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An integral approach to design the Roggenplaat intertidal shoal nourishment

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ABSTRACT

The Eastern Scheldt, a tidal basin in the southwest of The Netherlands, underwent large physical and ecological changes due to a system-wide human interference. The construction of a storm surge barrier at the seaward side and closure of the upstream branches in the 1980s resulted in intertidal flat erosion. This has far reaching consequences for the ecological functioning of these habitats, especially as foraging ground for many wader species. Therefore, a 1.3 million m^3 sand nourishment is foreseen on the Roggenplaat intertidal shoal to mitigate the erosion and preserve suitable foraging habitat for waders for the coming 25 years. This paper presents an integral nourishment design approach. It consists of the following steps: (i) understanding the morphology and ecology, (ii) translation of the nourishment objective into an evaluation framework, (iii) construction of a suitability map indicating potential nourishment locations, (iv) generation of nourishment designs, (v) short-term morphodynamic numerical model simulations, (vi) estimation of the long-term shoal development using a simplified approach, (vii) integral evaluation leading to the preferred design. This integral approach resulted in a design that is expected to fulfill the Roggenplaat nourishment objective, accounting for ecological, morphological, economical and technical aspects. This integrated approach could form a basis for future intertidal shoal nourishment designs worldwide.

1. Introduction

Intertidal flats are essential habitats of estuaries and other low energy marine environments. They are distributed widely along coastlines worldwide, accumulating fine-grain sediments on gently sloping beds, forming the basic structure upon which coastal wetlands build. Intertidal flats are found in e.g. in the Yangtze estuary, China (De Vriend et al., 2011; Zhu et al., 2017), San Francisco Bay, USA (Van der Wegen et al., 2017) and the Eastern and Western Scheldt, The Netherlands (De Vriend et al., 2011; De Vet et al., 2017). Two types of intertidal flats can be distinguished: intertidal shoals, which are surrounded by tidal channels, and fringing flats, which are attached to the shore. The physical structure of intertidal flats is diverse and ranges from mobile, coarse sand environments on more wave-exposed coasts to stable, fine-sediment mudflats in more sheltered environments. Its morphology is a complex outcome of tides, waves, sediment properties and ecological processes (Le Hir et al., 2000; Friedrichs, 2011; De Vet et al., 2018).

Intertidal habitats are highly productive and diverse components of shallow coastal ecosystems providing essential ecosystem functions and services (Barbier et al., 2011; Boerema and Meire, 2017). They are worldwide protected by international conventions and legislations, e.g. the Ramsar convention for the protection of migratory birds or the European Natura 2000 legislation. Intertidal flats, along with seagrass beds, saltmarshes and mangroves constitute coastal wetlands, a vital part of the coast. The intertidal flats form a buffer zone between deeper channels and the higher-lying salt marshes or mangroves, protecting the latter by dissipating wave energy (Bouma et al., 2016).

Despite their services and protection, intertidal flats are under pressure from human-induced changes that affect their quantity and

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quality (Lotze et al., 2006; Airoldi and Beck, 2007). At a global scale, climate change and sea level rise on the one hand, and development of coastal societies on the other hand, squeeze the intertidal coastal strip. At the larger scale, embankments, building of barriers and dredging activities have affected the hydrodynamics, morphology, biodiversity and ecological value of the intertidal flats (Thrush et al., 2004; Cozzoli et al., 2017). At the scale of an individual flat, land reclamation, artificial saltmarsh development and dike reinforcements have provoked considerable area losses.

The Eastern Scheldt, a tidal basin in the southwest of The Netherlands (Fig. 1), is a good example of a coastal system that underwent large physical and ecological changes due to a system-wide human interference. The completion of the Eastern Scheldt storm surge barrier at the seaward side and the closure of the upstream branches in 1986 led to a decrease in tidal velocity resulting in a decrease in sediment transport from the channels onto the intertidal flats. As wave-induced erosion continues, the net effect is erosion and flattening of the intertidal flats (Louters et al., 1998; De Vet et al., 2017). It is expected that by 2100 less than half of the original intertidal flats in the Eastern Scheldt will remain (De Ronde et al., 2013). The loss and flattening will have far reaching consequences for the ecological functioning of these habitats (Cozzoli et al., 2017), especially as a foraging ground for many wader species for which the Eastern Scheldt is of international importance.

As a measure to mitigate the loss of intertidal areas in the Eastern Scheldt, Rijkswaterstaat (the executive agency of the Ministry of Infrastructure and Water Management) started with pilot tidal flat nourishment experiments. Compared to beach and shoreface nourishments, a common practice along the Dutch coast, nourishment of intertidal flats in estuarine or coastal environments is relatively unexplored. A first small pilot was realized in 2008 on the Galgeplaat intertidal shoal (location indicated in Fig. 1). This pilot showed that intertidal flat nourishments have the potential to effectively counteract the negative ecological consequences of erosion (Van der Werf et al., 2015). Monitoring showed that the nourished sediment was relatively stable with an expected nourishment life-time of tens of years. The benthic macrofauna largely recovered after three years, especially in terms of species richness and total biomass. Community composition, however, still differed compared to nearby undisturbed sites (Van der Werf et al., 2015). Recovery of the benthic macrofauna on the nourishment was not uniform, with slower recovery and lower biomass values on the higher dryer parts and faster recovery with higher biomass values on the lower, wetter parts of the nourishments. This was also reflected in the use by birds of the nourishment, with lower numbers of foraging birds on these higher parts (Van der Werf et al., 2015).

Following this pilot and other studies, it was decided to fully implement this nourishment strategy to mitigate the erosion of the intertidal flats, and to nourish the Roggenplaat intertidal shoal (Fig. 1) with 1.3 million m^3 of sand, a tenfold of the Galgeplaat pilot nourishment. The planned borrow area is located in the Roompot tidal channel south of the Roggenplaat. The sediment in the borrow site contains low slit percentages (0.5–3.0%) and has a median grain-size between 0.18 and 0.40 mm (Vonhögen-Peeters et al., 2013). The Roggenplaat shoal was chosen as it is an important foraging area for wading birds. It suffers severely from erosion and is probably bound to lose most of its foraging function over the coming decades (De Ronde et al., 2013). It is expected that the sand nourishment will be executed in 2019–2020. The main aim is to ensure that in 2035 the bird foraging function of the Roggenplaat is at least equal to the reference year 2010, thus compensating for future tidal flat erosion and sea level rise (SLR) for a 25-year period.

This paper describes an integral approach for designing the nourishment of the Roggenplaat shoal. It does not consider (effects of) sand extraction. The design process consists of the following 7 steps:

1. Characterization of the Roggenplaat morphology and ecology based on existing knowledge and new monitoring data.
2. Translation of the main nourishment objective into an evaluation framework.
3. Construction of a suitability map indicating potential nourishment areas, based on morphological, ecological, economical and technical considerations.
4. Generation of nourishment alternatives and designs.
5. Calculation of the nourishment impact on short-term hydro-morphodynamics using a Delft3D numerical model.
6. Prediction of the long-term future shoal development using a simplified approach.
7. Integral evaluation of the nourishment alternatives leading to the preferred design.

