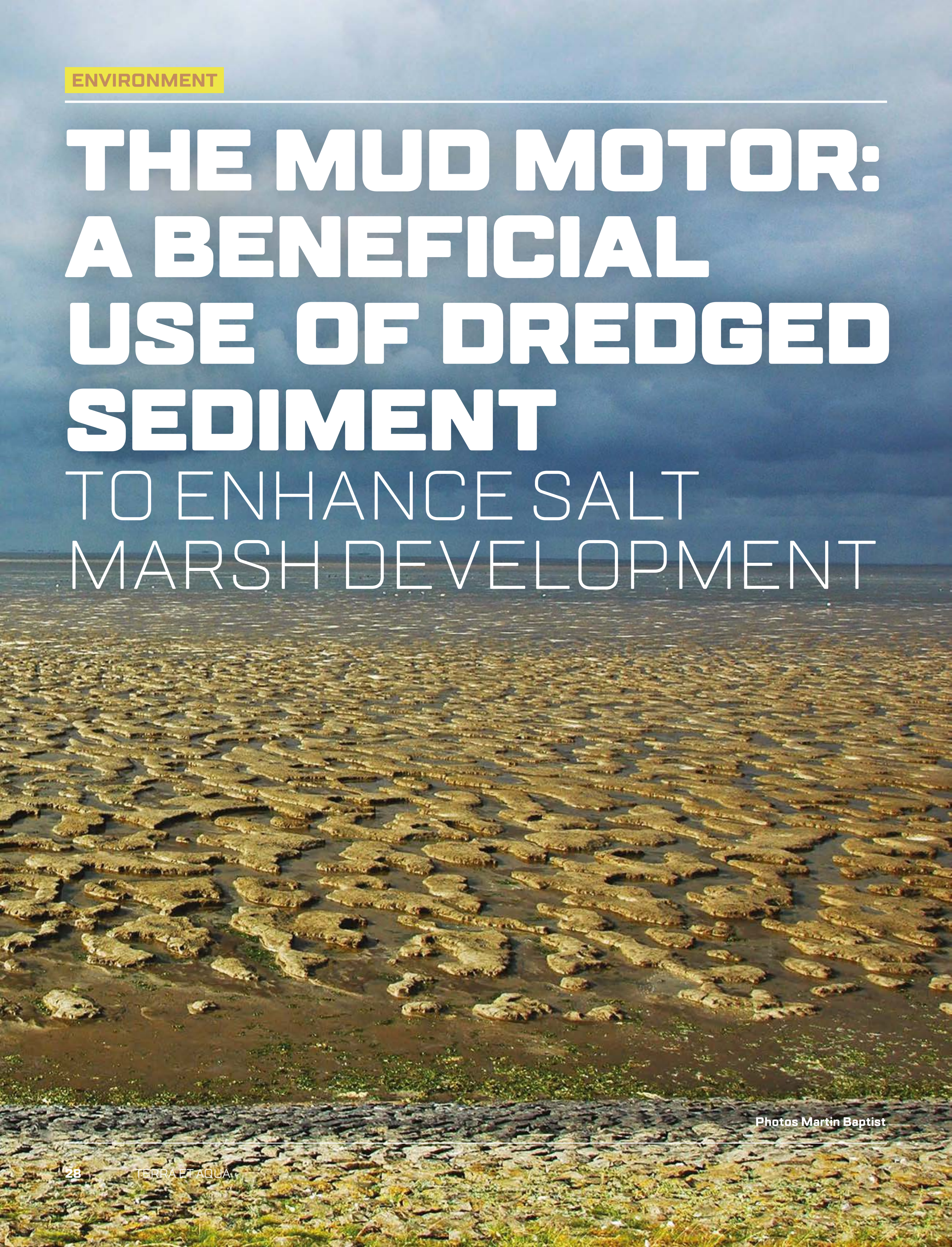

ENVIRONMENT

THE MUD MOTOR: A BENEFICIAL USE OF DREDGED SEDIMENT
TO ENHANCE SALT MARSH DEVELOPMENT

Photos Martin Baptist

An innovative approach to beneficially re-use dredged sediment to enhance salt marsh development has been tested. A Mud Motor entails the strategic disposal of dredged sediment to create a semi-continuous source of mud that allows natural processes to disperse the sediment to nearby mudflats and salt marshes. The concept has been piloted in the Kimstergat tidal channel near the Port of Harlingen in The Netherlands.

