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# BIOGEOMORPHOLOGICAL INTERACTIONS ON A NOURISHED TIDAL FLAT: LESSONS LEARNT FROM BUILDING WITH NATURE

## ABSTRACT

Tidal flats are valuable habitats for different plants and animals. However, the total area of tidal flats is decreasing worldwide caused by various problems like sea level rise, subsidence by gas extraction and erosion initiated by manmade constructions. Nourishing tidal flats might be a promising solution, but the impact both on the physical processes and the ecological system are unknown.

This article describes the lessons learnt from a pilot nourishment executed at the Galgeplaat tidal flat in 2008 (Eastern Scheldt, The Netherlands) with a total volume of 130,000 m<sup>3</sup> over a total area of 150,000 m<sup>2</sup>. The hypothesis is that as a result of the natural dynamics, i.e., the combined effect of currents and waves, the nourishment will gradually spread out and heighten the flat. To become a valuable habitat, the nourished area has to recolonise after the nourishment has buried all benthic fauna. To optimise nourishment strategies in the future with respect to shape, size and frequency, both the recolonisation of benthic fauna as well as the physical processes are monitored, modelled and analysed. After two years, only minor morphological changes of the nourishment are observed. Some redistribution of sediment

occurred, but the overall change in sediment volume is approximately only 2%.

The nourishment killed all benthic macrofauna when buried. The recovery started directly after the nourishment was put in place. On the nourishment the recolonisation of the benthic macrofauna was very patchy, with some sites having a relatively rich fauna, whereas at other sites hardly any macrofauna was observed. The latter are mainly situated on the higher parts of the nourishment, where sediments dry out more during low tide compared to lower sites on the nourishment. The shape and nourishing method appear to be important factors influencing benthic recolonisation. Model results confirm the (small) morphodynamic changes and reveal the influence of currents and locally generated waves on the degradation of the flats. Combining the monitoring and modelling results shows that the biogeomorphological interactions (morphological changes driving recolonisation

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Above: Aerial photo of the construction of the nourishment (24-09-2008). As a possible solution to the global problem of receding tidal flats, a pilot nourishment project at Galgeplaat was started in 2008. Tidal flats are an important habitat for plants and animals as well helping to maintain the coastal defense.

and vice versa) play a role and should be taken into account to come to successful nourishment strategies for tidal flats.

This article was first published in the *Proceedings of the CEDA Dredging Days*, Rotterdam, November 2011 and is reproduced with slight revisions with permission. Bas Borsje was the lead author and received the IADC Young Authors award for his work. Other contributing authors are Katherine Cronin and Harriette Holzhauser of Deltares, Isel de Mesel and Tom Ysebaert of IMARES – Institute for Marine Resources & Ecosystem Studies and Anneke Hibma of Van Oord, all of whom are also members of the EcoShape I Building with Nature team.

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the Dutch Ministry of Transport, Public Works and Water Management. The field measurements are carried out by the Dutch Ministry of Transport, Public Works and Water Management. Previous model work was carried out under the ANT (Autonome Neerwaardse Trend) Oosterschelde study commissioned by the Dutch Ministry of Transport, Public Works and Water Management.

## INTRODUCTION

Globally, tidal flats disappear at a fast rate as a result of intense human activities, sea level rise subsidence by gas extraction and erosion initiated by manmade constructions. Reduction in tidal flat area and elevation result in the loss of valuable habitats both for plants and animals and undermine the coastal

defense as dikes become less protected from waves and currents. In the Netherlands, the Eastern Scheldt is suffering from sand shortage as a result of the construction of the Eastern Scheldt storm surge barrier. Consequently, the tidal volume and current speed within the estuary decreased considerably and the dynamic balance between the accretion and erosion of tidal flats, salt marshes and mudflats has been disturbed. The tidal channels are now too large relative to the reduced tide and are infilling. With very little sediment transport through the storm surge barrier, the majority of this sediment demand comes from the adjacent tidal flats, a process that mainly takes place during storm events. Because of lower current speeds less suspended sediment can be moved back onto the tidal flats. As a result of the changes in sediment dynamics, the

elevation of the tidal flat is continuously lowered and the size of tidal flats is diminishing.

At the moment 50 hectares of mudflats and tidal flats are disappearing irrevocably under water each year in the Eastern Scheldt. It is expected that this will increase to 100 hectares per year (Jacobse *et al.*, 2008). This means that in the future valuable intertidal habitat, which is foraging ground for tens of thousands of birds, will disappear. The Oosterschelde is of international importance for many wader species. In addition, the tidal flats form a barrier against waves running up the dikes.

When these areas disappear, the wave exposure on the dikes along the Eastern Scheldt will increase and additional strengthening of the dikes will be required. To deal with these threats, innovative, cost-efficient and sustainable methods are required (Van Raalte *et al.*, 2008). Within the Dutch innovation programme "Building with Nature", in cooperation with Rijkswaterstaat Zeeland, ecodynamic solutions to mitigate tidal flat degradation in the Eastern Scheldt were investigated. One of these solutions consists of nourishing tidal flats. As a pilot the Galgeplaat tidal flat was chosen (Figure 1).

The Galgeplaat is subject to erosion, with an average erosion rate of about 0.01 m/year (Van Zanten & Adriaanse, 2008). Herein, all areas between +1 and -1 m NAP are eroding. The higher areas on the west of the Galgeplaat are flattening, spreading the sediment over the tidal flat. In order to mitigate the erosion, Rijkswaterstaat Zeeland executed a pilot nourishment in the period of August-September 2008 using sand recovered during dredging activities for the shipping access channel next to the Galgeplaat.

During the construction, a sand wall was first built approximately 1 m high, forming a ring with a diameter of 450 m. The ring was filled in with sand during the flood phase of the tidal cycle and spread by bulldozers during the ebb phase. This allowed for a controlled construction of the nourishment, as an increase in suspended matter concentration had to be avoided because of nearby commercial mussel beds. The total volume of the nourishment is 130,000 m<sup>3</sup> and the



Figure 1. Overview map of the Galgeplaat tidal flat located in the Eastern Scheldt (The Netherlands).



Bas Borsje (left) receives the IADC Award for the Best Paper by a Young Author from IADC Secretary General Rene Kolman at CEDA Dredging Days, November 11, 2011.

