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DOI
10.1016/j.ecoleng.2018.11.019

Publication date
2019

Document Version
Final published version

Published in
Ecological Engineering

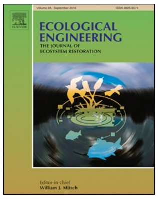
Citation (APA)
Baptist, M. J., Gerkema, T., van Prooijen, B. C., van Maren, D. S., Colosimo, I., Elschot, K., de Groot, A. V., Cleveringa, J., van Eekelen, E. M. M., & More Authors (2019). Beneficial use of dredged sediment to enhance salt marsh development by applying a 'Mud Motor'. *Ecological Engineering*, *127*, 312-323. https://doi.org/10.1016/j.ecoleng.2018.11.019

Ecological Engineering 127 (2019) 312–323

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



Beneficial use of dredged sediment to enhance salt marsh development by applying a ‘Mud Motor’

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ARTICLE INFO

Keywords:
Building with Nature
Nature-based solutions
Cohesive sediment
Dredging
Salt marshes
Intertidal flats

ABSTRACT

We test an innovative approach to beneficially re-use dredged sediment to enhance salt marsh development. A Mud Motor is a dredged sediment disposal in the form of a semi-continuous source of mud in a shallow tidal channel allowing natural processes to disperse the sediment to nearby mudflats and salt marshes. We describe the various steps in the design of a Mud Motor pilot: numerical simulations with a sediment transport model to explore suitable disposal locations, a tracer experiment to measure the transport fate of disposed mud, assessment of the legal requirements, and detailing the planning and technical feasibility. An extensive monitoring and research programme was designed to measure sediment transport rates and the response of intertidal mudflats and salt marshes to an increased sediment load. Measurements include the sediment transport in the tidal channel and on the shallow mudflats, the vertical accretion of intertidal mudflats and salt marsh, and the salt marsh vegetation cover and composition. In the Mud Motor pilot a total of 470,516 m^3 of fine grained sediment (D50 of ∼10 μm) was disposed over two winter seasons, with an average of 22 sediment disposals per week of operation. Ship-based measurements revealed a periodic vertical salinity stratification that is inverted compared to a classical estuary and that is working against the asymmetric flood-dominated transport direction. Field measurements on the intertidal mudflats showed that the functioning of the Mud Motor, i.e. the successful increased mud transport toward the salt marsh, is significantly dependent on wind and wave forcing. Accretion measurements showed relatively large changes in surface elevation due to deposition and erosion of layers of watery mud with a thickness of up to 10 cm on a time scale of days. The measurements indicate notably higher sediment dynamics during periods of Mud Motor disposal. The salt marsh demonstrated significant vertical accretion though this has not yet led to horizontal expansion because there was more hydrodynamic stress than foreseen. In carrying out the pilot we learned that the feasibility of a Mud Motor depends on an assessment of additional travel time for the dredger, the effectiveness on salt marsh growth, reduced dredging volumes in a port, and many other practical issues. Our improved understanding on the transport processes in the channel and on the mudflats and salt marsh yields design lessons and guiding principles for future applications of sediment management in salt marsh development that include a Mud Motor approach.

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https://doi.org/10.1016/j.ecoleng.2018.11.019
Received 8 May 2018; Received in revised form 6 November 2018; Accepted 17 November 2018

1. Introduction

World trade is growing, and over 80% of the volume of global trade is transported via sea (PIANC, 2011). Coastal ports handle seaborne trade and these ports need to maintain navigable depth to stay operational. Many ports are situated in deltas or regions with large loads of fine sediments. Consequently, many ports worldwide suffer from substantial volumes of maintenance dredging (IADC, 2015). Ports may additionally enhance the import of marine sediment e.g. by channel deepening, thereby worsening the siltation problems.

Dredged fine sediments are often considered unsuitable for re-use. However, as already written in Finding 29 of the 1985 book on Dredging Coastal Ports “Dredged sediment should be regarded as a resource rather than a waste” (National Research Council, 1985). Sediments, including fine sediments, can be a valuable resource, and even more so given relative sea level rise and sediment starvation due to engineering works (e.g. Meade and Moody, 2010). Authorities worldwide are therefore vigilant for initiatives involving the beneficial use of dredged material. Habitat development, beach nourishment, aquaculture, parks and recreation, agriculture, waste landfill, and construction uses are examples of beneficial use of dredged material from a 1987 engineer manual of the USACE (U.S. Army Corps of Engineers, 1987), all based on experience from as early as the 1960s and 1970s. A later USACE summary report by Brandon and Price (2007) on guidance and best practices for determining suitability of dredged material for beneficial uses distinguishes three broad categories of beneficial use, i.e. engineered uses, agricultural and product uses, and environmental enhancements. In the latter category Yozzo et al. (2004) give seven examples for habitat restoration/creation using dredged material: creation of artificial reefs and shoals, oyster reef restoration, bathymetric recontouring, creation/restoration and enhancement of intertidal marshes and mudflats, filling in dead-end canals and basins, creation of bird/wildlife islands and remediation/creation of upland habitats.

Coastal habitats such as tidal areas and salt marshes are ranked among the most important habitats regarding ecosystem services (Temmerman et al., 2013). One of these services is coastal protection, in addition to water infiltration and regulation, nurturing fisheries and providing livelihoods to communities from shellfisheries to tourist industries. Tidal flats and salt marshes even form a vital part of coastal safety worldwide (Kirwan and Megonigal, 2013; Spalding et al., 2014). Moreover, these coastal habitats are invaluable for conserving biodiversity (Dijkema et al., 1984).

Already by 1987, more than 130 freshwater and saltwater marshes have been purposely created using dredged material substrates in U.S. waterways. Marsh development techniques are, therefore, since decades sufficiently advanced to design and construct productive systems with a high degree of confidence (U.S. Army Corps of Engineers, 1987). All case studies on restoration and enhancement of intertidal marshes and mudflats known to us, involve the placement of dredged sediment directly onto the desired location, with the correct elevation, orientation, shape and size, and sometimes include artificial propagation of marsh plants. By far, most examples are known from the USA, in particular from the Mississippi River delta, such as studies on spray disposal (Cahoon and Cowan, 1988; Ford et al., 1999) and salt marsh raising with dredged material (Delaune et al., 1990; Graham and Mendelssohn, 2013; Mendelssohn and Kuhn, 2003; Tong et al., 2013).

Data of three decades of experience in the USA summarised by Streever (2000) suggest that dredged material marshes do not replace all of the functions of natural marshes. In most dredged material marshes Smooth cordgrass *Spartina alterniflora* successfully established and the marshes provided suitable habitats for birds, but these cannot be the only two attributes to determine the similarity between natural and dredged material marshes. When comparing a number of parameters including soil, biological and geomorphological characteristics, Streever (2000) found that some attributes of natural and dredged material marshes are reasonably similar while others are clearly different, such as for aboveground and belowground biomass of *S. alterniflora*, organic carbon in sediments, polychaete densities, and crustacean densities. A recent British study on saltmarsh restoration by managed realignment confirms that these saltmarshes also lack the topographic diversity found in natural habitats (Lawrence et al., 2018). Streever (2000) calls upon application of innovative research approaches to advance the field of marsh development using dredged material. In particular, Shafer and Streever (2000) suggest to develop methods to mimic natural marsh geomorphology.

Since 2007, private parties, government organisations, research institutes, universities and NGOs joint their forces in a Dutch foundation called EcoShape. They carried out the “Building with Nature” innovation programme (BwN) from 2008 to 2012 and are currently engaged in a second phase BwN innovation programme running to 2020. The programme aims to test and develop a new design philosophy in hydraulic engineering that utilizes the forces of nature thereby strengthening nature, economy and society. The USACE’s Engineering with Nature and the Working with Nature programme of the World Association for Waterborne Transport Infrastructure (PIANC) coincided with EcoShape’s programme. The BwN sub-programme Ports of the Wadden Sea is studying innovative approaches to sediment management in the Wadden Sea. The Dutch Wadden Sea has eleven small and four medium-sized ports, in total having an annual dredged volume of more than five million m^3. The Building with Nature approach facilitates the proactive utilization and/or provision of ecosystem services as part of the engineering solution to port dredging. Four concepts are or will be tested in real-life case studies, i.e. 1) optimising dredging strategies, 2) enhancing salt marsh development, 3) creating estuarine gradients, and 4) optimising flow patterns (Baptist et al., 2017; Van Eekelen et al., 2016) all in conjunction with extensive field campaigns to closely monitor the success of the pilots.