By applying the Building with Nature principles, an innovative method for the disposal of dredged sediment was considered and eventually piloted: the Mud Motor.

The Port of Harlingen is located in a sediment-rich estuary, which means significant maintenance dredging is necessary to keep it navigable. The dredged material, which is not contaminated, is disposed at two designated locations in the Wadden Sea, a UNESCO World Heritage site. Furthermore, the layout of the port (locally deepened and with fresh water releases in the basin) stimulates siltation and re-circulation. Part of the disposed sediment will sooner or later flow back into the port. By applying the Building with Nature (BwN) principles, an innovative method for the disposal of dredged sediment was considered and eventually piloted: the Mud Motor.

The Mud Motor entails the strategic disposal of dredged sediment in shallow water to create a semi-continuous source of mud that allows natural processes to disperse the sediment to nearby mudflats and salt marshes.Targeted at enhancing salt marsh development and thus fixating the sediment, both the local port authorities and local NGO's embraced the approach and a regional development fund, the Waddenfonds, supported the execution of the pilot . Within this article the pilot execution and accompanying research is described and the general application of Mud Motor concepts is discussed. The information in this paper is adapted from the Open Access scientific publication Baptist et al. "Beneficial use of dredged sediment to enhance salt marsh development by applying a 'Mud Motor'." *Ecological engineering* 127 (2019): 312-323.

Global background

The Port of Harlingen is not unique: 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 sometimes unintentionally stimulate 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, despite an ever-increasing amount of attention raised to regard dredged sediment as a resource rather than a waste (National Research Council, 1985; Meade and Moody, 2010). Beneficial use of dredged materials therefore is an important topic on the agenda of many authorities and organisations worldwide, often categorising into engineered uses, agricultural and product uses and environmental enhancements (Brandon and Price, 2007).

Coastal habitats such as tidal areas and salt marshes are ranked among the most important habitats regarding ecosystem services (Temmerman et al., 2013). 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). Logically, the creation of (freshwater and saltwater) marshes has been well-developed already in the 1970s and 1980s both in Europe and the US (for example USACE, 1987). Creation either involves the direct placement of sediment directly onto the desired location with correct elevation, orientation, shape and size or the creation of structures to enforce local hydrodynamic conditions favorable to settlement of fine particles and associated land creation. Sometimes the active introduction of plants is also applied.

Data suggests that these created marshes do not have the same quality as natural marshes in that some functions are not developed (Streever, 2000). Also salt marshes created by managed realignments lack the diversity found in natural habitats (Lawrence et al., 2018). Added value can thus be created by finding work methods to use dredge material for marsh development, while mimicking, using or stimulating natural marsh geomorphology (Shafer and Streever, 2000).

Also more generally, the inclusion of nature-based solutions (NBS) has drawn the attention in hydraulic engineering. Since 2007, the Dutch consortium EcoShape has been developing knowledge on the Building with Nature (BwN) philosophy

Who's Involved in the Harlingen Mud Motor Pilot?

The Mud Motor Pilot near Harlingen is one of the pilots of the BwN Wadden Sea Ports programme executed by EcoShape. Wageningen Marine Research, Arcadis, Royal Haskoning DHV, Deltares and Van Oord have teamed up to execute the pilot on behalf of EcoShape. The local port authority, the municipality of Harlingen and a ocal NGO 'It Fryske Gea' (a society for the protection of nature in the Dutch province of Friesland) joined EcoShape in its proposal to execute the pilot to enhance the salt marshes at Koehool. This proposal received funding from the regional development fund Waddenfonds.

In addition to the pilot execution, fundamental research took place. Researchers from the Royal Netherlands Institute for Sea Research (NIOZ), Wageningen University and Delft University of Technology, supported with practitioners from the EcoShape project partners, have executed fundamental research on the sediment transport and sediment dynamics around the Mud Motor and the targeted salt marsh as well as investigated ecological factors of importance to the salt marsh expansion.

The authors would like to specifically mention the following contributors: T. Gerkema, K. Schulz (NIOZ), M. van Regteren, K. Elschot, A.V. de Groot, M.E.B. van Puijenbroek (Wageningen Marine Research), B.C. van Prooijen, I. Colosimo (Delft Technical University), D.S. van Maren, J. Vroom, T. van Kessel, B. Grasmeijer, P. Willemsen (Deltares), J. Cleveringa (Arcadis), F. Schuurman, P.J.T. Dankers (Royal Haskoning DHV), H.J. de Lange (Wageningen Environmental Research), R.J. de Vries, J. Walta (Municipality of Harlingen), C. Bakker (It Fryske Gea), A. Bosch (De Laar).

by precompetitive collaboration between dredgers, consultants, knowledge institutes, governmental organisations and NGOs. As a part of their second BwN programme, the development issues of the ports of the Wadden Sea are studied, focussed at innovative approaches to sediment management in the Wadden Sea (Baptist et al., 2017; Van Eekelen et al., 2016).