#### IADC AWARD 2011 PRESENTED AT CEDA DREDGING DAYS, ROTTERDAM, THE NETHERLANDS NOVEMBER 10-11, 2011

An IADC Best Paper Award for a Young Author under the age of 35 was presented to Bas Borsje at the CEDA Dredging Days in Rotterdam on November 11, 2011, for the paper, "Biogeomorphological Interactions on a Nourished Tidal Flat: Lessons Learned from Building with Nature". Tidal flats are valuable habitats for diverse plants and animals, but unfortunately the total area of tidal flats is decreasing worldwide owing to problems such as sea level rise, subsidence by gas extraction and erosion initiated by artificial constructions. Nourishing tidal flats might be a promising solution. This paper describes the lessons learnt from a pilot nourishment project at the Galgeplaat tidal flat in 2008 (Eastern Scheldt, The Netherlands). Bas Borsje was the lead author.

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Each year at selected conferences, the IADC grants awards for the best papers written by younger authors. In each case the Conference Paper Committee is asked to recommend a prizewinner whose paper makes a significant contribution to the literature on dredging and related fields. The purpose of the IADC Award is "to stimulate the promotion of new ideas and encourage younger men and women in the dredging industry". The winner of an IADC Award receives €1000 and a certificate of recognition and the paper may then be published in *Terra et Aqua*.

total area is 150,000 m<sup>2</sup>. In order to give recommendations about future nourishment strategies an extensive monitoring campaign and a modelling study were set-up.

The hypothesis is that as a result of the natural dynamics, i.e., the combined effect of tidal currents and waves, the nourishment will spread over the tidal flat and heighten the tidal flat in the surrounding area. On a time scale of a couple of years the nourishment will balance the erosion of the tidal flat. Balancing the erosion will keep the tidal flat above low water and therefore birds will be able to forage long enough during low tide. Keeping the tidal flat above low water however is not enough for the birds; there has to be food to forage. The nourishment buries all benthic fauna. After some time the benthic fauna is expected to have recolonised the area.

The volume of the pilot nourishment is not sufficient to heighten the entire tidal flat, since this is the first nourishment put on a tidal flat in The Netherlands and the effects of the nourishment on the tidal flat and the surrounding area are not known.

Field measurements are carried out by the Dutch Ministry of Transport, Public Works and Water Management and Building with Nature to study the morphological and ecological developments. The main questions are:

- does the sediment spread over the tidal flat,
- how does it spread, and
- how long does it take the benthic fauna to recolonise the nourished area.

The processes of sediment spreading and benthic recolonisation are coupled and interact with each other. Therefore integrated measurements and data analyses are needed.

The aim of this research is:

- (1) to quantify the impact of the nourished area on both the biotic and abiotic system of the tidal flat and
- (2) to give recommendations for successful nourishment practice in intertidal areas.

To achieve these objectives an overview of the results of the monitoring campaign executed around the nourishment (see Monitoring) is given, and the results of the process-based model (see Modelling). Subsequently the

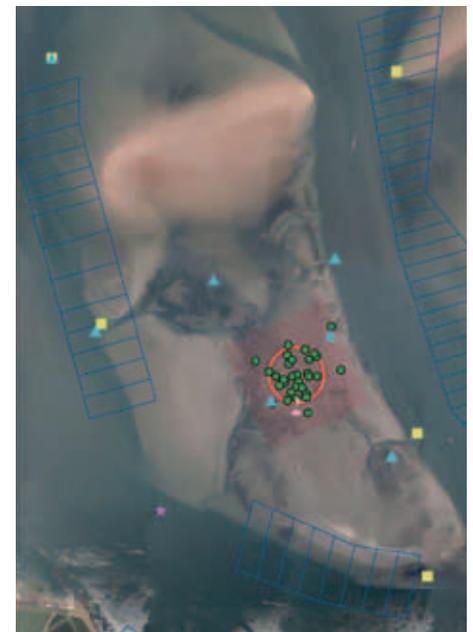
nourishment is modelled at another location to assess the morphological changes (see Discussion). Finally, the main conclusions are given.

## MONITORING

### Galgeplaat nourishment monitoring

A detailed monitoring programme was set up to follow the morphological and ecological development of the nourishment on the Galgeplaat in space and time (Figure 2). Morphological developments were monitored monthly in the first year and later on every third month through visual inspections at the edge of the nourishment, sedimentation-erosion plots at 14 locations along three transects and elevation measurements with RTK-DGPS with a spatial resolution of 25 m. Hydrodynamic measurements of waves and currents are being done with ADCP shortly after the construction of the nourishment, for a period of a month, to better understand the sediment dynamics in the area.

Additionally, a Waverider was installed 200 m southwest of the Galgeplaat in order to measure the dominant wave climate

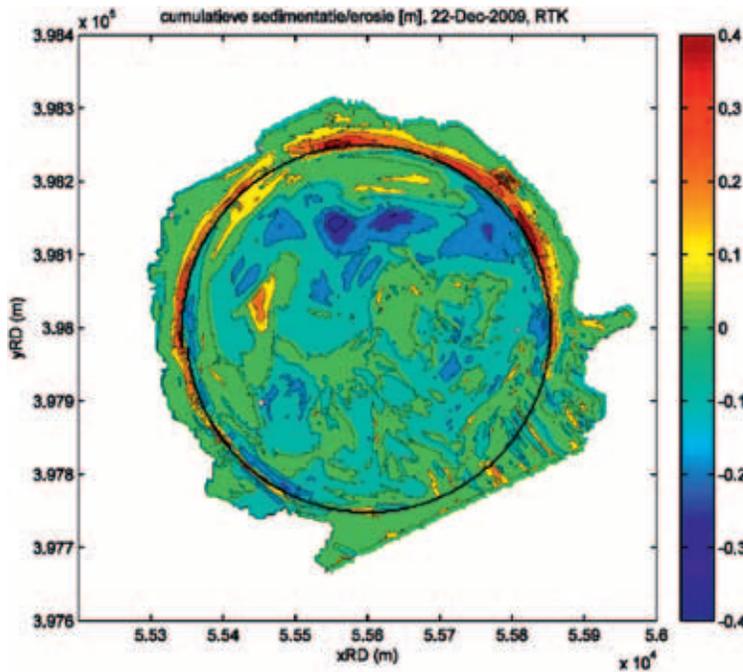


#### Legend

- |                   |                |
|-------------------|----------------|
| Nourishment       | Waves          |
| ARGUS-bio station | Benthic sample |
| Flow velocity     | Bed level      |
| Suspended matter  | Musselbed      |

Figure 2. Overview of the field measurements and the commercial mussel beds on the Galgeplaat.