One Building with Nature concept to be tested in a pilot study is using fine-grained dredged sediments as a resource to enhance salt marsh development. Bringing mud in the currents that feed a salt marsh is expected to accelerate vertical and lateral marsh-growth, while maintaining the desired gradients that are associated with the growth of perennial vegetation. Other conditions need to be met before salt marshes can expand, such as a sufficient transport capacity of mud and limited erosion stress. Also surface elevation, wave energy, sediment supply and drainage need to be suitable for pioneer plants to establish (Dijkema, 1983; Dijkema et al., 1990). Perennial halophytic vegetation typical for marshes, such as *Spartina anglica* and *Puccinellia maritima*, can establish near mean high water (MHW) (Dijkema et al., 1990). Once perennial vegetation has established, it will stimulate accretion, reduce erosion and geomorphological patterns in the marsh platform start to develop by positive feedback processes (Langlois et al., 2003; Schwarz et al., 2015; Van Wesenbeeck et al., 2008; Vandenbruwaene et al., 2015). Salt marsh vegetation lowers the hydrodynamic load from currents and waves, thereby increasing the sedimentation rates on the marsh (Leonardi et al., 2018; Neumeier and Amos, 2006). Root systems stabilize the soil which reduces erosion potential (Allen, 1989). As a result, a vegetated saltmarsh is likely to continue accumulating sediment and develop a natural marsh biology and geomorphology.

We test an innovative approach to beneficially re-use dredged sediment to enhance salt marsh development: deposit the dredged sediment as a semi-continuous source of sediment in a tidal channel and allow natural processes to disperse the sediment to nearby salt marshes (see graphical abstract). This method was named Mud Motor. Differing from the Sand Motor or Sand Engine, in which a large volume of sand was deposited at once (Aarninkhof et al., 2012; Stive et al., 2013), the Mud Motor will serve as a semi-continuous source of sediment. While applying the Mud Motor method dredged material will supplement and accelerate natural marsh growth without direct disturbance and thereby maintaining natural marsh biology and geomorphology. The potential economic and ecological benefits are threefold, a reduced necessity for dredging, increased and sustainable ecosystem based coastal protection, and conserving valuable habitats for marsh-specific flora and fauna.

The goals of this paper are to describe the various aspects involved in the set-up and design of the Mud Motor pilot, to describe the monitoring and research programme and preliminary results, and to present a conceptual framework with guiding principles for future applications of sediment management in salt marsh development.

2. Materials and methods

2.1. Study area

The Wadden Sea is the largest coherent system of intertidal sand flats and mudflats in the world and is listed as UNESCO World Heritage since 2009 because of its Outstanding Universal Value on geological and ecological processes and biodiversity (Reise et al., 2010). This protected nature reserve is part of Europe's network Natura2000 and has strict regulations for nature conservation.

The Port of Harlingen, one of the four medium-size ports in the Dutch part of the Wadden Sea, was chosen for a pilot using the Mud Motor method for enhancing salt marsh development. Approximately 1.3 million m^3 of fine sediment (D50 of $\sim 10\,\mu m$) is dredged annually from the port and deposited in two designated disposal areas close to the port (K1 during ebb and K2 during flood, see locations in Fig. 1). In current operations an unknown but possibly considerable proportion of the dredged sediment flows back into the port. The port authority was looking for opportunities to reduce maintenance dredging, including a reduction of the return transport of the disposed fine sediment. Simultaneously, the local nature management organisation It Fryske Gea is not satisfied with the narrow rim of salt marshes northeast of Harlingen. This salt marsh was lacking floral diversity and breeding birds due to its limited width. The combination of the large dredging volume and possibly high return transport into the port together with the poor condition of the neighbouring salt marsh made this case fit for the Mud Motor pilot.

In this pilot, the regular maintenance dredging operations with a small 600 m^3 Trailing Suction Hopper Dredger (TSHD) continued. For the duration of this experiment part of the dredged volume was deposited further away from the port at a Mud Motor (MM) disposal location, Fig. 1. The MM disposal location is chosen based on its water depth at low water (LW), mid water (MW) and high water (HW), to guarantee accessibility by the dredger, and on its effectiveness in transporting the sediment towards the upper zone of the mudflat and salt marsh as predicted by numerical simulations (see next sections). Disposal of dredged sediment from the hopper took place through bottom doors.

The targeted salt marsh is located to the northeast of Harlingen in a local indentation of the coastline between Koehool and Westhoek. A tidal channel, Kimstergat, runs parallel to the coastline from the deeper waters near the port of Harlingen toward shallow waters to the northeast. Historical data on the bathymetry of the study area are available from Rijkswaterstaat since 1926, just before the moment of closure of the Zuiderzee by the Afsluitdijk. Historical bed level changes over the period 1926–2016 are shown in Fig. 2. The intertidal area along the dike between Koehool and Westhoek increased with 2–3 m in the last century. Fig. 2 shows the bed level accretion of two representative transects, Koehool (Transect 1, unvegetated) and Westhoek (Transect 3, vegetated). Transect 2 is partially vegetated, i.e. a few meters of vegetation width in its upper zone. At the north-eastern side, Transect 3, the bed level increased to levels above Mean High Water (MHW). Such conditions provide possibilities for pioneer vegetation establishment and germination (Dijkema et al., 1990) and have resulted in salt marsh formation and subsequent rise of the bed level to 2 m +NAP. At the south-western side near Koehool these high bed levels are not (yet) reached and no vegetation has developed.

Lateral salt-marsh growth was determined from historical aerial photographs, showing that the salt-marsh surface area has increased for the past two decades. Salt marsh growth started in the year 1996 in the north-eastern part, closest to the tidal divide. The salt marsh grew between 1996 and 2003, after which stabilisation occurred. A new period of growth took place between 2008 and 2013, after which again stabilization occurred. These observations indicate that for a certain set of conditions salt marsh establishment may prevail, but that these conditions are not necessarily met in each successive year, in concordance with the Windows of Opportunity concept (Balke et al., 2014). The extension of the salt marsh took a south-western direction along the coast. In the most sheltered part of the study area, the salt marsh reached its present maximum width.

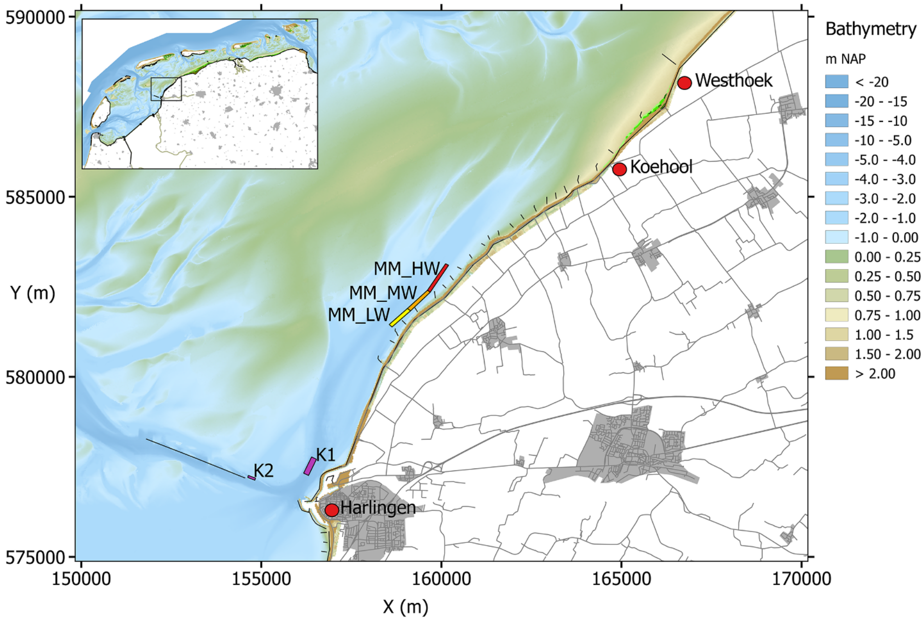

Fig. 1. Bathymetric map of the study area, with dredged sediment disposal locations K1, K2, MM_LW, MM_MW and MM_HW. Coordinates shown in Dutch grid EPSG:28992.