The Harlingen Mud Motor Pilot setup

Setting

About 1.3 million m^3 of mainly fine sediments are dredged annually in the basins of the Port of Harlingen to safeguard navigation. The dredged sediment is disposed in the Wadden Sea, at locations with large water depth in the vicinity of the port at locations K1 and K2 (see Figures 1 and 2). It is expected that an unknown, but potentially considerable, amount of sediment shows a return flow towards the port, leading to a cyclic series of dredging and disposal.

During the Harlingen Mud Motor 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 disposed (not deposited at one single spot) further away from the port at a Mud Motor (MM) location (see Figures 1 and 2). The Mud Motor 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. This salt marsh area has developed from 1996 and has shown some periods of growth and others of stabilisation, indicating that conditions for salt marsh growth are not met every year.

Design and set-up

Numerical simulations

The first step in the design of the Mud Motor pilot was the exploration of a suitable disposal location. The most suitable location has sufficient depth for (bottom door) release of the material, in this case a minimum water depth of 3 m, while being as close (both cross-shore and long-shore) to the targeted salt marsh as possible. Due to channel characteristics of the Kimstergat (moving away from the coastline closer to the target area), the cross-shore and long-

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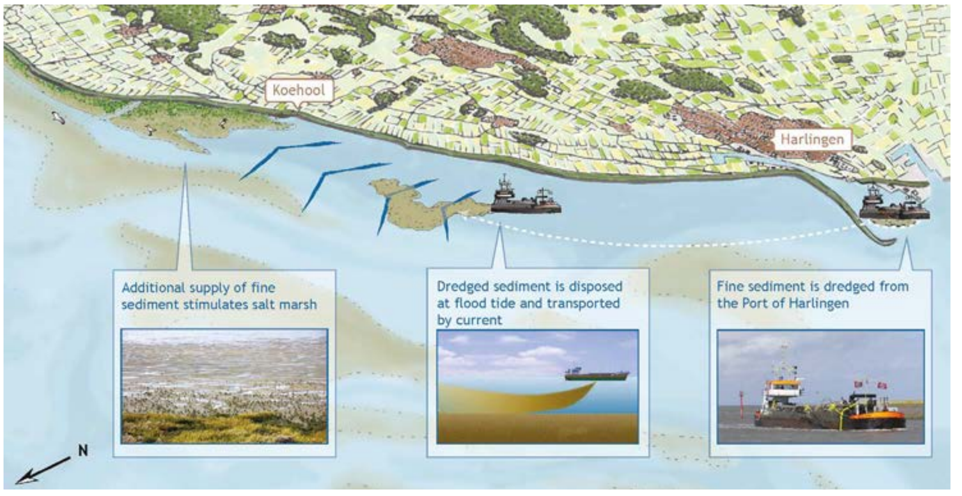

FIGURE 1

Illustration of the sediment transport route of the Mud Motor Pilot including dredging, disposal and flow.

shore distance became a trade-off, which was evaluated with a numerical sediment transport model. The numerical model (see Vroom, 2015) for details) revealed that sediment released close to the shore is more effective in nourishing the Koehool mudflat than sediment released at the landward limit of the channel. In Figure 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.

Tracer study

Based on the numerical simulations, a preliminary disposal location was chosen in shallow water on the south-eastern bank of the tidal channel. Prior to the Mud Motor experiment, a tracer experiment was carried out to determine how much of the sediment would be transported from the new disposal location towards the target area, in comparison with one of the original disposal locations. For each of the two locations, a different coloured fluorescent tracer with a particle size distribution and behaviour similar to sediment dredged from the port of Harlingen was applied. Tracer particles were released completely mixed with dredged sediment.The (relative) recovery of the tracer particles is then an indicator for the transport of sediment towards the desired salt marsh coast. Multiple