The paper is organized as follows. Section 2 describes the Roggenplaat morphology and ecology (i.e. Step 1). The approach to design the Roggenplaat nourishment is described in Section 3, including the evaluation framework and suitability map (Steps 2 and 3). This section continues with the Delft3D numerical model set-up and the simplified approach to predict the long-term intertidal area development. Section 4 describes and evaluates three nourishment alternatives, followed by the generation and evaluation of three more detailed designs (Steps 4–7). The results are discussed in Section 5. Section 6 presents the conclusions, and the general lessons learned from this study are given in Section 7.

2. Morphological and ecological characterization of the Roggenplaat

The Roggenplaat is the largest intertidal shoal of the Eastern Scheldt, the Netherlands. It has a surface area of 14.6 km^2 between mean high water and mean low water (situation 2013). The Roggenplaat contains two northwest-southeast orientated drainage channels of which the eastern one is more than 100 m wide, see Fig. 2. Before the Eastern Scheldt storm surge barrier was constructed (1986), sediment accreted on the Roggenplaat (Louters et al., 1998). However, the Roggenplaat eroded on average 0.5 cm/year vertically after the completion of this barrier (De Ronde et al., 2013). As also visualised in Fig. 2, the area with more than 50% exposure time (bed level, z_b > NAP[1]-0.04 m) decreased from 751 ha in 1990 to 615 ha in 2013. The area with more than 80% exposure time (z_b > NAP + 1.02 m) was decreased from 5 ha in 1990 to 4 ha in 2013. The areas with 50–80% exposure time are important because they provide sufficient time for wader species to search for and feed on macrobenthic animals.

In Fig. 3 the measured morphological evolution along a transect is visualised. The largest erosion rates occur in the south of the Roggenplaat. De Vet et al. (2018) showed that the sediment transport on the Roggenplaat is mainly in north-eastern direction, which is in line with the dominant wind (and thus wave) direction. This main sediment transport direction caused the high ridges on northern part of the shoal not purely to decrease in elevation but also to propagate in north-eastern direction, see also Fig. 3.

The sediment on the Roggenplaat can be characterized as fine sand with an average median grain size of 210 ± 3 μm (based on 113 sampling locations distributed over the entire shoal, measured in 2016). The spatial distribution on the Roggenplaat shows somewhat coarser sediment in the western part. Locally, in the vicinity of oyster reefs (*Crassostrea gigas* mixed with blue mussels *Mytilus edulis)*, the sediment is more silty (max. 33% of silt; silt is defined as sediment with grain size smaller than 63 μm), but on average silt content is low (4%). No correlation between sediment composition and exposure time was observed. Oyster reefs cover about 3% (45 ha) of the Roggenplaat, and

[1] NAP is the Dutch vertical datum close to mean sea level.

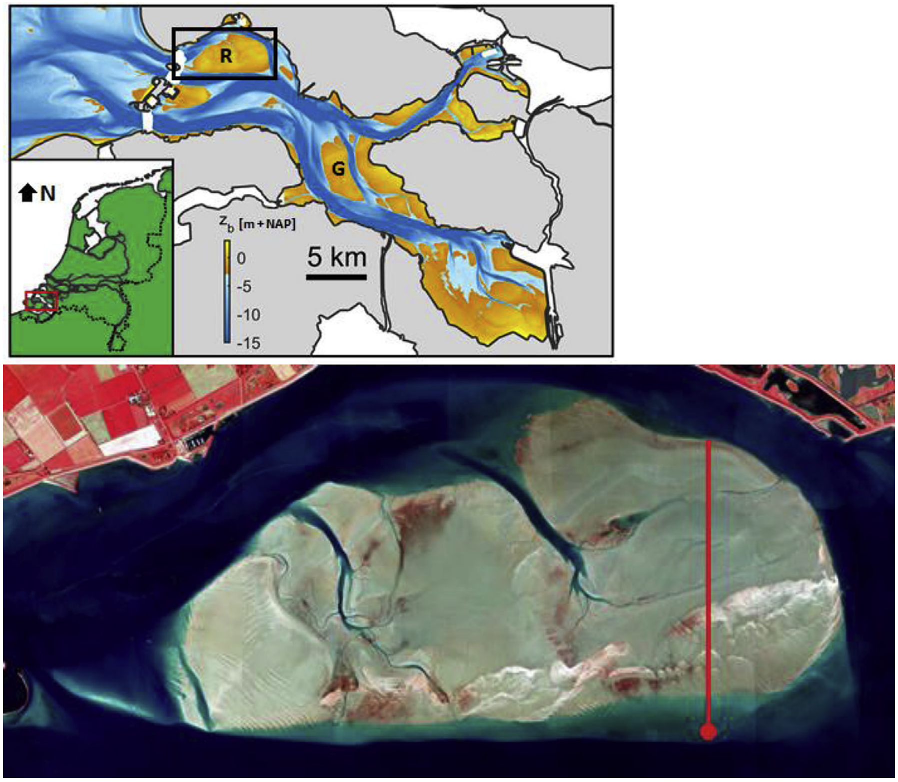

Fig. 1. Upper panel: the Roggenplaat intertidal shoal (R, black box) in the Eastern Scheldt tidal basin located in the southwestern part of The Netherlands. Also the Galgeplaat intertidal shoal (G) is indicated in this panel. The bathymetry is based on 2013 data. Lower panel: 2014 aerial photo of the Roggenplaat (in false colors) (courtesy Edwin Paree, Rijkswaterstaat) with the location of the transect shown in Fig. 3 (circle is the start of the transect). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

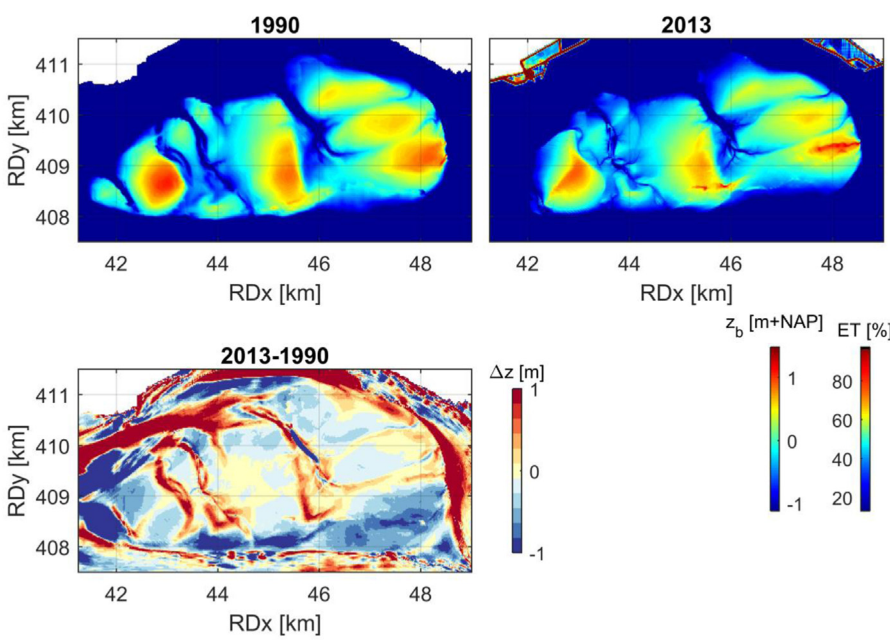

Fig. 2. Top: bathymetry maps of the Roggenplaat for the years 1990 and 2013. Both the color scale in meters as in exposure times (ET) are provided. Bottom: bathymetry difference map. The bathymetry maps are a combination of single beam, multibeam and LiDAR measurements (courtesy data Rijkswaterstaat). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