Figure 3. Cumulated sedimentation (red) and erosion (blue) of the nourishment in December 2009.



continuously. During the construction phase suspended matter concentration was measured in the channels around the tidal flat. Ecological measurements include regular sampling of benthic macrofauna, sediment characteristics (grain size) and chlorophyll-a (i.e., measurements for the presence of algae) to track the benthic recolonisation in time.

Sampling sites on the nourishment (n = 10) are compared with reference stations (n = 6) in nearby undisturbed sediments. Macrofauna samples consisted of three cores (3 × 0.005 m<sup>2</sup>) pushed 30 cm into the sediment within a 1-m radius of the sample site. Sediment samples for grain size and chlorophyll-a concentrations were taken with a 1-cm diameter tube pushed

3 cm and 1 cm into the sediment respectively. Samples were taken in June 2008 (before the nourishment took place), and shortly after the completion of the nourishment (September and October 2008). In 2009 and 2010 sampling was done in April, July and October. In July and October 2009 and 2010 additional samples (n = 25 in total) were taken of the nourishment to get a better picture of the spatial patterns of recolonisation on the nourishment.

Additional high frequency monitoring by means of the Argus-Bio station is carried out to map the nourishment and wet areas, track the foraging behaviour of birds and track the development of algae, oysters and sandworms

on the nourishment. The Argus-Bio station is a station with four fixed Argus-cameras and one movable monitoring camera on a pole in a protective housing at a platform at +17 m NAP. The station has been operational since 31 July 2009. The system is programmed such that the nourishment is monitored during low tide and there is sufficient light.

**Abiotic development**

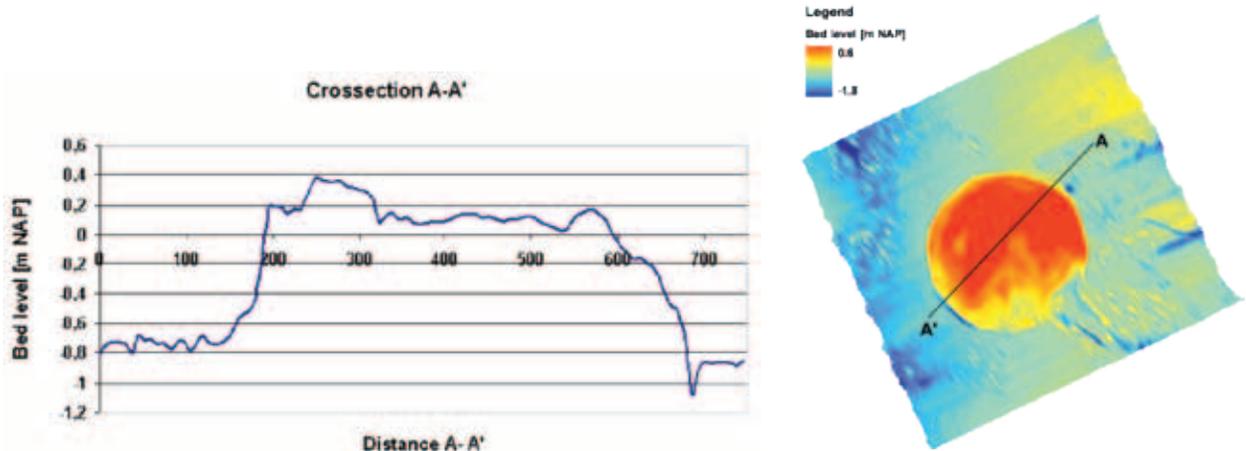
After two years the nourishment is still clearly visible at the Galgeplaat. Initially the bed level had been raised by the nourishment from -0.5 m NAP to +0.5 NAP on average. The morphological development is minor. The field measurements showed that the nourished volume decreased circa 2% (Figure 3). The nourishment is not constructed entirely flat. The northern part is higher than the south-western part (Figure 4). Field measurements show that the erosion is greatest at the high northern part of the nourishment (> +0.25 m NAP). Most of the eroded sediment is transported in a north-eastern direction and accreted along the edge of the nourishment (Figure 3).

Sediment from maintenance dredging work in the adjacent channels of the Galgeplaat was used for the nourishment. The median grain size observed on the nourishment was coarser compared to the surrounding undisturbed sediment (206 ± 3.6 µm and 166 ± 7.7 µm, respectively) and hardly changed over time.

**Ecological development**

A sampling just before the start of the nourishment (June 2008) at sites on the nourishment area and at reference sites in the surrounding

Figure 4. Bed level after construction of the nourishment (September 2008).