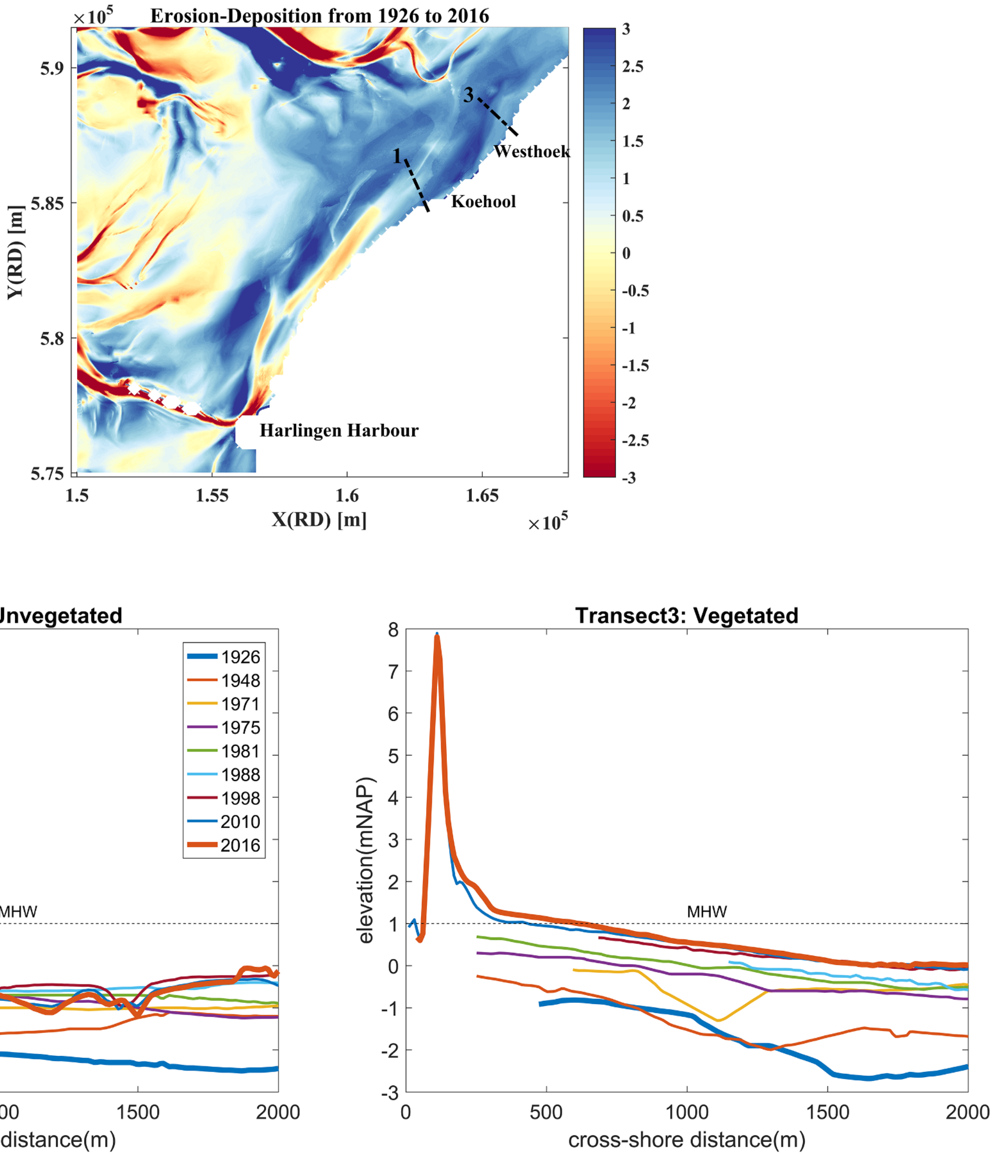

Fig. 2. Top: Change in bed elevation from 1926 to 2016 where negative values (in red) show erosion and positive values (in blue) show accretion. Coordinates shown in Dutch grid EPSG:28992. Bottom: profile evolution of an unvegetated transect (Koehool) and a vegetated transect (Westhoek) where the absolute bed level is shown relative to Dutch Ordnance Level NAP. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Design and set-up of the Mud Motor pilot

2.2.1. Numerical simulations

The first step in the design of the Mud Motor pilot is exploration of a suitable disposal location. An important criterion is the tide-varying water depth, as the draught of the TSHD requires a minimum water depth of 3 m. Another criterion is the distance to the targeted salt marsh. Close to Koehool, the tidal channel does not only shallow, also the distance between the channel and the coastline increases (see Fig. 1). This implies that the closer the disposal location is placed towards Koehool, the larger the cross-channel distance will be. This cross-shore distance seemed to be an important parameter in the initial fate of released sediments, which was evaluated with a numerical sediment transport model. The numerical model (see Vroom (2015) for details) revealed that the initial dispersal of released sediment by tides only is primarily regulated by shore-parallel flow patterns. As a result, sediment released close to the shore (albeit relatively far away in the alongshore direction) is more effective in nourishing the Koehool mudflat than sediment released at the landward limit of the channel. In Fig. 1, showing the final disposal locations, this is translated in an MM_HW high water disposal site, an MM_LW low water disposal site and an MM_MW for the disposal with intermediate water levels, in order to guarantee the minimum navigation depth. The high tide site is furthest away from the Port of Harlingen and due to the shallow water depth only available closely before or after high tide, before tidal flow reverses.

2.2.2. Tracer study

Based on the numerical simulations, a preliminary disposal location was chosen in shallow water on the right bank of the tidal channel. Prior to changing the original dredging strategy of the port, a tracer experiment was carried out to determine how much of the disposed sediment would be transported from the new disposal location towards the target area, i.e. the tidal flats and salt marshes near Koehool, in comparison with one of the original disposal locations. For each of the two locations, we applied a different coloured fluorescent tracer with a particle size distribution and behaviour similar to sediment dredged from the port of Harlingen, having a D50 of ~10 μm. After completely mixing tracer with dredged sediments in the hopper, we assume the tracer particles to be encapsulated in flocs formed by the natural

Table 1
Percent recovery in the area of interest of the blue tracer (released at existing disposal location K2) and the green tracer (released at the new location) after 5 days, 2 weeks, and one month. See Vroom et al. (2016) for details.

Time after release	Blue	Green
5 days	1%	13%
2 weeks	5%	12%
1 month	20%	80%

sediments, and thereby behave similarly. For both locations an amount of 100 kg dry weight per tracer colour was used equivalent to $\sim 4 \times 10^{14}$ tracer particles. The retrieval of the tracers in the study area determined the effectiveness of dredged sediments reaching the target area. The evolution of sedimentation patterns over time was assessed by carrying out multiple sampling campaigns (one, two, and 4–5 weeks after release of the tracer). By using a large amount of sampling locations (~100), not only the amount but also the variability of the sedimentation within the area of interest could be assessed. The total amount of sedimentation of each sediment tracer in the area of interest could be compared to the total amount of tracer particles released as a measure of the effectiveness of the disposal location. The results showed that after one month 80% of the mud disposed at the new disposal location reached the targeted intertidal area where salt marsh enhancement is desired, compared to only 20% from the existing disposal location, Table 1.

2.2.3. *Legal requirements*

Dredging projects are regulated by national and European legislation (Sheehan and Harrington, 2012). Because the Wadden Sea is protected by the nature conservation laws of the EU Habitats and Birds Directives a permit to work within the protected Natura2000-nature area had to be obtained. According to European law an Appropriate Assessment had to be written, giving a detailed account of the natural values that potentially were at stake and describing possible options for mitigation (Baptist, 2015). The activities that needed to be assessed included the disposal of the mud as well as the research activities that were planned in the study area. Important natural values such as haul-out locations for seals and natural mussel beds were more than two kilometres away from the planned activities, so these did not pose a problem. Closer to the disposal location, albeit still at more than 500 m distance, moulting shelducks *Tadorna tadorna* assemble in July-August and these could potentially be disturbed. The additional turbidity resulting from the disposal could potentially hamper primary production in spring and summer. Moreover, a disposal during spring may lead to burial of germinating seeds and hamper vegetation establishment. Therefore, to minimise potential effects on the ecosystem and the salt marsh system, disposal at the new location was only allowed in autumn and winter, i.e. between September 1st and April 1st, and only during daylight hours to minimise disturbance.