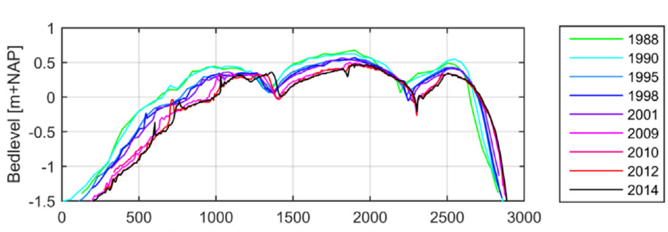

Fig. 3. The morphological evolution of a cross-section of the Roggenplaat (courtesy data Rijkswaterstaat). The location of the transect is indicated in Fig. 1, the transect starts at the south.

occur in the north-eastern part and near the two drainage channels. Ridges of bivalve shells occur along the southern edge, visual as the whitish areas in Fig. 1.

The benthic macrofauna on the Roggenplaat consists mainly of polychaetes, bivalves and crustaceans. In 2016, 81 taxa were observed in total (based on 113 sampling locations), with on average 11 ± 0.5 taxa per locations. The average abundance was 5026 ± 615 ind.m^{-2}, the average biomass 31 ± 4 g AFDW.m^{-2}. The most common species were the polychaete *Scoloplos armiger*, the amphipod *Urothoe poseidonis*, and the bivalve *Limecola balthica*. In terms of biomass bivalves dominate, with the cockle *Cerastoderma edule* as the most important species (35% of the total biomass) (Ysebaert et al., 2016).

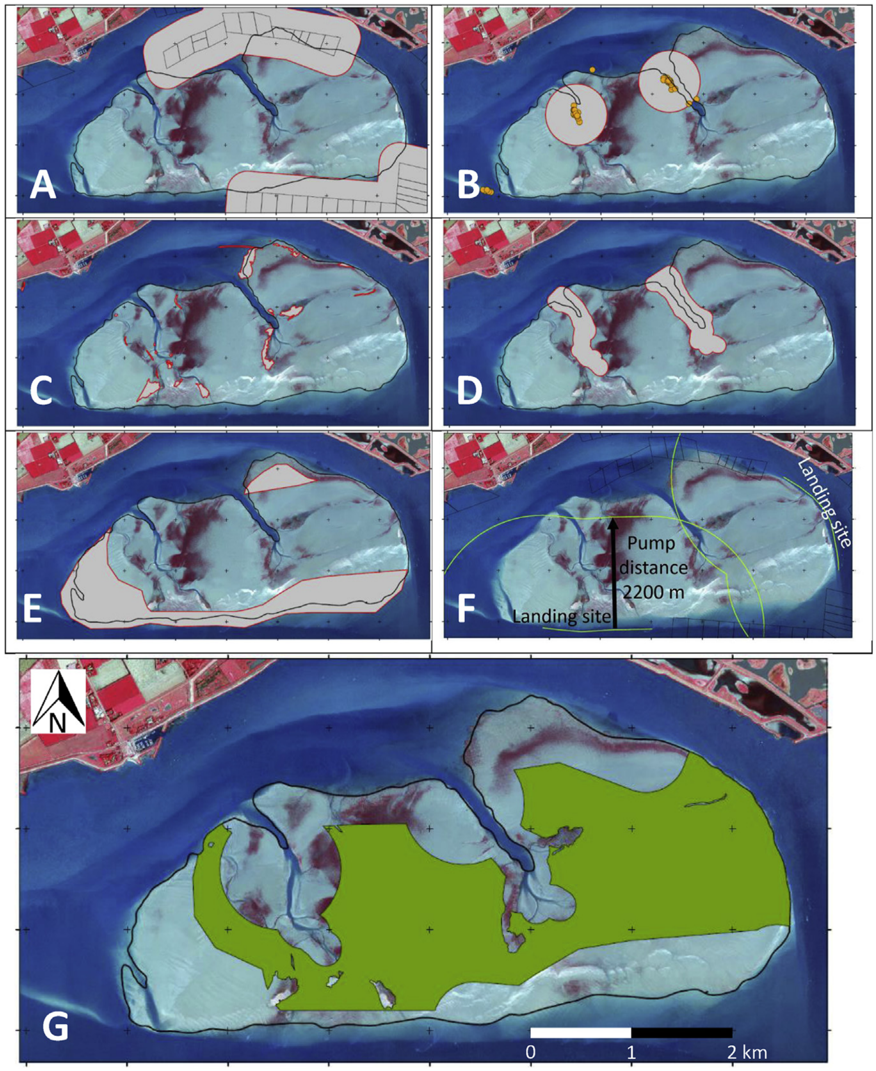

Fig. 4. A–G: Roggenplaat areas excluded as potential nourishment areas. A: 400 m away from commercial mussel beds (grey lines). B: 600 m away from the two main seals resting areas (orange dots: observed seals). C: oyster reefs. D: 150 m away from the two main tidal creeks. E: highly erosive areas. F: nourishment to be constructed within 2200 m pumping distance from the two possible landing sites. G: in green the resulting area suitable for nourishment. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The Roggenplaat is one of the most important foraging areas for wader species in the Eastern Scheldt, with up to 20,000 waders feeding here at low tide during winter and migration periods (e.g. Arts et al., 2017). The most common species include Dunlin (*Calidris alpina*), Bar-tailed Godwit (*Limosa lapponica*), Oystercatcher (*Haematopus ostralegus*), Eurasian Curlew (*Numenius arquata*), Grey Plover (*Pluvialis squatarola*), Sanderling (*Calidris alba*) and Knot (*Calidris canutus*).

The Roggenplaat is an important resting area for common seals (*Phoca vitulina*) and grey seals (*Halichoerus grypus*). In the season 2015/2016 a maximum of 89 common seals and 7 grey seals were counted at one occasion (Arts et al., 2017). The seals mainly occur along the steep banks of the two drainage channels.

The Eastern Scheldt is an important area for the cultivation of mussels and oysters, and along the north side and south side of the Roggenplaat 25 mussel bottom-culture plots are located. The total surface of these culture plots is 427 ha. The plots cover partly the intertidal zone and partly the shallow subtidal zone, but nowadays only the subtidal part is used for growing mussels.