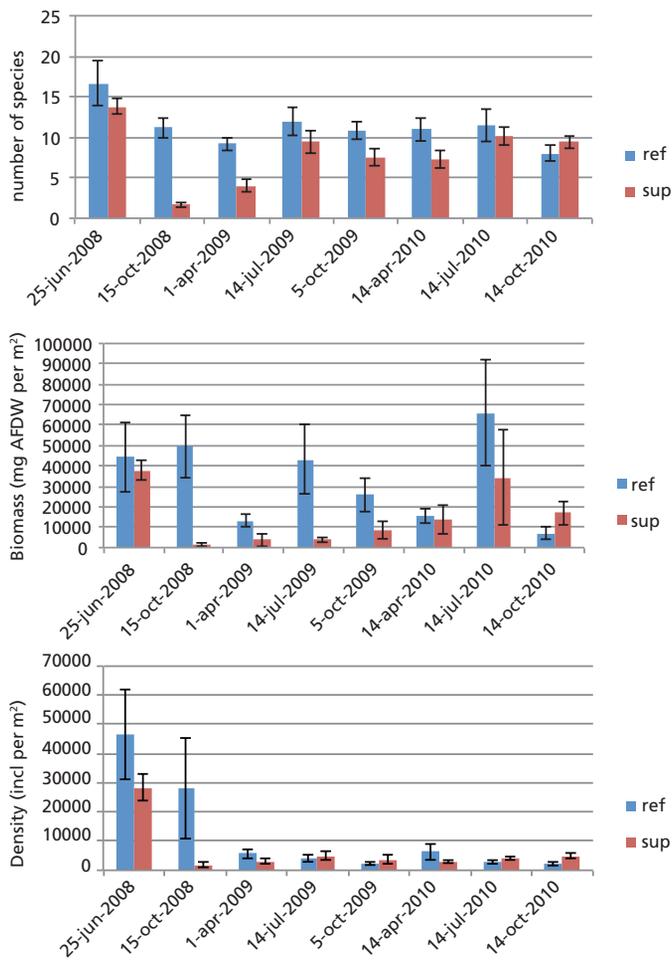


Figure 5. Total number of species (average number  $\pm$  SEM), total biomass (average mg AFDW per  $m^2 \pm$  SEM) and total density (average number of individuals per  $m^2 \pm$  SEM) of the benthic macrofauna.

area revealed similar chlorophyll-a concentration and similar total density, biomass and species richness (i.e., total number of species present) of benthic macrofauna (Figure 5). Chlorophyll-a concentration dropped drastically after the nourishment and recovery to pre-nourishment values is still ongoing after 2 years.

The nourishment killed almost all benthic macrofauna. Shortly after the nourishment, in September and October 2008, only a few organisms were observed in the samples, mainly being adult mud snails (*Hydrobia ulvae*) which migrated from the surrounding undisturbed area. This species was very common in the summer of 2008 and is capable of travelling over large distances by floating. In 2009 further recolonisation of the

nourishment by benthic macrofauna was observed. In July and October 2009, one year after nourishment, densities were similar between the nourishment and the reference sites, but both biomass and species richness was still lower on the nourishment.

The second year, in July and October 2010, both biomass and species richness were similar to the reference area. The much lower density observed in the reference stations in 2009 and 2010 was a result of the almost complete absence of *Hydrobia ulvae*, by far the dominant species in the summer of 2008.

*Hydrobia ulvae* is known to show great year-to-year variation in the whole Eastern Scheldt and therefore these fluctuations are not abnormal (Troost and Ysebaert 2011).

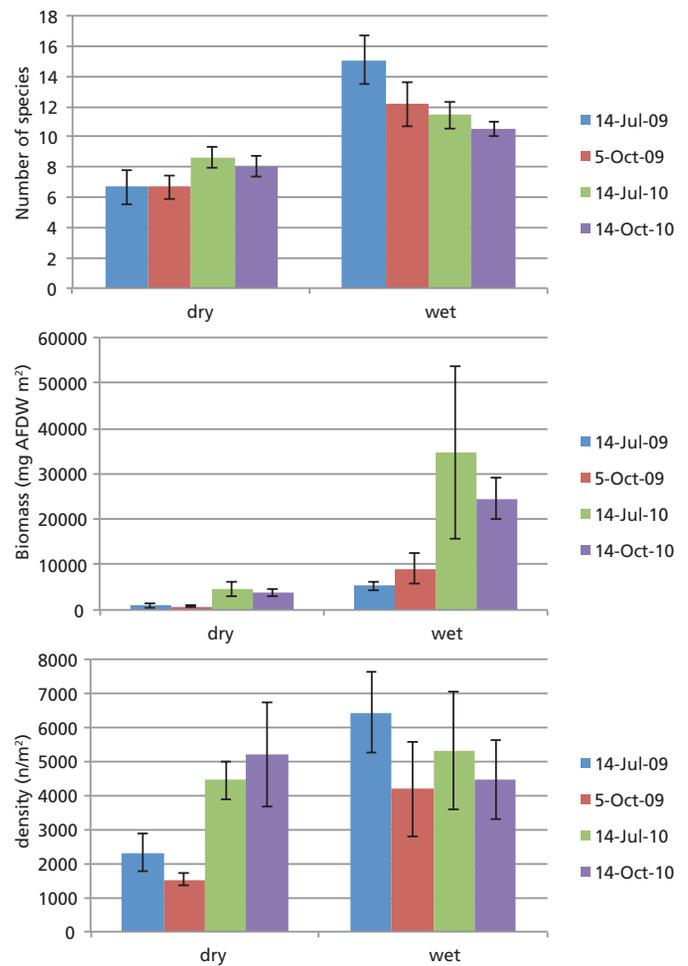


Figure 6. Total number of species (average number  $\pm$  SEM), total biomass (average mg AFDW per  $m^2 \pm$  SEM) and total density (average number of individuals per  $m^2 \pm$  SEM) in the dry ( $n=12$  sampling locations) and wet ( $n=12$  sampling locations) areas on the nourishment.

On the nourishment the recolonisation by benthic macrofauna was very patchy. This is most likely a result of topographical differences on the nourishment, as the northern part is more elevated compared to the southern part (Figure 5). As a consequence the higher areas dry out more quickly during low tide, whereas in the lower area wet areas remain. Based on the Argus Bio-camera images a link was observed between the occurrence of wet and dry areas and the position of the sampling locations for the benthic macrofauna. In the wet areas, recovery of the benthic macrofauna was better compared to the dry areas. More particularly, the number of species, biomass and total density of the macrofauna recolonising the nourishment was higher on the wet areas compared to the dry areas (Figure 6).



Figure 7. The KustZuid wave grids (left) with the nested Galgeplaat wave grid (right) (Das, 2010).

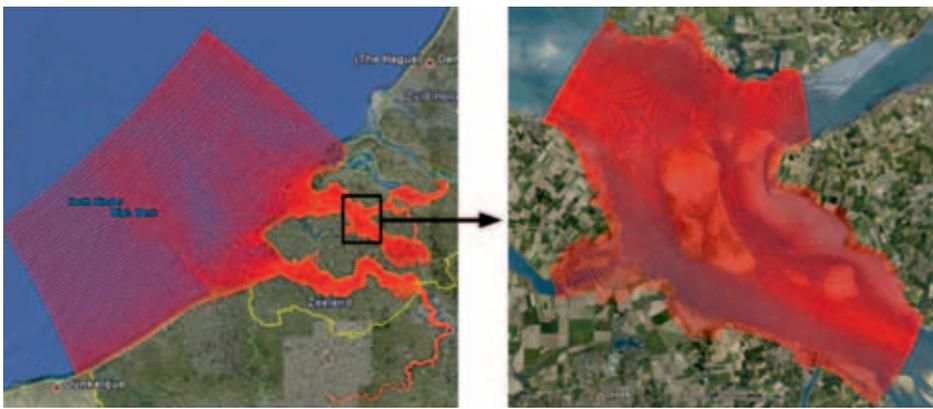


Figure 8. The KustZuid hydrodynamic grid (left) with the nested Galgeplaat grid (right) (Das, 2010).