One of the objectives of the Mud Motor is to expand the salt marsh area. This objective is in itself in conflict with the nature conservation law. The law aims at conserving the surface area of EU habitat types and any activity that leads to a significant decrease in habitat area cannot be allowed. An increase in salt marsh area (EU Habitat 1310) will lead to a decrease in mudflat area (EU Habitat 1140A), with potential knock-on effects on subtidal area (EU Habitat 1110A), because the salt marsh expansion can only go forward due to coastal squeeze (Doody, 2013, 2004), and hence will be covering other existing and protected habitat. Similar issues of habitat trade-offs that were conflicting with large-scale tidal marsh development projects were apparent in the New York-New Jersey Harbor (Yozzo et al., 2004). Obviously the nature conservation law is primarily meant to stop activities that remove natural habitat, and although in this case there is only a shift in habitat type, strictly following the law, the significance of habitat loss should be assessed. A maximum salt marsh extension of 16 ha was expected prior to the Mud Motor pilot, potentially leading to habitat loss of 0,0012% of the total intertidal area in the Dutch Wadden Sea and this was considered insignificant.

2.2.4. *Planning and technical feasibility*

After determining a suitable new disposal location for the Mud Motor pilot, and having obtained the necessary licences, the planning of the dredging operations needed to be detailed. Based on the sailing distance, dredge cycle times, tidal water level predictions and daylight windows an assessment of the disposal options was made. Disposal was planned only during flood tides, i.e. when flow is directed towards the salt marsh target area. An analysis of the co-occurrence of flood flows and daylight hours revealed that in December and January there was not enough time for mud disposal of the required volumes. A change request for the permit was granted to extend the working hours to between 07:00 h and 19:00 h, when sunrise and sunset were within this interval. Taking all boundary conditions into account, a maximum dredge volume of 300,000 m^3 could be disposed over one autumn and winter season (Grasmeijer, 2016).

2.3. *Monitoring and research programme*

An extensive monitoring and research programme was designed to measure sediment transport rates and the response of intertidal flats and salt marshes to an increased sediment load. Within the project, detailed measurements of suspended sediment transport processes, and numerical modelling of the mud transport from the subtidal zone, through the intertidal area and towards the salt marshes, are conducted. Furthermore, studies on the influence of biota on salt marsh expansion are carried out. Such in-depth knowledge is essential for upscaling the concept of the Mud Motor to different and/or larger environments.

2.3.1. *Sediment transport rates*

The disposal of the dredged sediment in the tidal channel leads to increased concentrations of suspended fine sediment in the water column. Field observations and ship-based measurements quantified the cross-shore and long-shore dispersal of large-scale frequent mud disposals in response to tides, waves, storms and nearby freshwater discharge events.

Ship-based measurements were carried out in June 2015, April 2016, October 2016 and October 2017. The first two cruises were sailed before the start of the Mud Motor pilot, and the latter two during the pilot. On each cruise, suspended particulate matter (SPM) concentrations and current velocities were measured for 13 h to calculate the residual SPM transport at two locations: close to the port of Harlingen and near the new disposal location. Current velocities were measured with two acoustic Doppler current profilers (ADCPs), one mounted on the ship, downward-facing, to profile the lower part of the water column, another one attached to a bottom lander (deployed nearby the ship), upward-facing, to profile the top part of the water column. The two data sets were combined, and, where necessary, interpolated to obtain current profiles covering the whole water column.

Vertical profiles of turbidity were obtained with optical backscatter sensors (OBS). The sensors were attached to a frame that was lowered from the stern of the ship in intervals of 15–20 min. Simultaneously, water samples with a Niskin bottle were taken and filtered over pre-weighed GFF filters to obtain the total suspended matter content. Water from the same Niskin bottle was sampled with another OBS in a dark box to obtain a linear regression between turbidity values and SPM concentration. The OBS in the box was then intercalibrated with the OBS on the frame to calculate the corresponding SPM concentration from the turbidity profiles.

Additionally, the frame was equipped with sensors for salinity and temperature, and (only for the last cruise) with a Laser In-Situ

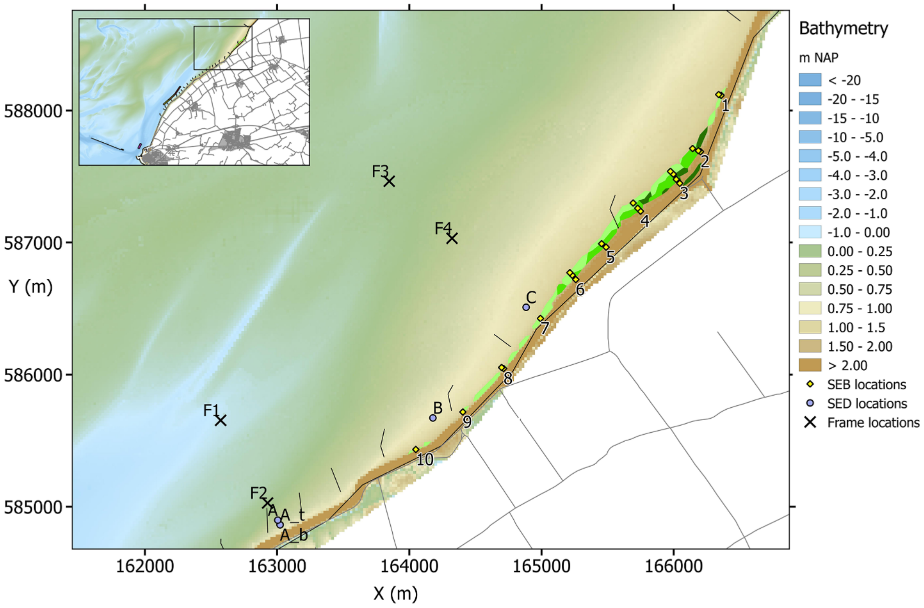

Fig. 3. Measurement locations. F1, F2, F3 and F4 are hydrodynamic and suspended sediment frame locations. A, A_t, A_b, B and C are Surface Elevation Dynamics (SED) sensor locations. Transects 1–10 show 22 Sedimentation-Erosion Bar (SEB) locations in the salt marsh, with adjacent permanent quadrats (PQ). Coordinates shown in Dutch grid EPSG:28992.

Scattering and Transmissometer (LISST-200X, Sequoia Scientific Inc.) to measure the in-situ grain size distribution of the suspended matter. Details on the ship-based campaigns and an analysis of the data from the first thee cruises can be found in Schulz and Gerkema (2018).

Additional to measurements in the tidal channel, hydrodynamic and suspended sediment measurements on the intertidal mudflats have been carried out. Instrument frames have been placed at two different transects: The Koehool transect, where the upper flat is bare; and the Westhoek transect, where the upper flat is vegetated (Fig. 3). The frames are equipped with ADCP (Nortek Aquadopp), ADV (Nortek Vector), OBS (Campbell OBS 3+) and pressure sensors (OSSI-010-003C). The instruments are used to determine the flow velocities, water depths and suspended sediment concentrations in order to quantify the sediment fluxes.

The monitoring activities on the tidal flats aim at quantifying the suspended sediment fluxes and assess the seasonality of mud transport in the area, with and without the Mud Motor pilot. Therefore, three field campaigns have been carried out. In spring 2016 (i.e. before the Mud Motor pilot started), a one-month monitoring campaign has been conducted at locations F1 and F2. From mid-April to mid-May 2017 (i.e. after the pilot started), a similar campaign has been carried out at locations F3 and F4. From December 2017 to February 2018 the mudflats were investigated simultaneously during winter, severe, weather conditions. Four instrument frames have been installed at locations F1, F2, F3 and F4 using thirty instruments in total (ADVs, AQUADOPPs, OBSs, CTDs, Wave Loggers and Surface Elevation Dynamics sensors), some of which measured continuously at very high frequency (8–10 Hz).