3. Methods

3.1. Design approach

The main objective of the 1.3 million m^3 Roggenplaat sand nourishment is to maintain the bird foraging function for 25 years in light of future tidal flat erosion and SLR. The nourishment volume is based on the expected loss of intertidal area with a 50–80% exposure time between 2010 and 2035 (De Ronde et al., 2013). The design process aims to find the nourishment configuration (height, location, geometry) that best fulfills this objective.

First, the nourishment objective was translated into an evaluation framework, and a suitability map indicating potential nourishment areas was constructed. Second, the preferred nourishment alternative was selected from three alternatives based on different operating principles. Third, the preferred alternative was detailed, resulting in three nourishment designs of which one was selected. The selections were based on the evaluation framework, fed by system understanding, (Delft3D) numerical model simulations of short-term hydro-morphodynamics and a simplified approach to estimate the long-term intertidal area development.

3.2. Evaluation framework

The evaluation framework serves two goals. It is set up to systematically and objectively assess and compare effectiveness and impact of the nourishment designs. Also, it plays a process role as a shared guiding structure in the cooperation among multidisciplinary researchers and as a means of communication with stakeholders. The evaluation framework was constructed in the first project phase during two workshops with scientists and a selection of stakeholders.

The key indicator reflects the bird foraging function of the Roggenplaat. The Eastern Scheldt is an EU Bird Directive (2009/147/EC, site code NL3009016) designated area for 14 migratory bird species, all but one are wading birds. The foraging function is determined by three factors: 1) the size of the intertidal area, 2) the exposure time, i.e. the time the intertidal area is accessible for foraging, so not covered with water, and 3) the food availability and food quality. Although there are variations between the bird species, the intertidal area (IA) with 50–80% exposure time (IA50-80%) was shown to be most important for the Eastern Scheldt as is enables birds to feed longer which is crucial during the winter months (De Ronde et al., 2013). Hence this was defined as the key indicator. In 2010, IA50-80% was equal to 606 ha and is predicted to decrease to 421 ha in 2035 with the autonomous development. Therefore, a nourishment design is considered suitable when the IA50-80% in 2035 is at least 606 ha.

The food availability and food quality represented by the benthic community are related to exposure time, but also to other factors such as hydrodynamic conditions and sediment composition (Cozzoli et al., 2013). As insufficient knowledge was available for quantification, this aspect was included qualitatively through expert judgement in the evaluation framework.

Two additional support indicators were defined. The footprint is the area where existing benthic life will be destroyed by the placement of nourishment sand. A minimal footprint is considered positive, even though no quantitative target is set. The nourishment circumference is the length of the waterline which is a possible hotspot for foraging birds. A longer nourishment circumference is considered positive, but again no quantitative target is set.

Exclusion criteria for the nourishment location resulting in a suitability map (see next paragraph, 3.3) are also part of the evaluation framework. Finally, the construction costs were considered in a relative sense.

3.3. Suitability map

The nourishment suitability map distinguishes between areas that are considered suitable and not suitable to nourish with sand (Fig. 4G). It excludes areas based on a combination of economical, ecological, morphological and technical considerations, as explained below.

3.3.1. Commercial mussel beds

There are several commercial mussel beds on the northern and south-eastern side of the Roggenplaat tidal flat. Nourishments can have negative impacts on mussels in two ways. First, fine sediments that wash out from the nourished sediment may lead to an increase in suspended sediment concentrations, which might reach the mussel culture plots, which in turn can lead to a decrease in the food intake by the mussels. Second, nourishments can cause undesired sediment coverage of the mussel beds during the construction phase (mainly fines) and thereafter (mainly sand).

During the construction phase, nourishment techniques will be used that restrict the amount of fines released from the nourished sediment, for instance by spouting the sediment onto the tidal shoal during low tide only. Also suspended sediment concentrations will be monitored continuously during nourishment operations, and eventually construction operations will be stopped when suspended sediment concentrations exceed a threshold value. It is expected that suspended sediment concentrations will not increase a lot, because of the relatively coarse sediment (D_{50} between 0.18 and 0.40 mm) that will be used for the nourishment, containing very little silt (0.5–3.0%). The possible, temporary increase in suspended sediment concentrations is taken care of during the nourishment construction and monitoring, and not part of the design process.

Sessile benthos organisms such as mussels and oysters can cope with sediment deposition of only 1–2 cm (Essink, 1999). Based on experience with the Galgeplaat nourishment (Van der Werf et al., 2015), the migration of Roggenplaat bedforms (Fig. 3) and computations of the initial morphological development (Section 4.4), we estimate that the nourishment sand will move with a rate of ~1–10 m/year in the dominant, northern/northeastern, transport direction. This corresponds to a maximum distance of 200 m during a typical 20 year nourishment lifetime. A buffer of 200 m was added to further limit the risks, leading to the exclusion of areas within 400 m from the mussel beds (Fig. 4A). An area near the two drainage channels was also excluded (see further), as to diminish the possible outflow of fines through these channels in the direction of the mussel plots.

3.3.2. Resting areas of seals

Harbour seals and grey seals often rest and give birth to pups at the banks of the two main drainage channels of the Roggenplaat (Arts et al., 2017), see Fig. 4B. Dutch legislation allows approaching seals up to a distance of 1200 m. Following this rule would cancel out a too large part of the Roggenplaat as potential nourishment location. A field experiment was conducted to find a more workable distance, still respecting the seals resting areas (Dekker, 2016). This experiment demonstrated that seals raised their heads at ≈700 m distance from a small group (2–4) approaching researchers. At distances of ≈400 m seals started to move. Based on this experiment it was chosen to exclude areas within 600 m from the centre point of the two main resting areas (Fig. 4B).

3.3.3. Oyster reefs

Oyster reefs, mixed with blue mussels, are present on the Roggenplaat. They have a relatively high species richness and biomass. Furthermore, these reefs are able to protect the underlying and surrounding sediment against erosion (Walles et al., 2015). Therefore, the oyster reefs were excluded from the suitability map (Fig. 4C).

3.3.4. Tidal drainage channels

The two main tidal drainage channels are not suitable for nourishments. They will mainly discharge the nourished sediment away from the tidal flat into the channel, reducing the nourishment lifetime and possibly affecting the nearby commercial mussel beds. Therefore, the two main tidal creeks, defined through the mean low water line and a 150 m buffer zone were not included in the suitability map (Fig. 4D).

3.3.5. Erosive areas

In order to avoid a quick erosion of the nourished sand, it was decided to exclude areas with high erosion rates (> 14 mm/year based the 1990–2010 linear trend, De Ronde et al., 2013), see Fig. 4E. The erosion of the southern edge of the Roggenplaat was already present in the 19th century and is not so much related to the construction of the storm surge barrier in 1986 (De Vet et al., 2018).

3.3.6. Feasibility nourishment construction

The trailing suction hopper dredger can approach the Roggenplaat only from two sites, related to the navigation depth of the surrounding channels and the presence of the commercial mussel beds. From here the sediment pumping distance (without the need for a booster) is about 2200 m. This means it is technically feasible to nourish almost the complete Roggenplaat (Fig. 4F).