## MODELLING

As part of the work of Das (2010) a depth-averaged, two-dimensional horizontal (2DH) Delft3D-FLOW hydrodynamic model was set up for the Galgeplaat with a horizontal grid resolution of 25-45 m. Delft3D-WAVE (SWAN) was used to simulate waves on the Galgeplaat grid (coupled with the hydrodynamic model) which was nested in a larger wave domain (Figure 7).

Delft3D-FLOW is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation programme which calculates non-steady flow and transport phenomena, including sediment transport that results from tidal and meteorological forcing on a rectilinear or curvilinear, boundary fitted grid, including the robust simulation of drying and flooding of inter-tidal flats (Deltares, 2010). When coupled with Delft3D-WAVE, current-wave interactions are included (see Deltares, 2010 for a description of these models). This coupled model was in turn nested in the KustZuid model. This larger model simulates the hydrodynamics (including

waves) of the southern part of the North Sea, Western Scheldt and Eastern Scheldt (Figure 8).

This work was continued as part of the ANT project where a series of sensitivity tests were carried out in order to understand the processes responsible for (non-cohesive) sediment transport on Galgeplaat (2001 bathymetry) and to examine the influence of meteorological forcing on morphological development.

In this work the hydrodynamics and sediment transport in the Eastern Scheldt were simulated for a November spring/neap cycle (winter) and an April spring/neap cycle (spring) in order to assess the effect of these processes on the nourishment. The bathymetry in the model was updated using the latest available echo-soundings (2007 bathymetry) and the nourishment was included at two locations – the present location and another more dynamic location further north where transport rates are higher – in order to investigate the behaviour in a more dynamic location.

## KustZuid Model

The offshore boundary conditions for the KustZuid model are astronomic water level constituents. The model timer was kept the same in all scenarios (28 October 2009 – 15 November 2009) to avoid differences resulting from nodal correction of the astronomical tide. A time-step of 0.5 minutes was used and bathymetry from 2001 and 2004 as it was the most complete dataset for the entire model. Wave and winds from the wave buoy Europlatform (51.9N 3.3E) were used to force the model. A Manning coefficient of 0.025 was applied. Boundary conditions were generated for the Galgeplaat model with an offline nesting procedure.

## Galgeplaat Model

The Galgeplaat model has three open boundaries, to the north-west (NW), north-east (NO) and south-east (ZO). The north-west is a mixture of current and water level boundary segments, the south-east and north-east are current boundaries. Simulations were set up to examine the effect of wind and wave forcing on morphological change over the tidal flats. The outer domain of the Galgeplaat wave model was also forced by waves from Europlatform with winds from Stavenisse Station. Winds were predominately from the south-west in November 2009 (average 6 m/s; maximum 15 m/s) and from multiple directions in April, but a large proportion from the north-east (average 4.5 m/s; maximum 11.5 m/s).

Runs with and without wind or waves, for both the winter and spring scenarios were set up to examine the effect of tide only and different meteorological conditions on the morphological development of the Galgeplaat. These simulations were repeated with the presence of the nourishment to examine the behaviour of both the nourishment under different conditions and on erosion rates of the flats. Two additional runs were set up with the nourishment in a more dynamic location further north. Winter and spring forcing conditions were again used. An overview of simulations is given in Table I.

A time step of 0.5 minutes was applied and a uniform non-cohesive sediment diameter of 200 $\mu$ m. This sediment diameter was chosen as it best represented the nourishment grain size. A Chézy coefficient of 65 m<sup>1/2</sup>/s was used in all

**Table I. Overview of simulations shown.**

Simulation	Nourishment Included	Wind & wave forcing
Winter 2009 - reference (G01)	No	Europlatform waves & Stavenisse winds from 28/10/2009 – 15/11/2009
Spring 2009 (G02)	No	Europlatform waves & Stavenisse winds from 28/03/2009 – 15/04/2009
Winter 2009 (G03)	Yes in current location	Europlatform waves & Stavenisse winds from 28/10/2009 – 15/11/2009
Winter 2009 (G07)	Yes in another location in the northern part of the flats	Europlatform waves & Stavenisse winds from 28/10/2009 – 15/11/2009

runs. In the morphological parameterisation, bed updating was switched on and a morphological factor of 6 was applied with an initial spin-up period of 12 hours before bed-updating began. Therefore results of the morphological simulations represent 6 spring-neap tides. This should be borne in mind when looking at the cumulative sedimentation/erosion rates of the winter simulations. The sediment transport formula of van Rijn (1993) is used by default.

### Validation and Results

A comparison was made between waves at Keeten and the closest model observation point (~300m NW) (Figure 9). Significant wave height was predicted correctly for most of the simulation period, with the exception that lower wave heights around 9 November 2009 were overestimated. Current velocities were also compared with measurements done on the flats in 2008. A run with 2008 wind and wave forcing was set-up for this purpose. Velocity magnitudes compare well at some stations in the field and are slightly underestimated in others. The direction of the flow velocities over the flats vary throughout the tidal cycle. Kohsiek *et al.* (1988) found during field measurements in the adjacent western tidal channel of the Galgeplaat that the current direction near the bottom is along the edge of the shoal, but that the current direction near the surface is shifted 20 degrees and is directed onto the shoal. This occurs around the maximum flood velocities.

Although the model is 2D, the vectors do appear to curve inwards towards the flats mid-way through the flood (11:00) and around high water (13:00) on the western side. During ebb, large current velocities are directed off the flats.

Figure 10a shows the Galgeplaat spring simulation (G02) with a spatially averaged erosion of  $-0.002$  m. Figure 10b shows the winter scenario (G01) with much more erosion of  $-0.018$  m – an order of magnitude difference. The south-westerly wind and wave conditions during the simulation period are also reflected in the dominant direction of the transport vectors. Prior to the construction of the storm surge barrier, calm weather generally resulted in an overall trend towards slight vertical accretion. Under storm conditions however substantial amounts of sediment were stirred up by wave action and picked up by the current.