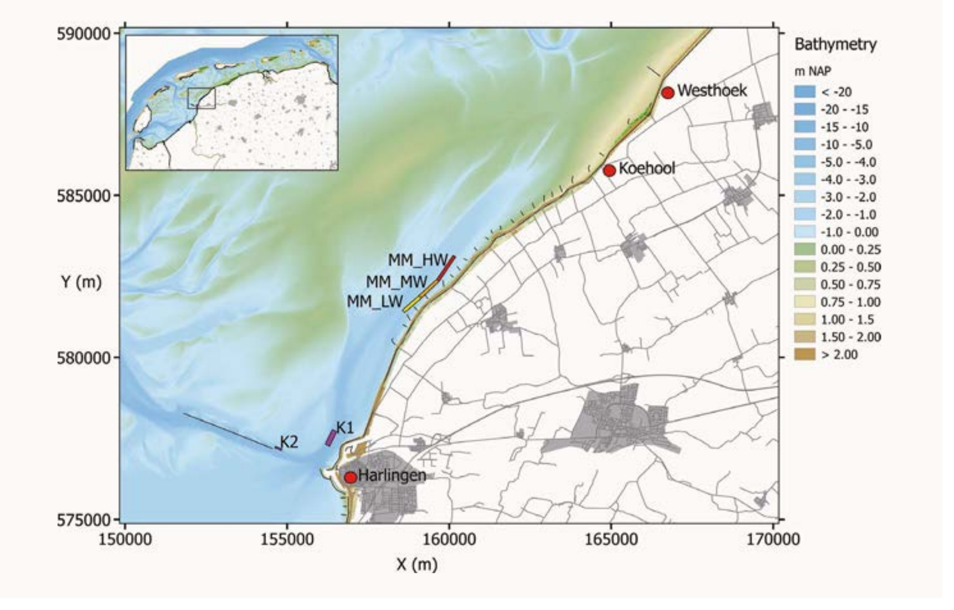

FIGURE 2

Location chart of the Harlingen Mud Motor Pilot.

sampling campaigns were conducted using a large number of sampling locations. The total amount of 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 (see Table 1).

Legal requirements

Dredging projects are regulated by national and European legislation (Sheehan and Harrington, 2012). Because the Wadden Sea is protected by the

By careful and strategic sediment management – disposal of dredged material in conditions and locations favourable to salt marsh growth – the pilot reveals that the Mud Motor concept can be viable.

nature conservation laws of the EU Habitats and Birds Directives, a permit to work within the protected Natura2000-nature area was required. 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.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 initially 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; Doody, 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.

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%

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 the hours of 07:00 and 19:00, with sunrise and sunset 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)

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. This includes 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. Furthermore, studies on the influence of biota, particularly oligochaeta, on salt marsh expansion were carried out.

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 disposal in response

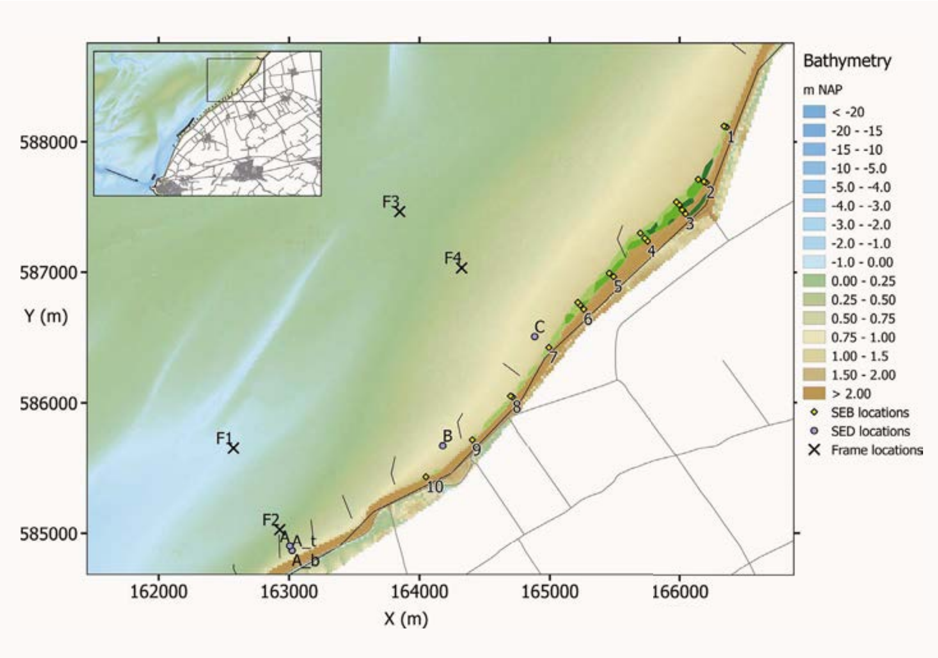

FIGURE 3

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.