2.3.2. Mudflat and salt marsh accretion

The mudflat and salt marsh bed level changes were measured with two types of in-situ instruments, i.e. Sedimentation-Erosion Bars and Surface Elevation Dynamics sensors. The multi-annual surface-elevation change was determined with Sedimentation-Erosion Bars (SEBs). This instrument is described in Nolte et al. (2013). The setup consists of two horizontally aligned poles inserted into the ground until they reach a stable horizon. During measurements, a 2 m-long bar with 17 holes 10 cm apart is placed on the poles and a ruler is placed through these holes to measure the distance to the soil surface. Through repeated measurements the accuracy of the time series is about 1.5 mm vertically. In the study area 41 SEB-stations were aligned in transects perpendicular to the dike. Twenty-two stations were located on the vegetated salt marsh (shown in Fig. 3) and 19 were on the bare mudflats. Another 15 SEB-stations were located in a reference area to the northeast of the study area. The surface elevation is determined four to five times per year.

Short-time surface elevation changes were determined with Surface Elevation Dynamics (SED) sensors. An extensive description with illustrations of this novel instrument is found in Hu et al. (2015a). A SED-sensor is essentially a pin containing a semi-continuous array of 200 light sensitive cells that is inserted vertically in the sediment leaving approximately half of the measuring section above the seabed. The aboveground cells and belowground cells give high and low voltage outputs accordingly, resulting in a transition point at the bed level. The distance between two adjacent cells is 2 mm, and the measuring interval can be set from one second to a few hours, depending on the application. The measurement interval used in the current study was 30 min. The applied SED-sensors rely on daylight, and hence do not work overnight or when submerged. Updated sensors are being developed with hydro-acoustic sensors, to be able to measure overnight and when submerged. The SEDs placed at our project site also contain pressure sensors to measure waves at an interval of 10 min. In the target area 5 SED-sensors were deployed from mid-July 2017 till January 2018. SED-sensors were placed at three locations A, B and C at 100 m distance from the dike toe or salt marsh edge (if present) and also at A_b at the bottom of a hollow and at A_t on top of a hummock at 60 m from the dike toe (Fig. 3). The SEDs were checked approximately every eight weeks to ensure data collection, clean the sensors and retrieve the data. Collected raw data from the Surface Elevation Dynamics (SED) sensors were converted using well-documented software (Willemsen et al., 2018).

For a synoptic view of the surface level of the mudflats and salt marsh, an Unmanned Aerial Vehicle (UAV) with on-board LiDAR was flown annually over the study area. Light Detection And Ranging (LiDAR) works by sending laser pulses into an array of accurately defined directions in fast succession. Measuring the travel time it takes for each laser-pulse to be reflected from the targets and returned to the LiDAR-scanner allows reconstruction of distances and directions of surfaces surrounding the scanner. Attaching a LiDAR scanner to a moving platform like a UAV allows 3D mapping of larger surface areas as the UAV platform is moving ahead. While scanning the surface, the UAV also makes aerial orthophotos mapping the study area. Although the vertical accuracy of the scans is in the same order of the average expected increase in bed level by the Mud Motor, the scans can be used to assess changes in the small-scale morphology. The bare mudflat in front of the salt marsh is characterised by a pattern of small hollows and hummocks, with a size of several meters and a height of several decimetres that are clearly captured by the LiDAR images.

2.3.3. Salt marsh vegetation cover and composition

The development and cover of salt marsh vegetation was studied with historical aerial and recent UAV orthophotos. Yearly, in situ measurements of vegetation diversity and density were performed at permanent quadrats (PQ) located adjacent to the salt marsh SEB-stations (Fig. 3). Following the vegetation developments in the PQ-plots for multiple years allows us to compare the study area to reference salt marshes and to determine the rate of expansion and marsh stability.

An additional study aims to clarify the biogeomorphic role of oligochaete bioturbation in facilitating or hindering vegetation establishment in the salt marsh transition zone. Oligochaetes (Annelida) are active bioturbators that can be present in high densities in the transition zone between intertidal flats and salt marshes, especially in fine grained sediments. Microcosm experiments were performed to assess the effect of oligochaete bioturbation on sediment properties, oxidation depth, algal biomass, seed distribution, and germination success of pioneer species *Salicornia* spp. (Van Regteren et al., 2017). The effect of external environmental variables, such as inundation, temperature and algae on pioneer vegetation development has been investigated in a field experiment in summer 2017. In another field experiment we will study the interaction between sediment dynamics and seed availability by manually adding seeds to the mudflat and monitoring seed fate as a proxy for expansion potential.

3. Results

3.1. Execution of the pilot

The mud was dredged from the basins of the Port of Harlingen using the 604 m^3 TSHD 'Adelaar' of the company De Boer Dredging. Dredging operations were carried out daily. The average cycle time for the Mud Motor disposals was around 1:45 h. The realised number of mud disposals was dependent on appropriate high tides inside the available time window, and on other factors such as weather conditions and technical issues. An average number of approximately 22 mud disposals per operating week, with a weekly volume of 13,288 m^3 was achieved, Table 2. In the first Mud Motor Season from 1 September 2016 to 31 March 2017 in total 300,188 m^3 of dredged sediment was disposed at the Mud Motor (MM) disposal sites. In the same period another 433,672 m^3 was disposed at the K1 and K2 sites, Fig. 1. In the second Mud Motor season, from 1 September 2017 to 1 December 2017 a total of 170,328 m^3 was disposed at the MM disposal site and another 201,780 m^3 at the K1 and K2 disposal sites.

Remarkably the dredged volume needed to maintain navigable depth in the Port of Harlingen has decreased with 23% in 2017 to 1.0 million m^3 compared with the long-term average of 1.3 million m^3, Table 3. A reduction of the return transport may have resulted from disposal at the Mud Motor site, however, it may also be that the year 2017 has fallen within the variability found in the annual dredged volumes, similar to year 2012.

3.2. Sediment transport rates

3.2.1. Channel

The ship-based measurements in the Kimstergat channel revealed two main factors that influence the suspended sediment transport under calm wind conditions: an asymmetry between ebb and flood current, and a periodic vertical salinity stratification that is built up during flood, and destroyed again with the onset of the ebb current. Data and figures of current velocity, SPM concentration and salinity from ship-based measurements are displayed and discussed in Schulz and Gerkema (2018).

The stronger flood currents cause stronger resuspension and therefore a higher concentration of suspended matter compared to the ebb phase. The SPM concentration decays when the flood current slows down and slack tide is approached, as the sediment settles. Although SPM concentrations are found to be generally higher during flood current than during ebb in most of the observed data sets, it has to be kept in mind that advective effects play a role, besides local resuspension. Advection may bring sediment that was resuspended elsewhere, where the current might behave differently than at the measurement location. This is especially relevant with regard to sediment coming from the Trailing Suction Hopper Dredger, which may cause additional peaks in SPM concentration not related to local resuspension.

It is known from estuarine studies that (already a weak) periodically occurring density stratification can affect the residual current and the residual transport of SPM (Jay and Musiak, 1994; Scully and Friedrichs, 2003; Simpson et al., 1990). A vertical gradient in salinity (and consequently in density) hinders turbulent motions and reduces vertical mixing, including the upward-mixing of sediment. In a classical estuary (e.g. a river flowing into the sea), a density stratification is built up during ebb current, when light (fresh) water is transported on top of dense (saline) water, and destroyed again when dense water is pushed into the estuary with the flood. In the Kimstergat channel, however, a fresh water source (discharge from lake IJssel) is located at the mouth of the channel. Consequently, the periodic stratification is inverted compared to a classical estuary: density stratification is built up during flood, and destroyed during ebb. Following the theory of sediment transport in estuaries, this periodic stratification triggers a residual SPM transport in the direction of the freshwater source, which is in this case the ebb direction, i.e. out of the Kimstergat.

To determine to what extent the asymmetric tidal current and the periodic salinity stratification affect the residual SPM transport in the Kimstergat, an idealized 1D water column model was set up. In this model, the tidal current can be chosen to be either asymmetric, as observed in the velocity data, or purely sinusoidal. Independent of the current, the salinity can either be set to exhibit the observed periodic stratification, or to be constant. Without the periodic density stratification, transport rates into the Kimstergat would be around 60% larger. In the absence of tidal asymmetries, the periodic salinity stratification would reverse the direction of the sediment transport and cause an export of suspended sediment.