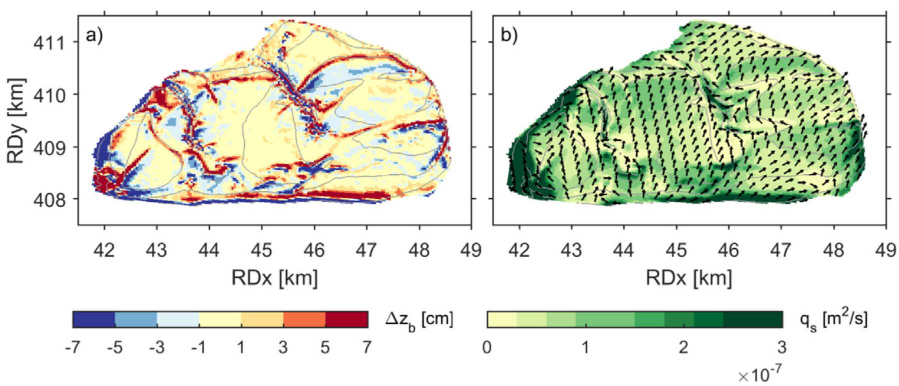

Fig. 5. Computed bed level changes (a) and net sand transport rates (b) on the no-nourished Roggenplaat during 1 year based on the May 2015 forcing and a morphological factor of 12. Only values above MLW (mean low water) are shown for clarity reasons. Red colors in (a) indicate accretion, blue colors erosion. The net sand transport vector field (b) was thinned with a factor of 30. The arrows in (b) only indicate the net sand transport direction, not the magnitude. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.4. Delft3D numerical modelling

The nourishment impact on hydrodynamics (waves and current), sand transport and short-term (1 year) morphological change was evaluated with a 2DH (two-dimensional, depth-averaged) Delft3D morphodynamic model (Lesser et al., 2004). The computational domain covers the western part of the Eastern Scheldt with a maximum grid size resolution of 30 m at the Roggenplaat. The model is forced by time series derived from nesting within larger models. Wind and offshore wave forcing were based on measured time-series. The single-fraction (D_{50} = 0.21 mm) sand transport was computed solving the advection-diffusion equation for suspended sand concentrations in combination with the Van Rijn (2007a, b) transport formulas. See De Vet et al. (2018) for more details on the model set up.

The model was validated based on field measurements using a 1-month velocity data set at 16 locations and a 2-months wave height data set at 3 locations on the Roggenplaat. The root-mean-squared deviations ranged between 3.5 and 7 cm/s and 4.2–7.0 cm, respectively (see De Vet et al., 2018 for more details). Fig. 5 shows the computed net sand transport rates and bed level change for the May 2015 forcing with wind conditions representative for the 2011–2015 period. This corresponds to 1 morphological year using a scale factor (MorFac) of 12. The net transport is predominantly in north-eastern direction and the higher parts of the Roggenplaat migrate in the same direction, in accordance with the observations (Fig. 3). The computed bed level changes are larger than observed due to model artefacts. Therefore, we used the Delf3D model to evaluate the nourishments in a relative sense (compared to the no-nourished case), in conjunction with system understanding and expert judgement.

3.5. Simplified approach to predict future loss of intertidal area

The Delft3D model is capable of predicting the short-term nourishment impact in a qualitative sense, but less suited to predict the long-term (i.e. 25-year) evolution of the targeted 50–80% exposure time area. This is because the complex morphodynamic interaction processes cause a relatively large model uncertainty and long computation times.

Therefore, we investigated the evolution of the 50–80% exposure time area using a simplified approach. The main assumptions are that i) the average lowering rate of the Roggenplaat is spatially uniform, ii) the relative (with respect to mean sea level) erosion of the Roggenplaat is due to a constant SLR and bed level erosion rate, iii) the bed level erosion rate is not affected by the nourishment. The first assumption is supported by the evolution of the Roggenplaat hypsometry between 1990 and 2013 (see De Vet et al., 2017). The Delft3D model results showed that the nourishment only has a local impact on the morphodynamics (see Fig. 9), supporting the third assumption. We take a 0.4 cm/year future SLR (KNMI, 2015) and a 0.5 cm/year erosion rate based on the observed 1990–2010 evolution (De Ronde et al., 2013). These are possibly conservative estimates, as the current SLR is 0.2 cm/year and the erosion seems to have slowed down since around 2010 (see e.g. Fig. 3). We have preferred the 1990–2010 erosion trend over the 2010–2014 trend as it is based on more data points over a longer period. The erosion could be temporary slowed down between 2010 and 2014, similar to the period 1995–2001.

Under these assumptions, we predicted the evolution of the no-nourished/nourished Roggenplaat by shifting the bathymetry vertically down with a rate of 0.9 cm/year (0.4 cm/year future SLR + 0.5 cm/year erosion rate). From this we derived the required development of the 50–80% exposure time area, and other areas as well. The 0.9 cm/year rate implies 20 cm relative erosion between 2013 (latest bathymetry) and 2035 (target year). The nourished sand is most effective when placed in regions that will fall below the 50–80% exposure time area in 2035, if no measures are taken. This implies that nourishments are most effective below the current 50% exposure time elevation, (NAP -0.04 m) plus the expected 20 cm erosion, thus below NAP +0.16 m (Fig. 6). Section 4 elaborates further on how this simplified approach was used to design and evaluate the nourishment design.

4. Roggenplaat nourishment design

4.1. Nourishment alternatives

The total nourishment volume is fixed (see Section 3.1); the nourishment design variables are location (restricted by the suitability map and anticipated future bed levels, Fig. 6), height and shape. With this in mind we generated three nourishment alternatives with different design principles (Fig. 7):

1. *Sand Ridge.* Two ridges of sand (top at NAP +0.55 m) that directly increase the 50–80% exposure time area.
2. *Sand Relief.* Ten nourishment elements (top at NAP +0.48 m) that directly increase the 50–80% exposure time. The sheltered areas between the elements are intended to encourage ecological recovery.
3. *Sand Source.* Two high (NAP +1.7 m) sediment sources to feed the

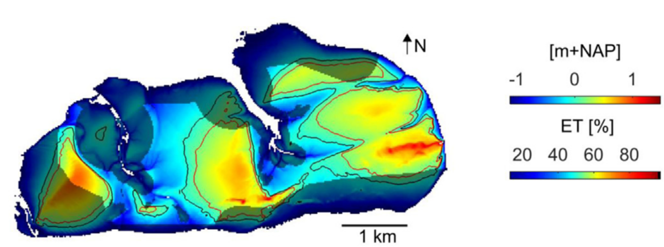

Fig. 6. Roggenplaat 2013 bathymetry with 50% exposure time contour lines (black) plus the expected 20 cm relative erosion between 2013 and 2035 (red). The shaded regions are excluded from nourishing based on the suitability map (see Fig. 4). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