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 hours to calculate the residual SPM transport at two locations: close to the Port of Harlingen and near the new disposal location. Details on the ship-based campaigns and an analysis of the data from the first three cruises can be found in Schulz and Gerkema (2018).

Living Lab for Mud

In the Living Lab for Mud, EcoShape is working with our partners on five pilot projects to develop knowledge about the sustainable use of fine sediment. Fine sediment is an essential material for global sustainable development. Excess sediment dredged from lakes, coasts and rivers can be used to strengthen dikes, reclaim land or create natural islands. That generates social benefits in terms of flood risk management, navigability, nature development, water quality and the local economy, and in the form of building material for land reclamation and dike construction. Combining the use of sediment with natural processes like currents and vegetation is a perfect example of applying Building with Nature. The Harlingen Mud Motor Pilot is one of the five EcoShape projects in this programme.

The mudflats were investigated from December 2017 to February 2018 in severe weather.

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 (see Figure 3). 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.

Mudflat and salt marsh accretion

The mudflat and salt marsh bed level changes were measured with two types of in-situ instruments. The multi-annual surface-elevation change was determined with Sedimentation-Erosion Bars (SEBs). The surface elevation is determined four to five times per year. Short-time surface elevation changes were determined with Surface Elevation Dynamics (SED) sensors (see Figure 3). The SEDs were checked

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				

approximately every eight weeks to ensure data collection, to clean the sensors and to retrieve the data.

For a synoptic view of the surface level of the mudflats and salt marsh, LiDAR was flown annually over the study area using an Unmanned Aerial Vehicle (UAV). 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.

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 (see Figure 3).

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 minuscule worms that can be present in high densities in the transition zone between intertidal flats and salt marshes, especially in fine grained sediments. Experiments were performed to assess the effect of the disturbing activities of these worms, referred to as bioturbation on sediment properties, oxidation depth, algal biomass, seed distribution, and germination success of the so-called 'pioneer species', the first plants to grow on bare mud flats, see Van Regteren et al. (2017).

Results

Execution of the pilot

The mud was dredged from the basins of the Port of Harlingen using the 604 m³ 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 hours. 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 m³ was achieved (see Table 2). In the first Mud Motor Season from 1 September 2016 to 31 March 2017 in total 300,188 m³ of dredged sediment was disposed at the Mud Motor disposal sites. In the same period another 433,672 m³ was disposed at the K1 and K2 sites (see Figure 1). In the second Mud Motor season, from 1 September 2017 to 1 December 2017 a total of 170,328 m³ was disposed at the Mud Motor disposal site and another 201,780 m³ at the K1 and K2 disposal sites.

The dredged volume needed to maintain navigable depth in the Port of Harlingen has decreased with both in 2017 and 2018to 1.0 million m³ compared with the long-term average of 1.3 million m³ (see Table 3). A reduction of the return transport may have resulted from the disposal at the Mud Motor site. However, it may also be that the both years has fallen within the variability found in the annual dredged volumes, similar to year 2012.

TABLE 3

Annual dredged volumes in the Port of Harlingen.

Year	Volume (m³)
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
2018	1,032,270