3.2.2. Mudflat

The field measurements using instrument frames on the intertidal mudflat show that the tidal flow is also flood dominant on the flat, implying higher flood velocities than ebb flow velocities. This favours flood dominated sediment transport towards the upper flat. However, the shallow conditions make the flow very sensitive to wind. We observed that the tidal flood flow direction (and thus the sediment fluxes toward the study area) can be reversed by a wind with opposite direction when the wind speed is about 10–12 m/s. As wind conditions of over 10 m/s are common and as wind speed and direction can vary in a few hours, the tide-only conditions cannot be considered representative. This implies a large temporal variability on daily time scale, but also seasonal and annual timescale.

Wind in the flood flow direction enhances the magnitude of sediment fluxes by significantly higher sediment concentrations. This is explained by an interaction of wind-induced flow, on a large (tidal basin) scale with the bathymetry of the area (shallower at the northern part compared to the southern ones). This shows that the functioning of the Mud Motor, i.e. the successful increased mud transport toward the mudflat and saltmarsh, is significantly dependent on the wind and wave forcing.

3.3. Mudflat and salt marsh accretion

Results of the measurements with Sedimentation Erosion Bars show relatively large changes in surface elevation. Layers of watery mud with

Table 2
Mud Motor disposed volumes per week. N is number of disposals per week, Volume is disposed volume per week (m^3) and Cumulative is cumulative volume (m^3) for Mud Motor Season 1 and Mud Motor Season 2.

Season 1	N	Volume	Cumulative	Season 2	N	Volume	Cumulative
week 2016–36	28	16,912	16,912	week 2017–36	23	13,892	13,892
week 2016–37	34	20,536	37,448	week 2017–37	24	14,496	28,388
week 2016–38	29	17,516	54,964	week 2017–38	22	13,288	41,676
week 2016–39	29	17,516	72,480	week 2017–39	16	9664	51,340
week 2016–40	16	9664	82,144	week 2017–40	22	13,288	64,628
week 2016–41	14	8456	90,600	week 2017–41	16	9664	74,292
week 2016–42	14	8456	99,056	week 2017–42	21	12,684	86,976
week 2016–48	30	18,120	117,176	week 2017–43	27	16,308	103,284
week 2016–49	25	15,100	132,276	week 2017–44	16	9664	112,948
week 2016–50	31	18,724	151,000	week 2017–45	28	16,912	129,860
week 2016–51	22	13,288	164,288	week 2017–46	30	18,120	147,980
week 2017–01	27	16,308	180,596	week 2017–47	29	17,516	165,496
week 2017–02	19	11,476	192,072	week 2017–48	8	4832	170,328
week 2017–03	28	16,912	208,984				
week 2017–04	31	18,724	227,708				
week 2017–05	29	17,516	245,224				
week 2017–06	27	16,308	261,532				
week 2017–07	3	1812	263,344				
week 2017–11	16	9664	273,008				
week 2017–12	30	18,120	291,128				
week 2017–13	15	9060	300,188				

Table 3
Annual dredged volumes in the Port of Harlingen.

Year	Volume (m^3)
2007	1,250,004
2008	1,448,480
2009	1,156,056
2010	1,357,188
2011	1,287,412
2012	1,036,555
2013	1,264,469
2014	1,412,866
2015	1,367,457
2016	1,441,748
2017	1,018,000

a thickness of up to 20 cm were deposited in some locations in the salt marsh over a two or three month period, though disappeared just as fast. The most important processes responsible for mud disappearance were compaction and erosion. If the watery mud layer persists at its location, a few successive warm days without inundation cause drying out and significant compaction. On the other hand, the watery mud layer can be eroded by waves and tidal currents. Our two- or three-monthly measurements could not differentiate between the processes erosion and compaction, but did show large fluctuations in bed height. The salt marsh SEB stations showed a net accretion between −0.3 and 13.3 cm with an average of 4.9 ± 0.9 cm (mean ± standard error) in the three year period from September 2015 to August 2018. Spatial variability in sedimentation was substantial with larger sediment dynamics (erosion as well as accretion) in the southern transects compared to the northern transects, Fig. 4. Net accretion appeared larger at the lower and higher salt marsh compared to the pioneer zone, although this was particularly pronounced for the December 2017 measurements. Highest sedimentation and erosion values occurred in winter and generally consisted of a layer of fluid mud that was deposited, or eroded again, in a single storm or a few high tides. The measurements did show notably higher sedimentation and erosion dynamics with the Mud Motor on compared to the Mud Motor off. SEB-stations on the mudflat (not shown in Fig. 4) showed an erosion/accretion between −4.6 and 6.0 cm with an average of 2.1 ± 0.6 in the two year period from September 2016 until August 2018. Generally, on the mudflat, the northern part of the area accreted whereas the southern part eroded slightly.

Results from the Surface Elevation Dynamics (SED) sensors are in agreement with the SEB measurements and also show rather large and fast bed level variations with accretion/erosion events of up to 10 cm on a time scale of days (e.g. 7 cm accretion in November at location B and C and 10 cm erosion in September at location A_t), Fig. 5. Such events were not observed in other tidal flats at a similar distance from the salt marsh edge or dike toe using similar instruments (Hu et al., 2017; Willemsen et al., 2018). These large bed level fluctuations are indicating the highly dynamic character of the study site, which is also reflected in the morphological pattern of hollows and hummocks, with a horizontal width of several meters and a height of several decimetres. An increase in sedimentation rates in relation with disposed Mud Motor volumes could not be established.

The UAV LiDAR measurements showed interesting morphodynamic phenomena in the dynamics of hummocks and hollows on the mudflats, but the data has yet to be analysed.

3.4. Salt marsh vegetation cover and composition

The permanent quadrats for vegetation composition did not show an increase in pioneer vegetation cover on the edges of the marsh. Neither was there accelerated succession in the vegetated plots within the short time period of the first two years.

Results of the UAV orthophotos taken at the end of summer/beginning of autumn each year showed that the salt marsh vegetation cover grew from 28.2 ha to 29.9 ha prior to the Mud Motor pilot between 2015 and 2016. The salt marsh cover lost 3.5 ha between 2016 and 2017, in which season 1 of the Mud Motor pilot was executed. It then increased to 27.9 ha with 1.5 ha between 2017 and 2018, during season 2 of the Mud Motor pilot.

Our experimental study indicated that small, though numerous, oligochaete bioturbators may reduce lateral expansion potential of the salt marsh by hindering the establishment of pioneer vegetation in the transition zone between saltmarsh and mudflat. Oligochaete conveyor belt feeding buried *Salicornia* spp. seeds until below the critical germination depth, thus negatively affecting *Salicornia* spp. germination and seedling establishment. The density of worms used in our experiments corresponded to 131,493 individuals/m^2. Because observed field densities of oligochaetes in our study site ranged up to 318,290 individuals/m^2, it seems likely that they can influence *Salicornia* establishment in the field (Van Regteren et al., 2017).