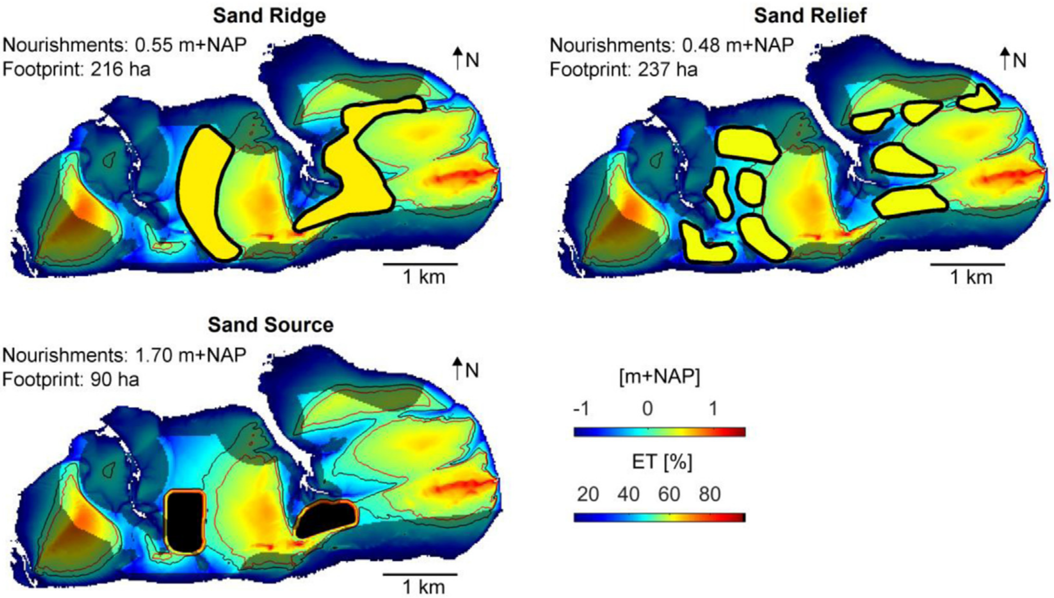

Fig. 7. The nourishment alternatives Sand Ridge, Sand Relief and Sand Source on top of the 2013 bathymetry with 50% exposure time contour lines (black) plus the expected 20 cm relative erosion between 2013 and 2035 (red). The shaded regions are excluded from nourishing based on the suitability map (see Fig. 4). The Sand Source nourishment has a black colour because its height is off scale. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Roggenplaat naturally, and with a relatively small footprint to have a minimal initial ecological impact.

4.2. Evaluation alternatives

Table 1 shows the characteristics and performance indicators (based on the evaluation framework described in Section 3.2) of the nourishment alternatives, as well as of the no-nourishment reference scenario. The key indicator is the intertidal area with a 50–80% exposure time in 2035. If this number is smaller than the 2010 value, the nourishment design is rejected. The other two indicators are the nourishment footprint (smaller footprint is considered positive, because of potentially faster ecological recovery) and the nourishment circumference (longer circumference is considered positive, because it means more feeding hotspots for wading birds). These three indicators, combined with expert judgement, are used to score the ecological and morphological aspects of the nourishment alternatives. Finally, the relative construction costs were estimated by a contractor.

The Sand Source alternative, although having a small footprint and the lowest costs, appears to be an unsuitable design. By the year 2035 the area with 50–80% exposure time in this alternative will have fallen to 442 ha, which is 164 ha less than targeted for. These intertidal areas were computed using the simplified model approach as described in Section 3.5. This ignores effects of horizontal sediment spreading (see Section 3.3). Even with a 200 m radial sand spreading (upper limit), the Sand Source alternative does not result in a sufficient increase of intertidal area with 50–80% exposure time. The dynamics are too low to anticipate on natural sediment spreading and not to put the sediment at

Table 1
Characteristics, performance indicators and scores of the Roggenplaat shoal nourishment alternatives and designs, and of the reference, i.e. no-nourishment scenario. The key performance indicator, the area with 50–80% exposure time, was estimated using a simple modelling approach. The scores on the morphological aspect were based on this key indicator and on expert judgment using Delft3D numerical model simulations, amongst other things. The ecological scores followed from an expert judgement based on the area with 50–80% exposure time, the nourishment footprint, the nourishment circumference, and other considerations. The relative construction costs were estimated by a contractor.

	Reference	Nourishment alternatives			Nourishment designs (Sand Relief)		
	No nourishment	Sand Ridge	Sand Relief	Sand Source	A	B	C
Nourishment characteristics							
Volume (M m^3)	n/a	1.3	1.3	1.3	1.3	1.3	1.3
# elements	n/a	2	10	1	6	6	6
Height [m NAP]	n/a	+0.55	+0.48	+1.70	+0.48	+0.30/+0.67	+0.20/+0.77
Area 50–80% exposure time (ha)							
Reference year (2010)	606	606	606	606	606	606	606
Pre-nourishment design (2013)	611	611	611	611	611	611	611
Post-nourishment design (2013)	611	741	752	631	755	749	755
Target year (2035)	421	607	612	442	607	619	624
Difference between target and reference year	**−185**	**+1**	**+6**	**−164**	**+1**	**+13**	**+18**
Other performance indictors							
Footprint (ha)	n/a	216	237	90	225	231	232
Circumference (km)	n/a	12	18	4	17	17	17
Relative scores							
Morphological aspect	n/a	0	+	–	++	++	+
Ecological aspect	n/a	0	+	–	+	++	++
Construction costs	n/a	+	0	++	+	+	+

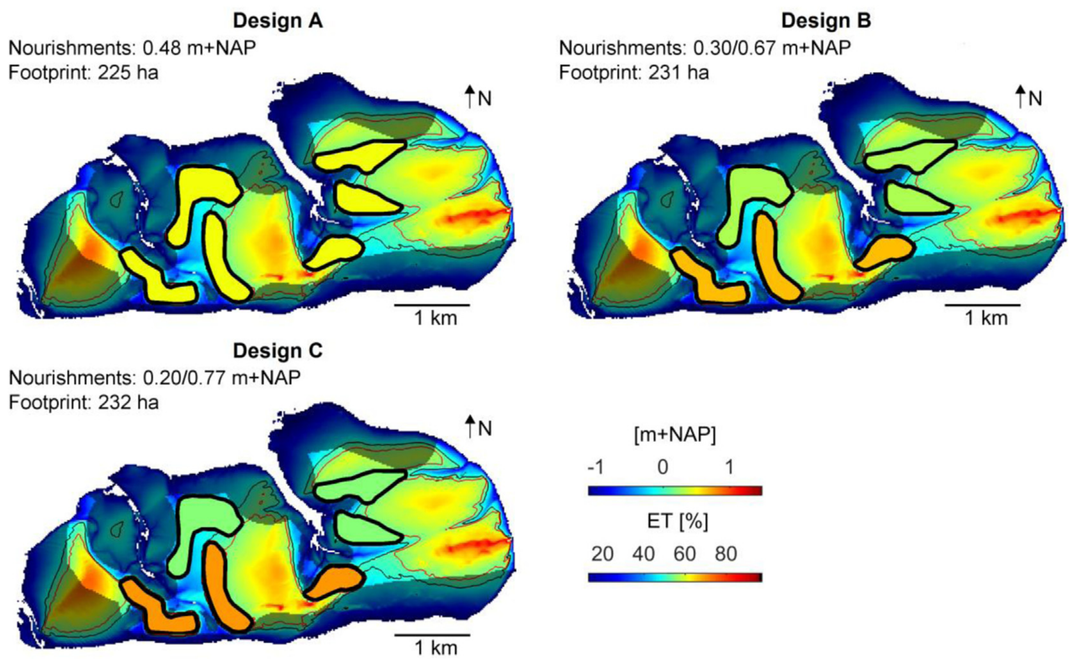

Fig. 8. The nourishment Designs A, B and C on top of the 2013 bathymetry with 50% exposure time contour lines (black) plus the expected 20 cm relative erosion between 2013 and 2035 (red). The shaded regions are excluded from nourishing based on the suitability map (see Fig. 4). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

the right place immediately.

