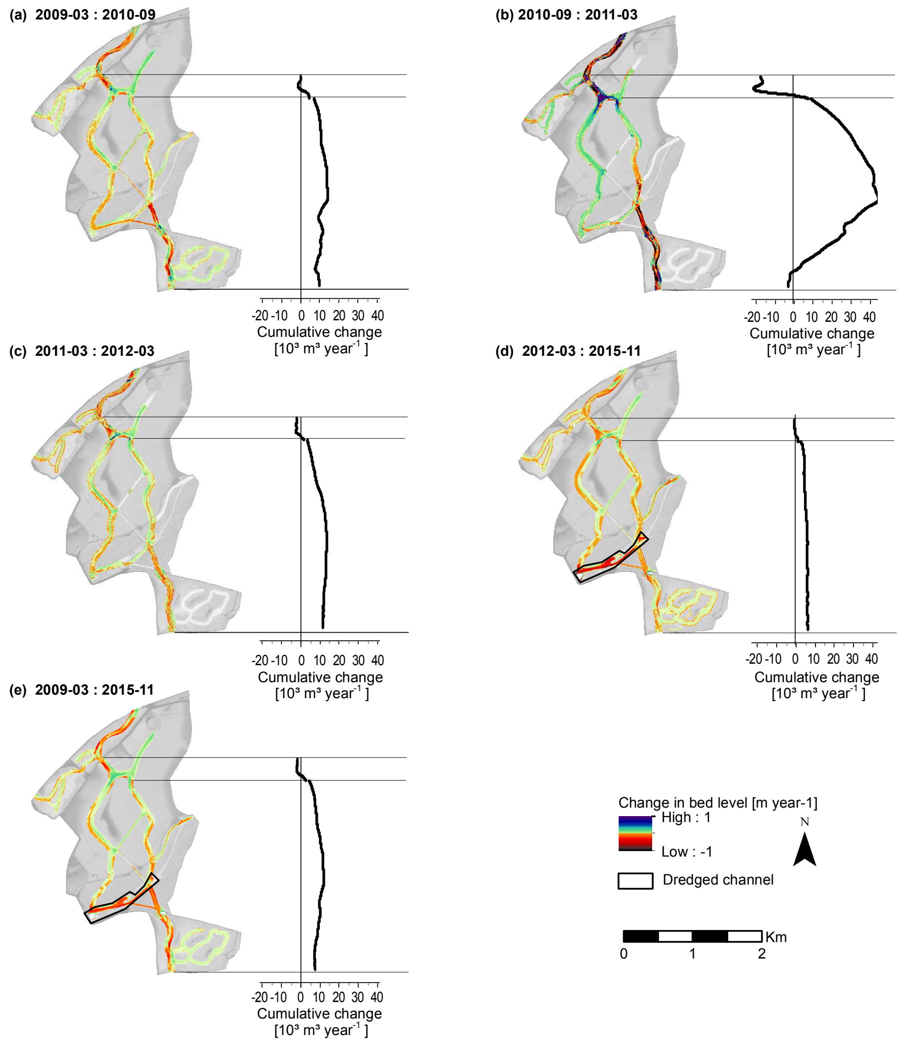


Figure 3. The difference in channel bed level and the cumulative channel bed volume ~~are shown~~ for each monitoring period. The cumulative channel bed volume is shown along a N-S transect starting from the Spiering polders (purple in Fig. 1). The budget of the Wassende Maan (blue in Fig. 1) is added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