To examine the effect of stronger currents in the model, the spring and winter simulations

were repeated as part of the ANT study (Cronin, K., 2011) with double the tidal currents at the boundary of the Galgeplaat model. With a doubling of currents the Galgeplaat still experienced spatially averaged erosion of  $-0.008$  m for the November scenario showing the dominance of wind and wave forcing, albeit the erosion was less. For the calmer April scenario, a spatially averaged deposition of  $+0.001$  m was simulated. This shows that accretion of the tidal flats is possible under calm conditions but that the current velocities since the construction of the barriers are reduced to such an extent that overall accretion is rare or impossible.

Including the nourishment in the model resulted in slightly less erosion in the winter scenario ( $-0.016$  m) as a result of the supply from the nourishment (G03) (Figure 11) and no significant difference in the spring scenario, where there was much less sedimentation and erosion on and around the nourishment.

Moving the nourishment to a more dynamic area of the flats, in the northern half, results in the same level of erosion for the winter forcing (G07) (Figure 12) as the winter reference scenario (Figure 10b). More erosion of the nourishment occurred and sand was transported in greater amounts to the

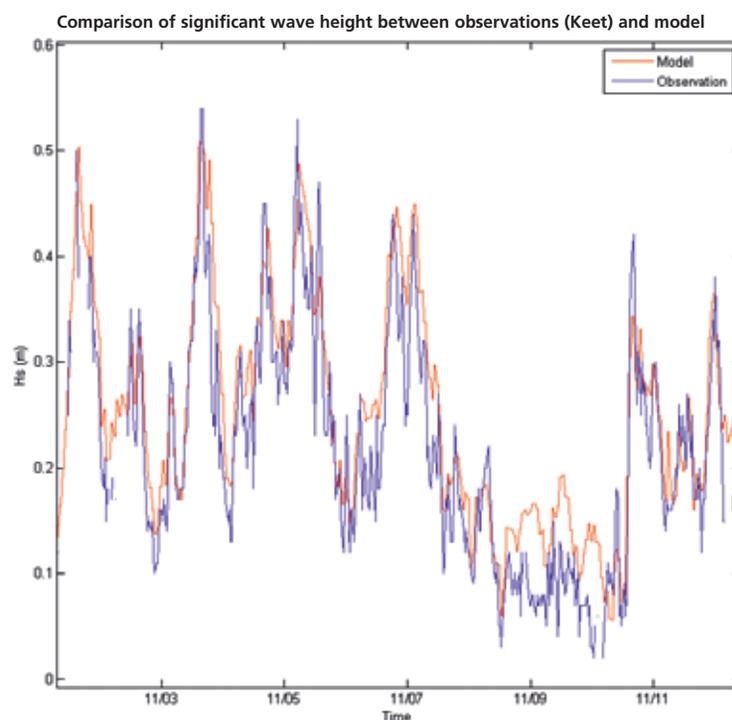


Figure 9. Simulated versus observed significant wave heights for November 2009.

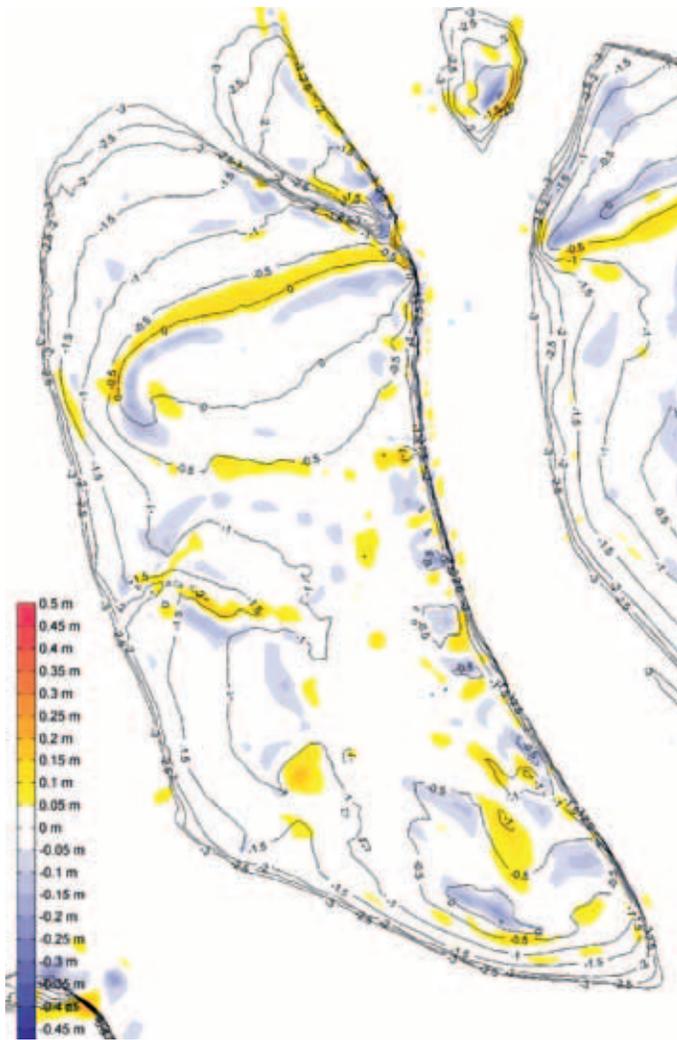


Figure 10a. Cumulative sedimentation/erosion for the spring scenario with no nourishment (G02).