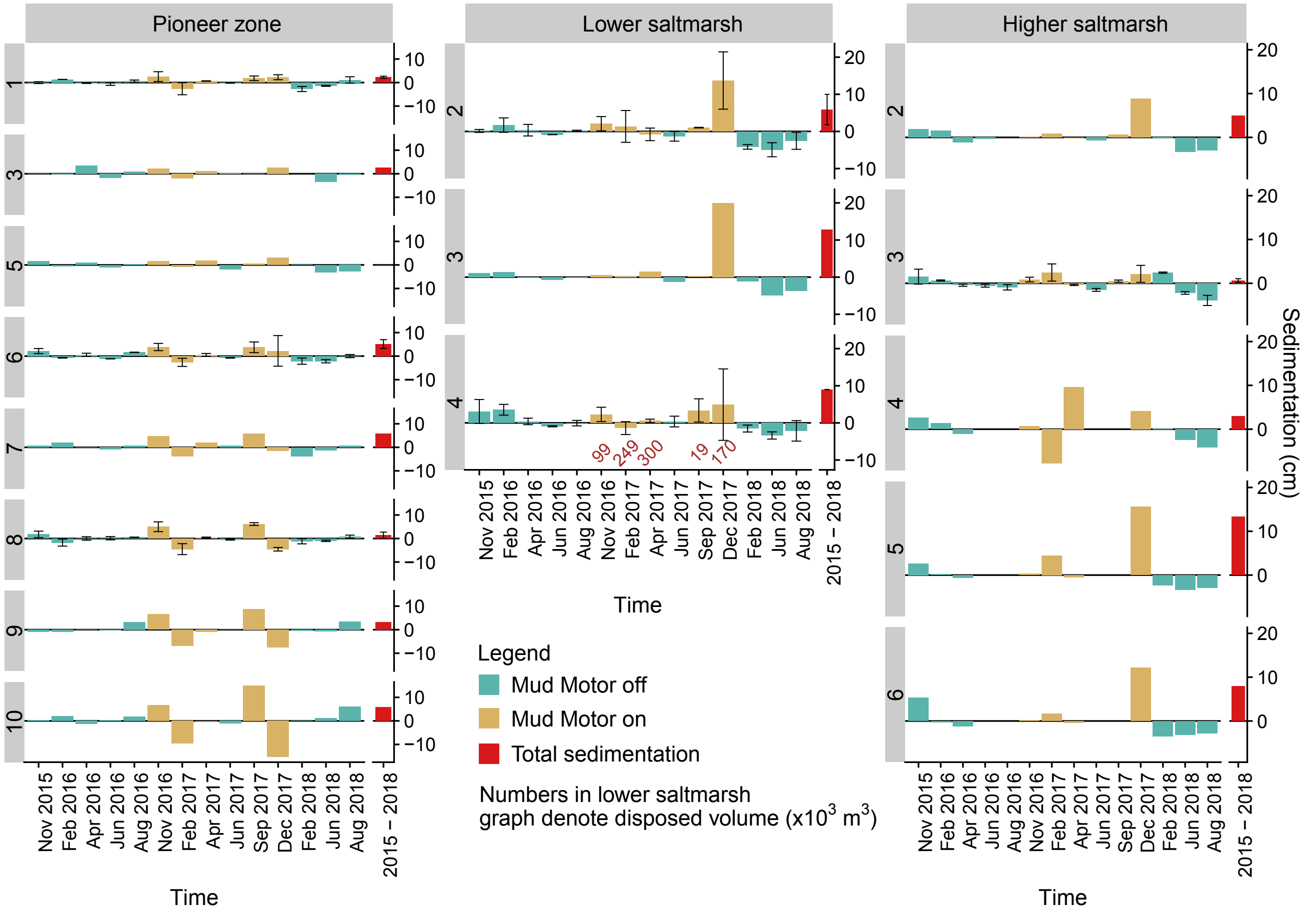

Fig. 4. Results of the Sedimentation Erosion Bar measurements of salt marsh stations. SEB-stations were allocated from north (transect 1) to south (transect 10) including pioneer zone, the lower salt marsh or the higher salt marsh and if identical, pooled together. If pooled, means and standard errors of the means are shown. Numbers in lower salt marsh graph denote disposed volumes (x10^3 m^3).

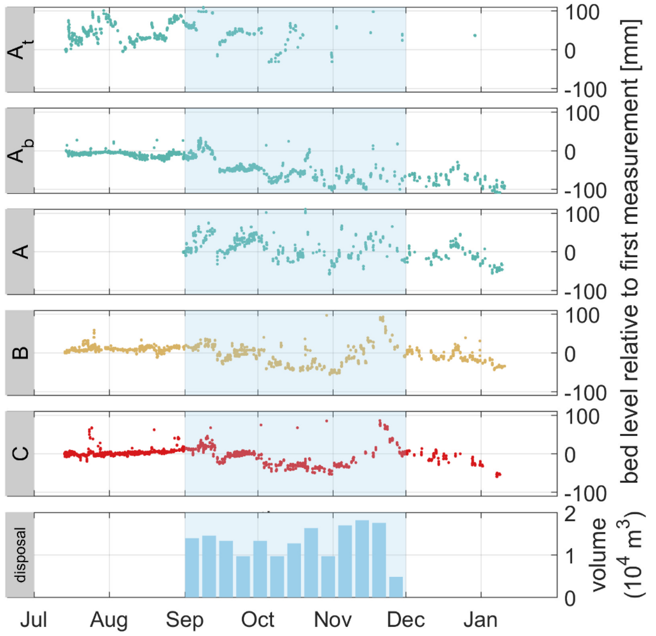

Fig. 5. Results in bed level variation as measured by 5 SED-sensors, at positions A, B and C at 100 m from the dike toe and position A_t at the top of a hummock and A_b at the bottom of a hollow at 60 m from the dike toe, see Fig. 3 for locations. Bottom plot shows disposed Mud Motor volumes per week.

4. Discussion

4.1. Lessons learned from the Mud Motor pilot

The Mud Motor was intended to stimulate salt marsh accretion in a period of months, which was thought to lead to salt marsh expansion in a period of years. The expected response was based on a conceptual model of the deposition and erosion in the tidal channel with direct transport of fine sediments from the channel towards the nearby tidal flats and salt marshes. Important findings from the measurement programme are that the transport of mud into the study area is highly affected by wind force and direction, as well as freshwater-induced circulation, and that the sediment remains only partially on the mudflats and salt marshes, depending on specific wind conditions that induce hydrodynamic stress leading to erosive events on short timescales.

Field measurements of suspended sediment transport rates in the tidal channel could not confirm an increased flux of mud as a result of Mud Motor disposals. All of our cruises were carried out during relative calm wind conditions, but our measurements on the mudflats have shown that the functioning of the Mud Motor, i.e. the successful increased mud transport toward the mudflat, is significantly dependent on shoreward wind and wave forcing.

Results of the tracer test showed that 80% of the disposed sediment reached the study area in four to five weeks, although a large uncertainty exists around this percentage. If this percentage would apply to the complete experiment, an additional accretion of almost 2 cm would have occurred (Vroom et al., 2016). Results of the sedimentation erosion bar measurements showed a net accretion of close to 5 cm, which could well be caused by a natural accretion of 3 cm plus a Mud Motor accretion of 2 cm, but results also showed that the interplay between erosion, transport and deposition processes yielded a dynamism that was much stronger than anticipated. Sedimentation measurements showed that layers of 10 cm of mud deposited on the mudflats in a time scale of days, but these layers (partially) eroded just as fast. The gross fluxes of mud were therefore much higher than the net accumulation and these fluxes seemed to be higher in periods with a functioning Mud Motor.

On the high and densely vegetated parts of the salt marsh the net vertical accretion was higher compared to the lower and sparsely vegetated pioneer zone. Horizontal expansion was not observed so apparently not all salt marsh habitat requirements were fulfilled for successful salt marsh expansion, although we applied the Mud Motor in a study area that shows ample sedimentation, has expanding salt marshes and gently sloping mudflats in front of the marsh. In evaluating the results of the Mud Motor pilot we conclude that there is more hydrodynamic stress than foreseen. We now hypothesize that the disposed mud was temporarily stored in our study area but was subsequently transported to the tidal divide further east. A possible explanation is that the growth of the salt marsh is not determined by short-term sediment supply from the tidal channel, but by a long-term sediment supply from the tidal divide further to the east, governed by waves and wind-induced transport. The development of the mudflats and salt marsh in this area does not seem to be restricted by the supply of suspended sediment but by the morphological evolution of the bed level in combination with other meteorological and ecological factors. Marsh growth alternated with stabile periods. For a mud motor to work more effectively a co-occurrence with a Window of Opportunity for marsh growth (Hu et al., 2015b) may be required.

We believe that the Mud Motor method applied at locations with different physical settings can be successful in promoting natural mudflats and salt marsh development. In determining a Mud Motor location, the vicinity to a large freshwater source is an important factor. In general, a transport flux toward a freshwater source is generated and this can be used to the benefit of a Mud Motor. Our study showed that this effect can be very important even in shallow near-coastal areas where vertical gradients in the water column are rather small. We therefore suspect that salt marshes located at the landward limit of tidal systems, for instance at the landside of a bay, may benefit from a Mud Motor because the trapping efficiency is expected to be larger. When the bay has a riverine freshwater outflow this may enhance the sediment transport. For example, we expect a more successful expansion of salt marshes using a Mud Motor approach in the semi-enclosed small bay called Mokbaai on the Wadden island Texel. At present, the maintenance dredging of the nearby port and navigation channel is carried out during ebb tide, which causes a net transport of sediment out of the bay. This is negatively impacting the sediment balance and leads to vegetative regression of the lower parts of the salt marsh caused by a lack of sediment (Baptist et al., 2016). A Mud Motor approach in which the flood tide can move dredged sediments towards the salt marshes can be beneficial for the ecological values in this site. Another possibly more successful location is the Dollard region in the Ems estuary even though suspended sediment concentrations are already very high here. The Dollard is a bay-like system with a river outflow in which an increased sediment load is probably better contained within the system compared to our study area. In any case, a thorough study will have to determine what factors are limiting salt marsh growth (for example too much energy exposure, sediment starvation, no seeds) before a Mud Motor is applied. A thorough (numerical) assessment is needed of the abundance of fine sediment and the natural variability in transport rates to determine whether a Mud Motor may be able to stimulate marsh development.