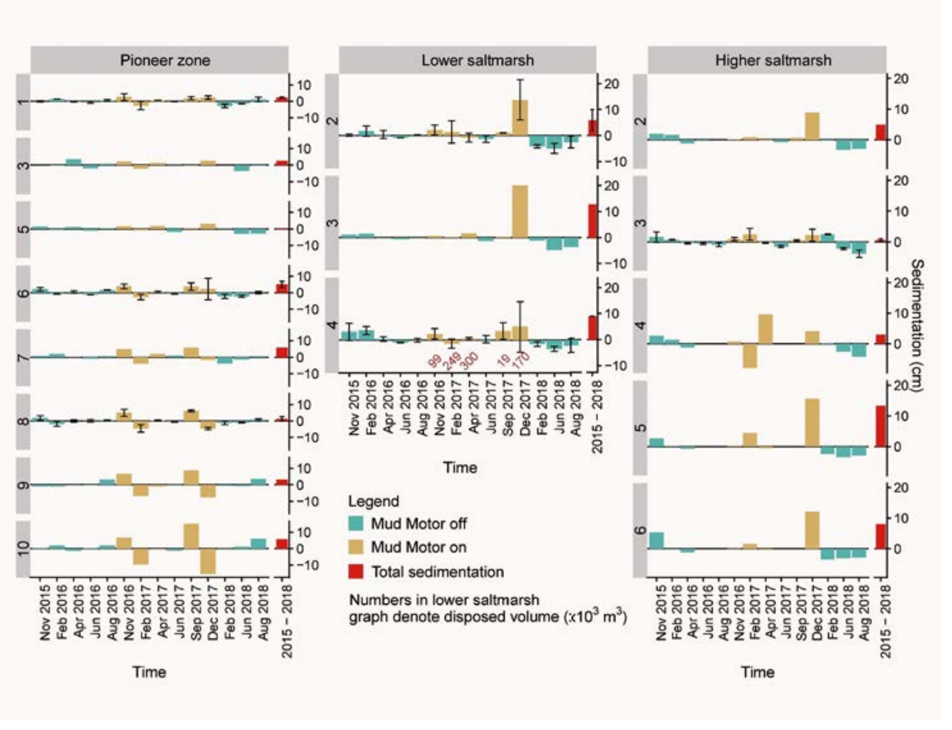

FIGURE 4

Results of the Sedimentation Erosion Bar measurements of salt marsh stations.

Sediment transport rates

Channel

The ship-based measurements in the Kimstergat channel revealed two main factors that influence the suspended sediment transport under calm wind conditions:

1. differences (asymmetry) between ebb and flood currents, and
2. a periodic vertical salinity stratification (fresh water from releases elsewhere are flowing on top of salt water).

Unlike the normal case in a classical estuary, the salinity stratification is built up during flood, and destroyed again with the onset of the ebb current. In short, the stronger flood currents have positive effects on sediment transport towards the target salt marshes. Likewise, the salinity stratification is attracting sediment toward the fresh water source, which is located at the mouth of the tidal channel. These two processes are thus counteracting one another.

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. It was 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.

Mudflat and salt marsh accretion

Results of the measurements with Sedimentation Erosion Bars (SEB) show relatively large changes in surface elevation. Layers of watery mud with 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 two- or three-monthly measurements could not differentiate between the processes causing this disappearance (erosion or compaction), but did show large fluctuations in bed height. The salt marsh SEB stations showed a net accretion 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 (see Figure 4). 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 in use compared to the Mud Motor not in use.

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 (see Figure 5). Such events were not observed in other tidal flats at a similar distance from the salt marsh edge or dyke 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.

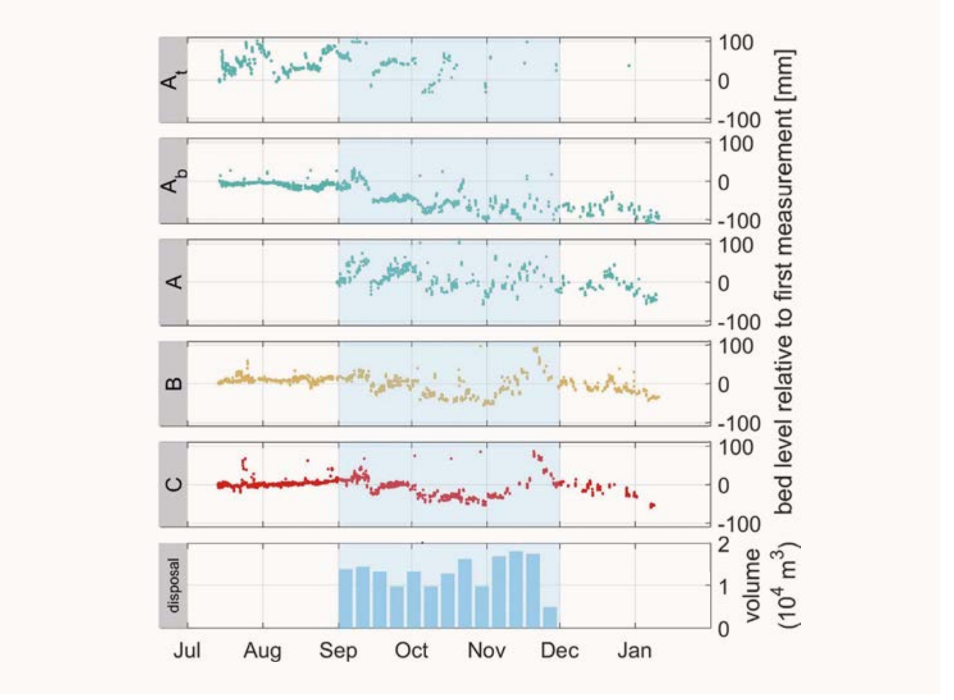

FIGURE 5

Results in bed level variation as measured by SED-sensors. Bottom plot shows disposed Mud Motor volumes per week.