The Sand Ridge and Sand Relief alternatives are expected to meet the required 606 ha 50–80% exposure time area until 2035. The Sand Ridge alternative consists of fewer elements than the Sand Relief alternative and is consequently less expensive to construct. The morphological development (somewhat stronger sediment spreading) and longer sand nourishment circumference of the Sand Relief alternative are expected to provide better ecological boundary conditions than the Sand Ridge alternative. Therefore, the Sand Relief nourishment alternative was selected as the preferred alternative, and was studied in more detail.

4.3. Nourishment designs

The Sand Relief nourishment alternative was further optimized. The number of nourishment elements was decreased from 10 to 6 to reduce construction costs. Furthermore, the nourishment locations were adjusted to slow down the water drainage and sediment transport from the tidal flat and to even further reduce the potential risk of sediment coverage on the mussel beds. The resulting Designs A, B and C only vary in nourishment height (Fig. 8). The higher southern nourishment elements are intended to shelter the lower northern elements by wave damping, and the height diversity could also provide additional ecological diversity and benefits. Differences in exposure time can lead to a larger differentiation in benthic community structure, and higher nourishment elements make them faster accessible for wading birds during low tide, and could serve as a hub from which the birds can start to forage on the lower parts.

4.4. Morphodynamic impact nourishment designs

Fig. 9 shows the computed bed level changes during a 1-year period for nourishment Design B. The figure shows that the nourishment elements mainly have a local impact and that bed level changes of the nourishment are of the same order of magnitude as the no-nourished Roggenplaat (Fig. 5). The southern nourishment edges erode, whereas the northern edges accrete. This implies a migration in northern direction, in line with historically-observed bed level changes (Fig. 3) and the dominant net transport direction (Fig. 5). The northward transport of eroded sand also causes the nourishments to change shape and heighten locally. The southern nourishment elements are exposed to the dominant southwesterly wind and wave direction and thus more dynamic than the more sheltered northern elements. This effect is strongest for the nourishment designs with higher sourthern elements, i.e. Design B and especially Design C. Therefore, it is expected that the higher southern elements will erode faster than the lower northern nourishments elements, and that this effect will be strongest for Design C.

4.5. Evaluation nourishment designs

Table 1 shows the characteristics and performance indicators of the nourishment designs. The estimated nourishment costs did not differ between the designs. Designs B and C both provide more variety in height which can have a positive effect on biodiversity compared to Design A. The expected erosion reduction of the northern nourishment elements in Design B and Design C compared to Design A is beneficial, while the southern nourishment elements are expected to erode faster. In case of the expected 0.2 m relative erosion, the (low) northern nourishments of Design C are in 2035 just high enough to contribute to the 50–80% exposure time area, making this not a very robust design. Therefore, Design B is preferred for the sand nourishment at the Roggenplaat.

5. Discussion

We developed an integral approach for designing nourishments on intertidal flats. The novelty of the nourishment design process is threefold. First, we followed a structured work flow with explicit steps to go from the objective to the preferred design. Second, system understanding based on a combination of monitoring data, numerical modelling and expert judgement played a crucial role. Third, we evaluated the nourishment designs on a range of criteria, combining economical, ecological, morphological and technical considerations.

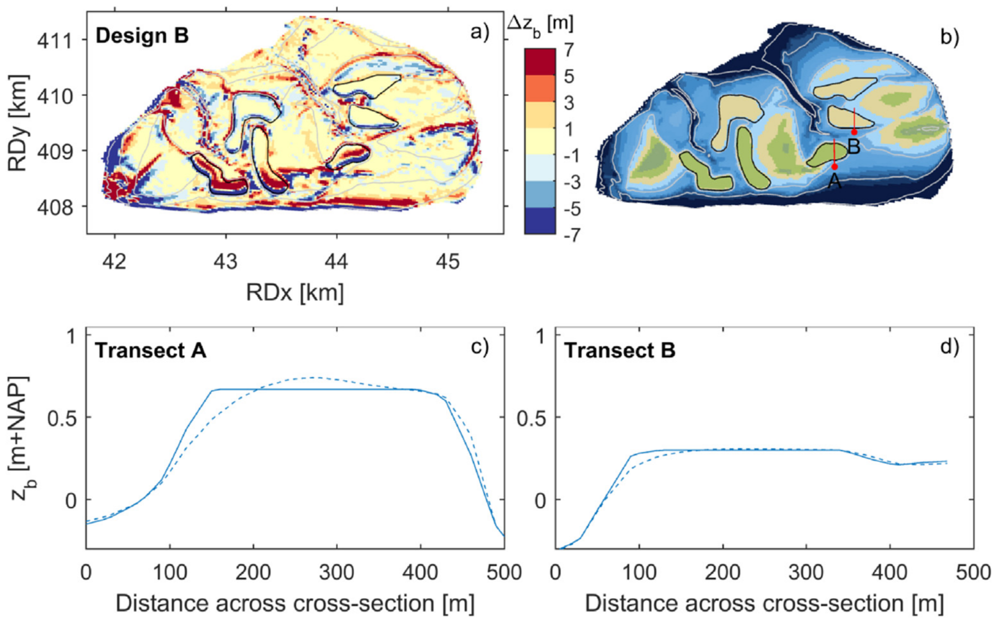

Fig. 9. A: Computed bed level changes of nourishment Design B during a 1-year period. Red colors indicate accretion, and blue colors erosion. Only values on the Roggenplaat values are shown for clarity reasons. The black lines indicate the contours of the nourishment elements. B: location of transects A and B on top of the nourishment Design B bathymetry. C: morphological development of Transect A, D: morphological development of Transect B. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

We studied the impact of nourishment designs on the short-term Roggenplaat morphodynamics with a process-based Delft3D model with a grid resolution of 30 m. This resolution is too coarse to resolve local features such as small tidal creeks and other bed level undulations. However, we believe that the main mechanisms controlling the Roggenplaat morphodynamics are captured, illustrated by the good reproduction of measured current velocities and wave heights on the shoal (De Vet et al., 2018) and the qualitative agreement with bedform migration and net sand transport direction, known from morphological data. Long-term (years) Delft3D morphological simulations require long computation times and model results are inherently uncertain. Therefore, we estimated the long-term intertidal area development using a simplified approach, assuming a uniform loss of intertidal area due to the combined effect of SLR and erosion. This approach is supported by historical data, and the short-term process-based model simulations. In this way we were able to properly evaluate the long-term morphological impact of the nourishment alternatives in order to choose the preferred design.