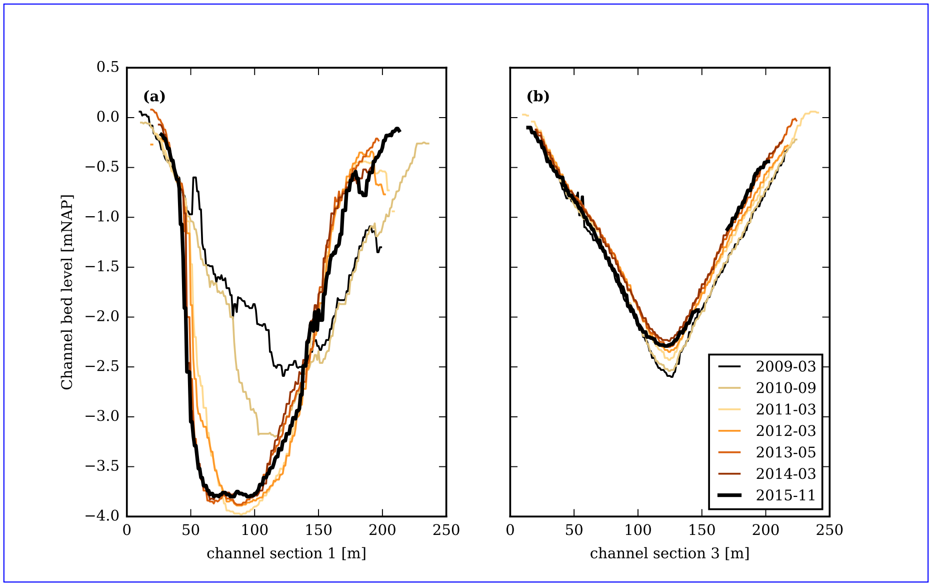


Figure 4. Bed level of channel section 1 (a) and 3 (b) for all monitoring campaigns. (see Fig. 1 for the locations of the cross sections)

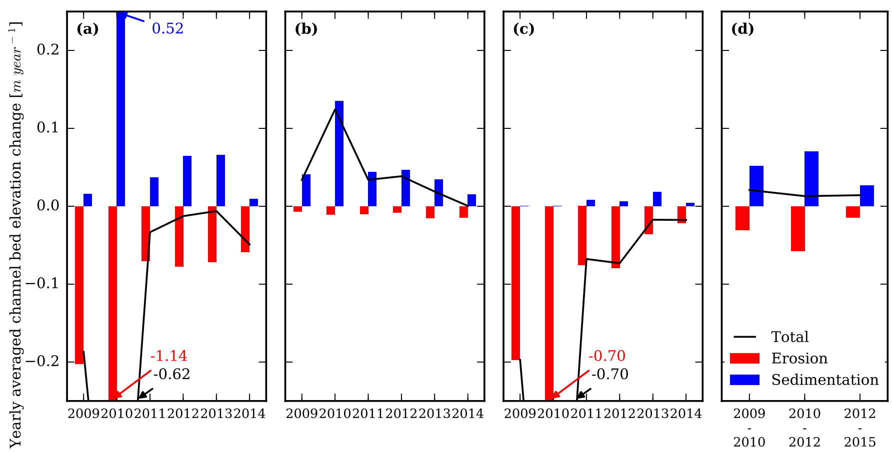


Figure 5. The yearly averaged channel section ~~deposition~~ sedimentation (blue bars), erosion (red bars) and total change in height (black lines) for the inlet (a), the centre (b), the outlet (c) and the entire study area (d), which was opened 7 May 2008 and experienced a peak discharge event from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

~~The total accumulation cmat the intertidal flats (a) and the location of the cutbanks (b) as measured during field campaigns of 2014~~