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. Aerial photos 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.

Conceptual Framework for BwN Guiding Principles for Salt Marsh Development

Based on a literature survey, a selection was made 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. A conceptual framework for BwN guiding principles for future applications of sediment management aiming at salt marsh development is presented (see Figure 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.

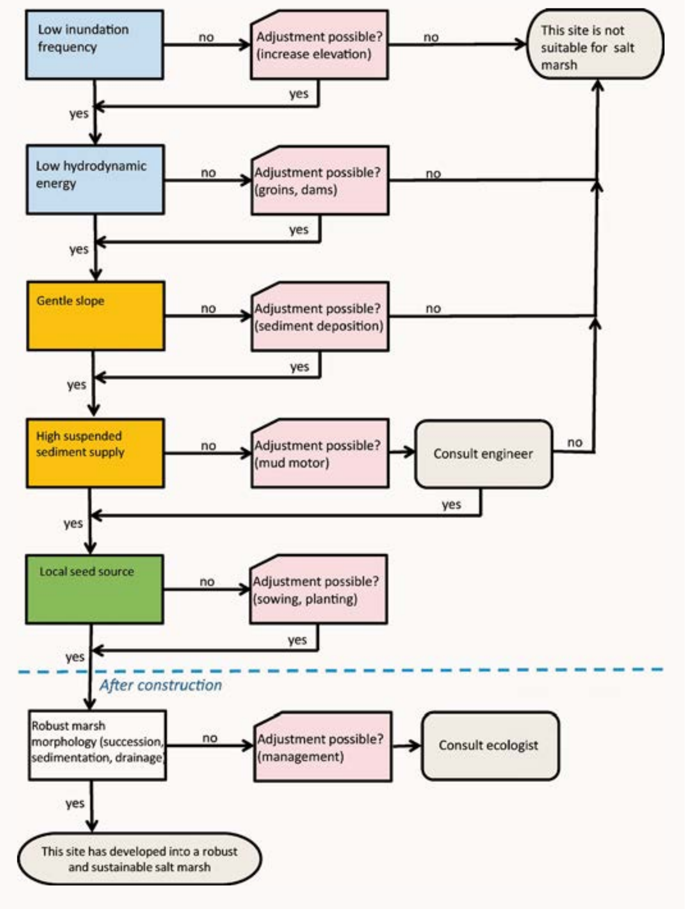

FIGURE 6

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

Our experimental study indicated that small, though numerous, oligochaetes may reduce the lateral expansion potential of the salt marsh by hindering the establishment of pioneer vegetation in the transition zone between salt marsh and mudflat. The way that these miniscule worms feed from the sediment buries *Salicornia* spp. seeds until below the critical germination depth, thus negatively effecting *Salicornia* spp. germination and seedling esablishment. 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).

Discussion

Lessons learned from the Mud Motor pilot

From the results of the various monitoring, it is clear that the system in which the Mud Motor pilot was executed had various influencing factors which were (and are) not fully understood. The numerical model and tracer study indicated that significant amounts of sediment disposed at the Mud Motor location was likely to move to the salt marsh and would cause the marsh to grow. However, the 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. On the other hand the SEB measurements indicate extra sedimentation on the salt marsh in line with the anticipated extra sediment released and transported according to the tracer study result (i.e., 3 cm natural salt marsh growth +2 cm level increase due to the Mud Motor). However, the winds were found to dominate the distribution of sediment transport, with an ability to transport significantly larger mud layers. In other words the gross fluxes of mud were therefore much higher than the net accumulation. Still, these fluxes seemed to be higher in periods with a functioning Mud Motor.

Although the Mud Motor was applied in a study area suitable for salt marsh vegetation expansion (ample sedimentation, sufficient vegetation present and gently sloping mudflats in front of the marsh), horizontal expansion was not observed. It seems that the hydraulic stress is higher than foreseen. 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 seemed to be dependent on a so-called Window of Opportunity (Hu et al., 2015b), which also can explain for the alternating growth-stabilisation periods of this marsh in the past.