In carrying out our Mud Motor pilot project we also learned that environmental regulations prescribe particular seasons and time slots for the disposal of dredged sediment. This strongly influences the strategy for mud disposal especially when the aim is to dispose sediment in shallow water under tidal conditions, so when the natural conditions also limit available time slots. The Mud Motor pilot extended sailing distances considerably, thereby lengthening the dredge cycle times and leading to increasing costs. Longer cycle times and a loss of flexibility in temporal windows for the disposal are putting the contractor under higher strain, since they have to maintain adequate capacity to fulfil the contract regulations for maintenance dredging works. Higher costs for a port authority may be balanced by reduced maintenance dredging. A wider cost-benefit analysis for salt marsh expansion may yield other, long-term and indirect financial benefits. Wider marshes can reduce dike maintenance costs as a result of the reduction in wave energy. A dilemma is that a port authority is not the beneficial recipient of this cost reduction, so complex financial arrangements need to be made for uncertain future developments. Ultimately, the feasibility of a Mud Motor depends on an assessment of additional travel time for the dredger (extra costs), the effectiveness on salt marsh growth (location of the disposal site and the salt marsh), reduced dredging volumes in a port (reduced costs), and practical issues (depth at the disposal location and time slots).

4.2. Guiding principles for salt marsh development with sediment management

The type of experiment we carried out resembles a Large-scale, Unreplicated Natural Experiment (LUNE). Despite their lack of replication, LUNEs have a unique power, not attainable in any other way, namely to test hypotheses at large scales and in complex systems (Barley and Meeuwig, 2017). Our thinking on the transport processes in the channel and on the mudflats and saltmarsh and our perception of the variations in bed-levels of mudflats and salt marshes has changed as a result of the Mud Motor pilot. Our improved understanding yields design lessons for future plans on Building with Nature sediment management schemes which include Mud Motor principles.

Based on a literature survey we made a selection of the most relevant parameters for salt marsh habitat requirements in relation to our Mud Motor pilot. These parameters are essential for the pioneer formation of salt marshes, i.e. inundation frequency, hydrodynamic energy, slope, suspended sediment supply and local seed source. We present a conceptual framework for Building with Nature guiding principles for future applications of sediment management aiming at salt marsh development, Fig. 6. First and foremost the bed elevation needs to be high enough (near MHW) to have low inundation frequency and allow pioneer vegetation to establish. Secondly, the hydrodynamic energy needs to be low enough for a long-term accumulation of fine sediments. Thirdly, the mudflat in front of the marsh needs to have a gentle slope in order to reduce hydrodynamic stress. Fourthly, a sufficient supply of suspended sediment is needed to increase marsh elevation. Finally, a local seed source needs to be present so pioneer vegetation can germinate and establish. When these criteria are fulfilled, and taking multi-annual Windows of Opportunity into account, a marsh may develop a robust morphology and may grow into a robust and sustainable salt marsh.

Acknowledgements

This work was supported by the Dutch Waddenfonds under grant number WF221847. Cash and in-kind co-funding was received from the consortium partners of EcoShape, from the Port of Harlingen and from It Fryske Gea. The study is part of the research program “Sediment for salt marshes: physical and ecological aspects of a Mud Motor” with Project Number 13888, which is partly financed by The Netherlands Organisation for Scientific Research (NWO). Manuscript writing was supported by the Wageningen UR Knowledge Base programme KB-24-

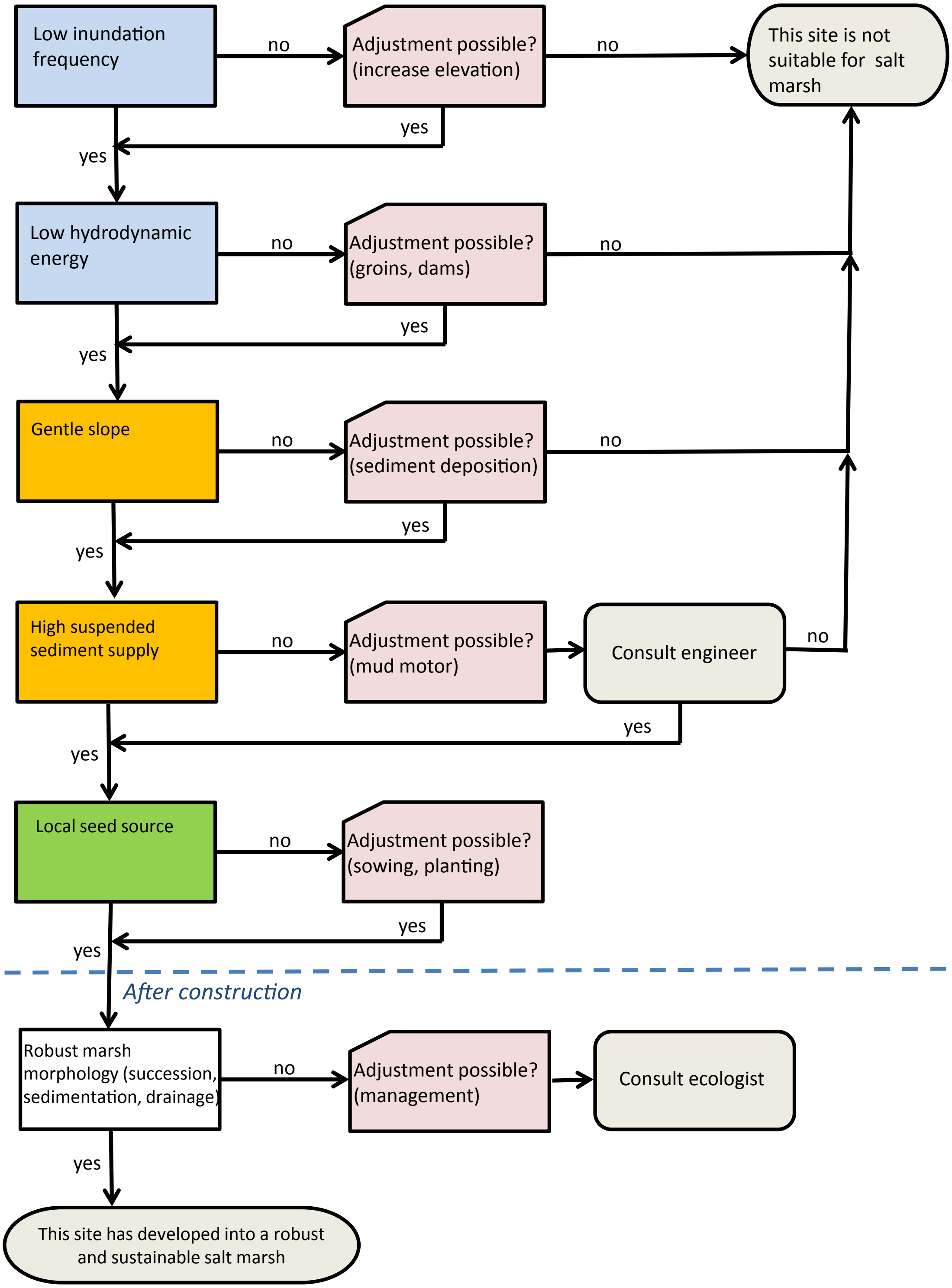

Fig. 6. Conceptual framework for Building with Nature guiding principles for salt marsh development with sediment management.

001-006. We particularly thank Reiner de Vries and John Walta of the Port of Harlingen, and Chris Bakker of It Fryske Gea for their fruitful cooperation and constructive comments. We also express our gratitude to Arjen Bosch for his perseverance in promoting Building with Nature in the Wadden Sea ports.

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