The Roggenplaat nourishment mainly has a conservation goal to preserve sufficient foraging grounds for birds that feed during low tide on benthic macrofauna. As there is limited experience with such measures, several uncertainties still exist with respect to the ecological development. Exposure time is one of the critical elements that determines the suitability of an intertidal flat as foraging ground for wading birds, besides food availability, sediment composition and behavior of the bird species themselves. The foreseen Roggenplaat nourishment targets the areas with an exposure time of 50–80%, aiming at preserving it until 2035. This is based on the historical development and current sea level rise scenarios, but changes in these might result in changes in the erosive trend. When erosion appears more rapidly, extra nourishments might be needed over time.

Although benthic animals live in sediment and crawl through it, they are sensitive to extreme burial events as occur during sediment nourishments (Speybroeck et al., 2006; Van der Werf et al., 2015). As a result, sediment nourishments will initially create large areas void of any living benthos. This is from an ecological perspective a highly undesirable situation for two important reasons. Firstly, for a certain period after the nourishment, the area has lost its function as feeding area for birds (Peterson et al., 2006), which will persist till the benthic community has recovered (up to 3 years in the Galgeplaat pilot nourishment, Van der Werf et al., 2015). This implies that a nourishment cannot be carried out over the whole surface of a tidal flat without impacting the bird community. In case of the Roggenplaat, the nourishment footprint (230 ha) is ~40% of the current 50–80% exposure area and ~15% of the total Roggenplaat intertidal area. In this way a large part of the Roggenplaat is kept intact for bird feeding while the nourished area is recovering over time. Secondly, the recovering benthic community might differ from the original community present, because of changes in exposure time and sediment composition (see also Van der Werf et al., 2015). This might change the food availability for birds, which in turn could lead to changes in numbers of certain bird species (positive as well as negative). In addition, creating large areas void of any living benthos typically offers opportunities to invasive species to expand their habitat. For example, at the Oesterdam sand nourishment high densities of the invasive manila clam *Ruditapes philippinarum* were observed a year after the nourishment (Boersema et al., 2018). The latter has also been clearly shown for hard engineering constructions in coastal waters, which can act as stepping stones facilitating invasions (Airoldi et al., 2005; Bulleri and Airoldi, 2005). For both reasons, it is desirable to develop methods that minimize the period during which the nourishment is without benthic life.

The concept of priming which we define as "giving an ecological imprint to an area void of a living benthic community due to human interventions" may offer an opportunity to minimize the risk of invading species to come in, community composition to shift and reduce the down-time as feeding habitat. The concept entails that the benthos-rich 30 cm high top-layer of the original tidal flat is removed before being nourished, and moved on top of the nourishment. In practice, this requires highly-organized working schemes. This may for example be envisioned by applying the sand nourishment as a series of bands. This approach will allow a band to be first covered with "nourishment sand", where after this band can be finished by adding a benthos-rich priming-layer. This priming-layer can be obtained by removing the benthos-rich 30 cm top-layer from the band directly adjacent to the nourished band, and which is the band that will be nourished next. To our knowledge, this priming approach has not yet been tested on a field-scale. Therefore, it is proposed to carry out a large experimental scale priming to test if we can accelerate and steer the development of a benthic community by priming.

More general, we emphasize the need to monitor the Roggenplaat nourishment in detail. This should include the hydrodynamics, the morphological development and the ecological development (benthos and birds). The monitoring should also target the mussel culture plots, as to demonstrate that the nourishment does not harm mussel production. The monitoring should ideally last for a period of at least 5–10 years during which the main developments are expected to take place. This will create a very useful database in order to assess to what extent the Roggenplaat nourishment meets its objective. More general, the data can be used to increase and improve our understanding and modelling of intertidal shoal morphology and ecosystem recovery dynamics. It is planned for to carry out such a monitoring program.

6. Conclusions

We have developed an integral approach for designing intertidal shoal nourishments, and demonstrated it for the design of the nourishment of the Roggenplaat intertidal shoal. It consists of the following steps:

1. Characterization of the Roggenplaat morphology and ecology based on existing knowledge and new monitoring data.
2. Translation of the main nourishment objective into an evaluation framework. The intertidal area with 50–80% exposure is the key indicator for the foraging function. The nourishment footprint and circumference are indicators of initial ecological disturbance and ecological recovery time-scale, respectively.
3. Construction of a suitability map indicating potential nourishment areas, based on morphological, ecological, economical and technical considerations.
4. Generation of nourishment alternatives and designs.
5. Calculation of the nourishment impact on short-term hydro-morphodynamics using a Delft3D numerical model.
6. Prediction of long-term future shoal development using a simplified approach.
7. Integral evaluation of the nourishment alternatives leading to the preferred design using the evaluation framework. This includes an expert judgement of the morphological and ecological aspects, and an estimation of the construction costs.

The final nourishment design consists of 6 nourishment elements. The nourishment height is such that the intertidal area with 50–80% exposure time is directly above the target value and is designed to stay so until 2035. The higher southern nourishment elements are intended to shelter the lower northern elements by wave damping, and the height diversity also provides ecological diversity.

7. Lessons learned from design process

The integrated approach enabled us to make a design that is expected to fulfill the Roggenplaat nourishment objective, accounting for ecological, morphological, economical and technical aspects. This integrated approach could form a basis for other intertidal shoal nourishment designs. In particular, we learned the following generic lessons:

- System understanding at the right scale is essential to make a good nourishment design. Ideally, system understanding is based on a combination of monitoring data, numerical modelling and expert judgement.
- A combination of a detailed, process-based short-term numerical modelling and a simplified data-driven approach to estimate the long-term intertidal area evolution enabled the evaluation of the morphological aspects of the nourishment designs.
- Translation of the objective in quantifiable indicators allows transparent and objective evaluation of the nourishment design. Furthermore, it guides the cooperation between multidisciplinary researchers and serves as a means of communication with stakeholders.
- Expert judgment is an important unavoidable element in the evaluation framework, as long-term predictions of morphological and ecological developments remain uncertain.
- A nourishment suitability map avoids unrealistic nourishment areas, limits the solution space, and is a powerful stakeholder communication tool.

Author contributions

J.J. van der Werf coordinated the research and was main author of Sections 1, 3.1, 4.1, 4.3, 5, 6 and 7. P.L.M. de Vet wrote Section 2 (morphology) and Section 3.5. M.P Boersema wrote Section 3.3. T.J. Bouma wrote the paragraph on priming in the discussion (Section 5), based on research by L.M. Soissons. A.J. Nolte wrote Section 3.2. R.A. Schrijvershof wrote Sections 3.4 and 4.4. J. Stronkhorst wrote Sections 4.2 and 4.5. E. van Zanten initiated this study and played an indispensable role in the nourishment design process. T. Ysebaert wrote Section 2 (ecology). All authors contributed to the introduction, discussion and conclusions.

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