Applying the Mud Motor concept at locations with different physical settings can be more successful in promoting natural mudflats and salt marsh development, specifically in cases where a freshwater source is less disturbing (or even enhancing) the estuarine flow patterns. It is suspected 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.

General application potential for a Mud Motor

In general terms, the pilot reveals that the Mud Motor concept can be viable by careful and strategic sediment management (disposal of dredged material in conditions and locations favourable to salt marsh growth). Whether a particular salt marsh can be expanded via this method is very much dependent on the functioning and interactions with the hydrodynamic and ecological system:

FIGURE 7

Researchers at Koehool doing height measurements (A) and other studies on the mudflats (B).

- The limiting factors for salt marsh growth need to be determined first, in order to indicate whether further supply of sediment will create/enhance opportunities for salt marsh growth, or whether other measures would (also) be necessary (see Figure 6).
- The abundance and variability in transport rates need to be determined, to determine whether a Mud Motor may be sufficiently effective and at what minimum scale.
- The limiting factors for disposal of the material, both technically (in terms of clearance for the dredging vessel and cycle times) and regulatory (in terms of permit limitations) must be assessed and optimised to meet the derived minimum scale (see Figures 7 and 8).

Following the above steps, the technical feasibility for a Mud Motor can be assessed. The next step will be the economic feasibility. The necessity to dispose a certain amount of sediment at a specific location might increase the execution costs for the dredging works; the cycle time can increase both due to extra sailing (such as in the Harlingen Pilot) or by the extra need for manoeuvring and other limitations. In order to assess whether such investment is worth, the full cost-benefit analysis must be taken into account. This means that direct effects should be accounted for, such as the decrease in circulation of dredged material after release, but also indirect effects must be assessed like for instance the values created by salt marsh growth, such as CO2 fixation, nature values, recreational opportunities and flood safety benefits. It is important to not only try to account the magnitude and (un)certainty of these values, but also to determine who will benefit from these values as to determine how that stakeholder could contribute to the project cost.

CO2 Footprint of the Harlingen Mud Motor Pilot

For the Harlingen Mud Motor Pilot the disposal of sediment at the Mud Motor location meant that the sailing distance increased, leading to an extra release of CO2. On the other hand, the fixation of sediment in the salt marsh and mud flat, and the additional salt marsh habitat will store CO2 and give rise for additional sequestration. Whether the CO2 footprint of the Mud Motor is positive would be dependent on the amount of additional sequestration compared to the additional release.

However, especially in quantifying the additional sequestration, the analysis is dependent on the boundary conditions and limitations of the analysis, especially on substitution effects. As sediment disposal at the traditional location leads to higher sediment availability in the whole of the Wadden Sea, part of this sediment will contribute to salt marsh developments, either at the target site or elsewhere in the system.

With respect to temporal developments, similar discussions can be raised: from the historical analysis it was observed that the Koehool salt marsh was developing. It can be argued that in the long term (>100 years) the Mud Motor efforts could best be observed as a measure to speed up development and not as a creation of new marshes. This means that the CO2 benefits of the pilot are limited to the fact that the salt marsh (and its associated sequestration) is realised at an earlier time. For that reason the pilot outcome on CO2 footprint could be either positive or negative. Also in broader application of the Mud Motor, the substitution effects should be considered as part of the CO2 footprint analysis.

FIGURE 8
Plant growth at the Koehool mudflats.

Summary

An innovative approach to beneficially re-use dredged sediment to enhance salt marsh development was tested by a 'Mud Motor', i.e., a dredged sediment disposal method in which a semi-continuous source of mud in a shallow tidal channel allows natural processes to disperse sediment to nearby mudflats and salt marshes. The pilot occurred over two winter seasons with both ship-based and field measurements on the intertidal mudflat. The pilot showed 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 other practical issues. It improved understanding of the transport processes in the channel and on the mudflats and salt marsh and provided guiding principles for future applications of sediment management that include a Mud Motor approach.

This article is based on the paper "Beneficial use of dredged sediment to enhance salt marsh development by applying a 'Mud Motor'" which debuted in *Ecological Engineering*, Volume 127, February 2019, pages 312-323, a publication of Elsevier. The original paper is available through Open Access.

The pilot reveals that the Mud Motor concept can be viable: By careful and strategic sediment management (disposal of dredged material in conditions and locations favourable to salt marsh growth).

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