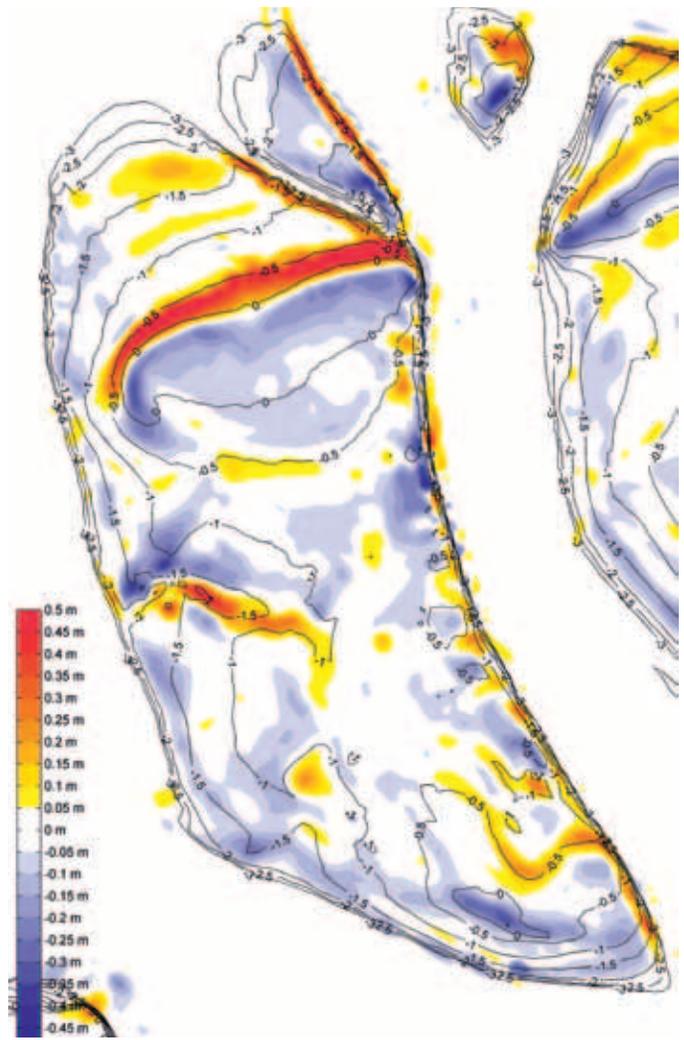


Figure 10b. Cumulative sedimentation/erosion for the winter scenario with no nourishment (G01).

surrounding area. Similarly for the spring scenario, more sand was transported from the nourishment to the surroundings.

Regarding the locations of erosion and deposition, the morphological patterns are partly in agreement with observations that show the western edge eroding and the sediment building up on the eastern channel edge. Louters *et al.* (1998) found that between 1987 and 1994 most of the sediment eroding from the Galgeplaat was deposited along the banks of the eastern channel, indicating the importance of westerly storms in this process. However these simulations show infilling of the main gully on the western side of the flats. This may also be caused by incorrect simulation of currents and transport around this area. In reality there is a

large area of oyster beds around this gully and flow patterns would therefore be affected.

## DISCUSSION

The Galgeplaat has been experiencing erosion rates of 0.01 m/year from 1985-2001 (Zanten & Adriaanse, 2008) with up to 0.02 – 0.05 m/year locally. This loss of tidal flats has a detrimental effect on the ecology of the system. In an attempt to reduce this degradation a nourishment was placed on the flat in 2008.

The impact of the nourishment is two-fold: next to short-term negative impact on the disturbed biota, over the longer term the nourishment will supply sand to the surrounding area, thus compensating the erosion of the valuable tidal flat for biota such as birds that use these areas as foraging grounds.

In order to understand and better predict these impacts, a monitoring study and a modelling study are underway. The morphological development of the nourishment was remarkably small: the nourished volume hardly eroded and the redistribution of sediment from the nourishment to the surrounding tidal flat was minor in the two-year period after placement.

The ecological development is still on-going after 2 years. Interestingly, the recolonisation on the nourishment showed clear spatial differences related to the differences in topography of the nourishment. In the analysis, wet areas, which remain covered with water for a longer time period during low tide, were distinguished from dry areas which dry up quickly. In terms of total densities, the nourishment site is comparable

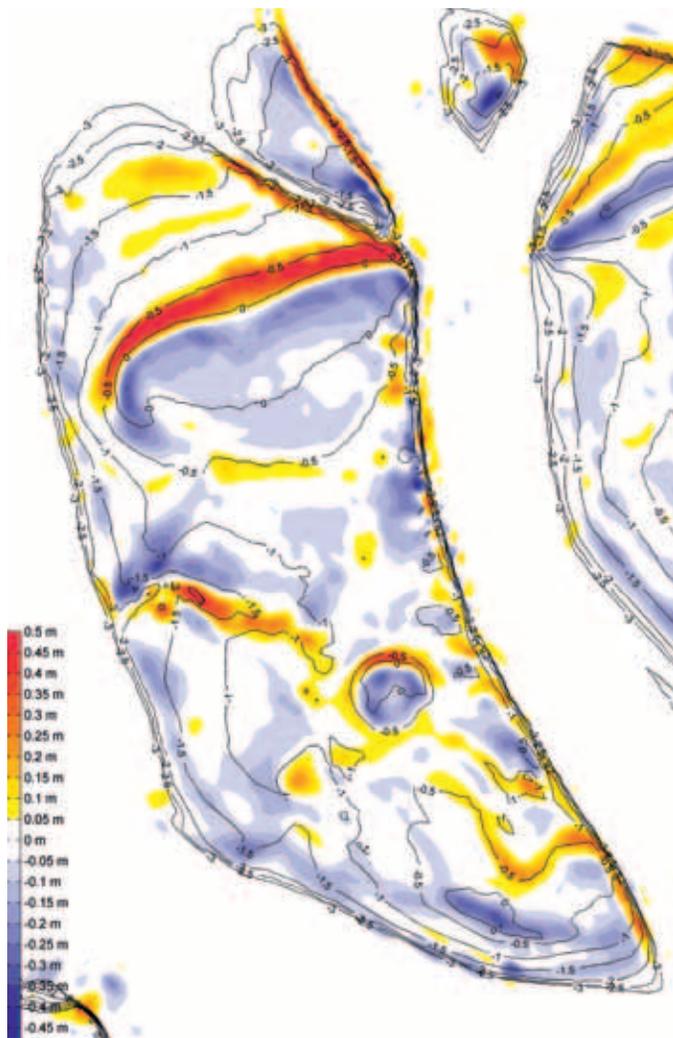


Figure 11. Cumulative sedimentation/erosion for the winter scenario with the nourishment in its present location (G03).