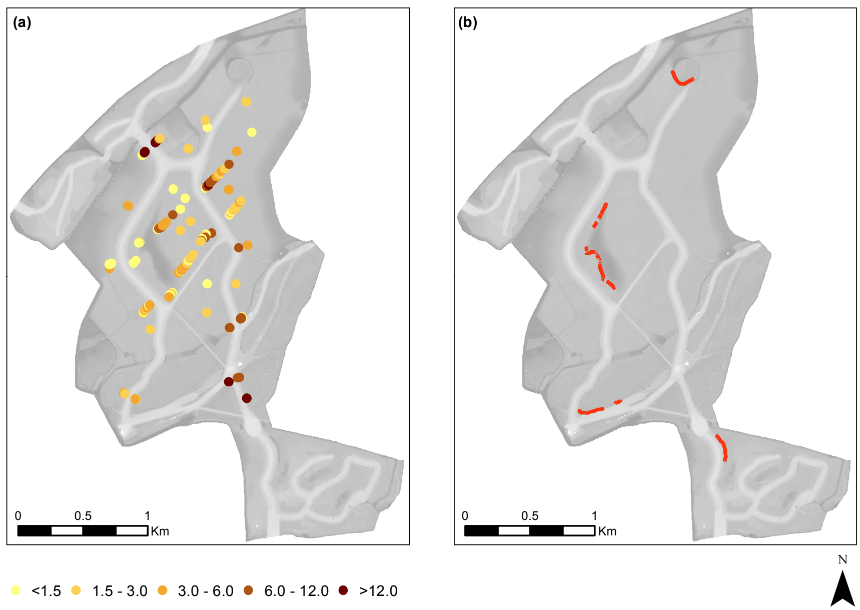
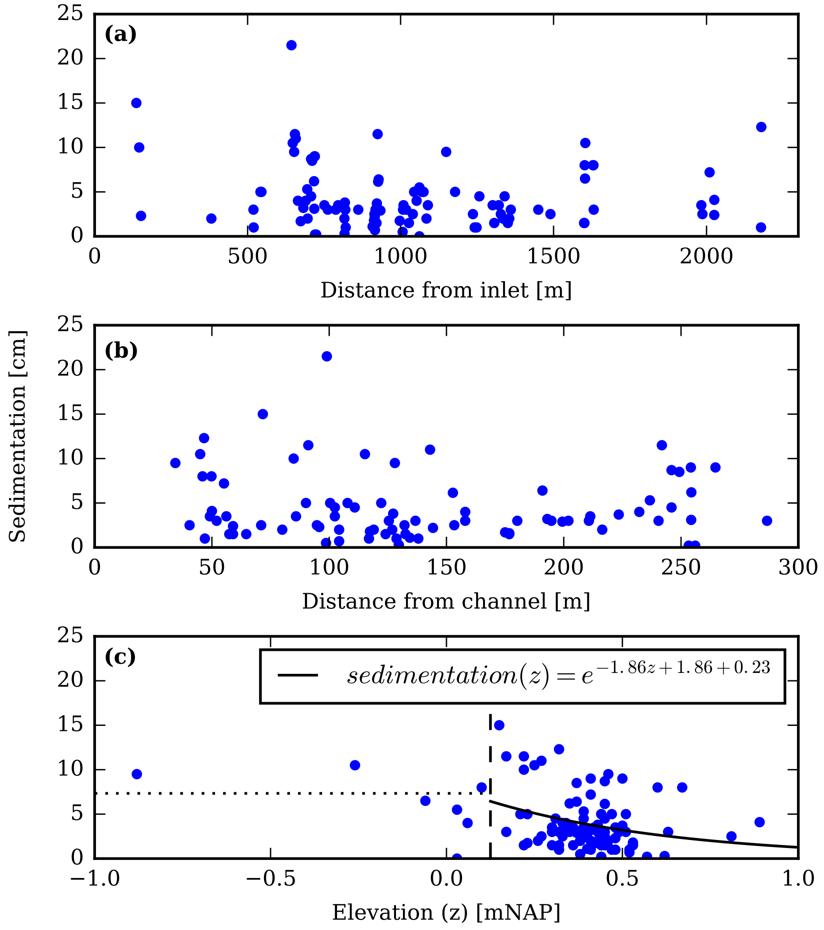


Figure 6. The total sedimentation [cm] in the subtidal and intertidal area (a) and the location of the cutbanks (b) as measured during field campaigns of 2014

~~Total accumulation during the period 2008-2014 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)~~

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)