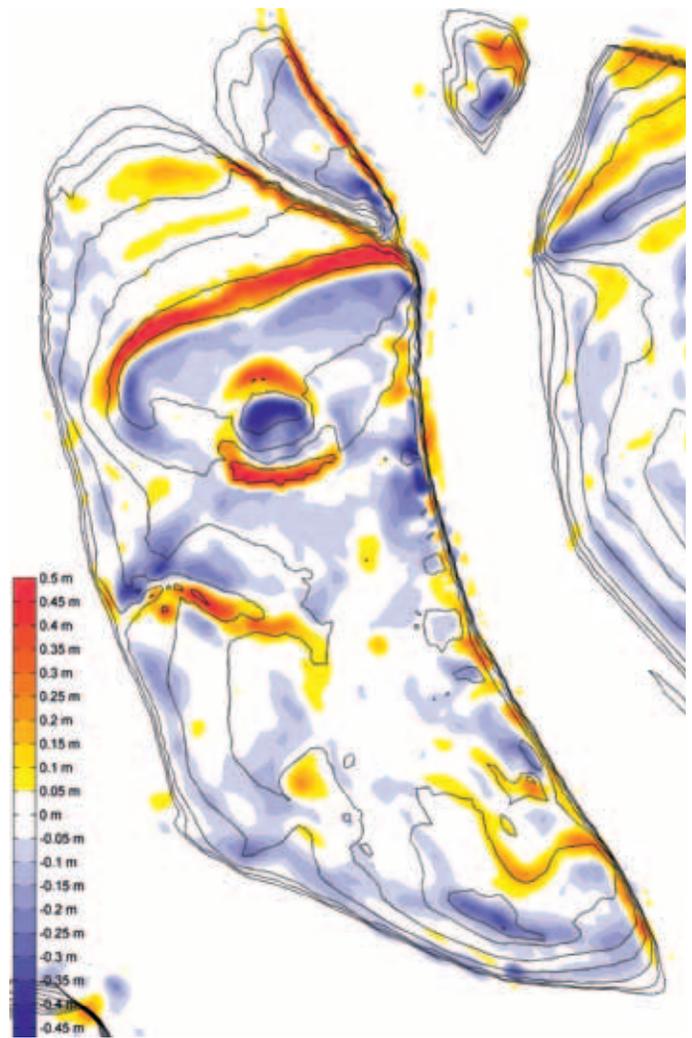


Figure 12. Cumulative sedimentation/erosion for the winter scenario with the nourishment in another location (G07).

to the reference site the second year after nourishing and spatial differences between wet areas and dry areas are small. Recolonisation was slower though in the dry than in the wet areas, as was clear from the observations in 2009.

For the biomass, however, overall averages indicate similar values in the nourishment and the reference site reached in 2010, but the spatial difference is high. After two years, biomass was much higher in the wet area compared to the dry sites. The number of species was initially higher in the wet areas than in the dry areas, but these differences are getting smaller as time goes on. It is foreseen that it will take several years to get a fully recovered benthic community. Also the recovery trajectory might be different

depending on the initial conditions of the nourishment compared to the original conditions (Defeo *et al.*, 2009). Although not constructed intentionally, the elevation differences allowed for a different recolonisation rate, probably as a result of different drainage patterns which affect the moisture of the sediment. This should be taken into account when designing nourishments on tidal flats. Instead of completely flat surfaces, probably a design with troughs or a gentle slope is more favourable for the biological recovery of the system.

Regarding the modelling, further work is needed on both the nested Galgeplaat model and the KustZuid model in order to improve understanding of the physical processes dominating the morphological changes in

nature and within the model. In this study only a relatively short period was simulated and the morphological patterns are still rather patchy. For a better understanding of these patterns a longer period needs to be simulated with a wider range of representative conditions.

These simulations showed that locally generated waves play an important role in the transport of sediments around and on the tidal flats. This transport should be investigated further by looking at the resuspension processes involved as a result of both currents, waves and wave-current interaction. The inclusion of biological features, such as oyster and mussel beds will also have an impact on the simulation of current magnitudes over the tidal flats and hence patterns of sedimentation/erosion.

Nonetheless, the model is already a useful tool to assess the behaviour of the nourishment under different conditions and at different locations. Simulating the present nourishment location, results show a similar pattern of deposition around the north and north-east of the nourishment as in reality. Currently, monitoring shows that the nourishment has remained quite intact with only a minor spreading of sediment.

The observed bed level changes over the nourishment cannot yet be compared to the modelled bed level changes. To do this a longer term simulation with realistic wave and wind forcing will be done. However, the model does show that little is happening to the nourishment under calm conditions and it is much more morphologically active under higher wind and wave conditions. The model is also useful to test the behaviour of the nourishment in another location, as much more morphological change occurred on and around the nourishment in a location further north-west.

Linking the simulated morphological change of different nourishment scenarios with the impact on biota and vice versa is, as of yet, complicated by both temporal and spatial scale issues. Further model work is under way to include the effects of the oyster and mussel beds on the morphological development of the Galgeplaat.

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## CONCLUSIONS

In order to (temporarily) stop the loss of intertidal area, a pilot nourishment was executed at the Galgenplaat, a tidal flat in the Eastern Scheldt, The Netherlands.

The morphological changes of the nourishment appear to be small. A detailed monitoring programme revealed that biological recovery at the nourishment site was highest at locations which were wet during a longer period of the tidal cycle. Two years after implementation, the overall average biomass reached similar values at the nourishment and the reference site.

The numerical morphological model of the Galgeplaat forms a useful tool to study the wind and wave conditions that have most impact on the spreading of the nourishment and to examine different nourishment strategies, both in terms of nourishment location and nourishment design (shape and size). More analysis is needed to connect the morphological patterns observed in the model and its effects on the biota since the nourishment has been put in place. The interaction

between the abiotic and biotic field measurements and the model is essential in understanding the impact of the nourishment. Field measurements are used to validate the model and model results will be used to pinpoint locations for more detailed field measurements like the wet areas.

Given the lessons learnt in this pilot project, the nourishment strategy can be improved and a nourishment is proposed:

- (1) on a more dynamic location, in order to spread the sediment over the tidal flat by currents and waves,
- (2) with topographical differences in order to speed up recolonisation and
- (3) to minimise the impact on other user functions in the area like commercial mussel beds.

Through the improved knowledge on the abiotic-biotic interactions, recommendations on the frequency as part of the nourishment strategy can also be given.

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