Memo

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1 of 29

Subject
TKI Dutch Coastline Challenge: morphological and ecological evaluation of nourishment concepts.

Contents

Reviewing procedure.

This memo is reviewed internally by the DCC project team at TUDelft (Bart van Westen, Arjen Luijendijk and Matthieu de Schipper) and aims to support the overall DCC report (DCC Syntheserapport 2023; in Dutch). Further details on the workflow and the model setup are available from the author upon request.

Samenvatting (NL)

Het algemene doel van het Topconsortia Kennis & Innovatie project Dutch Coastline Challenge (in het vervolg TKI-DCC) is om bouwstenen aan te leveren aan klimaatneutraal en opschaalbaar kustonderhoud door het ontwerpen en evalueren van concrete alternatieven voor het kustvak IJmuiden-Texel tot 2035. Hierbij richt het project zich op (1) duurzame en opschaalbare onderhoudsconcepten en uitvoeringsmethoden voor het kustonderhoud en daarbij passend (2) duurzaam samenwerken in de driehoek (overheid, bedrijfsleven en kennisinstellingen) op basis van slimme samenwerkings- en contractvormen.

Binnen werkpakket 2 (WP2) staat de volgende vraag centraal: Welke alternatieve onderhoudsconcepten zijn beschikbaar en wat is hun impact op het fysisch en ecologisch systeem? Deze vraagstelling wordt onderzocht aan de hand van drie taken:

1. Het maken van een *menukaart* van alternatieve concepten en hun mogelijke impact,
2. het evalueren van de huidige morfologische *voorspelkracht* en
3. het evalueren van de *impact* van enkele geselecteerde kustonderhoudsconcepten.

Deze memo behelst het laatste van de bovengenoemde drie punten. De morphologische en ecologische impact van enkele kustonderhouds projecten zijn gekwantificeerd voor zover dit mogelijk is met een numeriek model. We hebben de evaluatie van de concepten uitgevoerd aan de hand van een morfologisch model, Delft3D Flexible Mesh (Technische Universiteit Delft, 2023b; 2023c). Met behulp van geaggregeerde indicatoren (Technische Universiteit Delft, 2023d) is inzicht gekregen in de verschillen tussen de concepten. Deze inzichten zijn een belangrijke bron voor het afwegingskader van het DCC project.

In deze evaluatie staat de morfo- en ecologische evaluatie van de kustonderhoudsconcepten centraal en daarvoor zijn berekeningen bij de locatie Egmond-Bergen gebruikt. Er zijn drie groepen aan suppletieconcepten doorgerekend.

De eerste groep bestaat uit suppletieconcepten met een relatief klein suppletievolume (4 jaar, 0.125 mln m^3/jaar). De suppletieconcepten in de tweede groep hebben een groter volume (o.a. vooroeversuppletie, Zandmotor, continue suppletie; 4 jaar, 0.625 mln m^3/jaar) om het hele dwarseprofiel op termijn te laten meegroeien met de sedimentbehoefte. Om meer inzicht te krijgen in de ontwikkeling van grootschalige suppleties die de aanliggende kust voeden door kustlangse processen, is er een derde groep aan simulaties uitgevoerd met de focus op grootschalige suppleties (mega suppleties, kabel hopper; 10 jaar, 0.75 mln m^3/jaar).

Na de bewerking van de modeluitkomsten zijn de volgende kustindicatoren gekwantificeerd:

- Voorkomen van kusterosie
- Veranderingen in de oppervlaktes van de verschillende ecotopen
- Bedelving van het bodemleven
- Veranderingen in ruimte voor recreatieve functies
- Uitvoerbaarheid van de kabelhopper met betrekking tot de bodemveranderingen

De evaluatie heeft volgende hoofdboodschappen heeft opgeleverd:
Reguliere suppleties maken lokaal maatwerk mogelijk omdat suppletievolume, locatie (kustlangs en kustdwars) en tijdstip van aanbrengen vrij precies afgestemd kunnen worden op de lokale behoefte. De berekeningen bevestigen dat suppleties op het strand direct bijdragen aan kustlijnonderhoud, want al het zand wordt direct in de BKL-zone aangebracht. Het zand dat bij vooroeversuppleties wordt aangebracht heeft tijd nodig om in die zone terecht te komen. Een problematische BKL-overschrijding kan ze niet direct voorkomen. Een continue suppletie met een lozingspunt op het strand, zoals hier getest, creëert een sterke kustlijn kromming, maar reikt in de simulatie na 4 jaar niet veel verder dan 4 km van het lozingspunt. Dit onderstreept dat er lokaal versterking kan worden uitgevoerd met deze methode, maar dat

voor grotere kustlangse gebieden met een sedimentvraag wellicht naar andere alternatieven gekeken moet worden.

Met megasuppleties is beperkte ervaring langs de Nederlandse kust. De Zandmotor in Delfland (aangelegd als strandsuppletie/schiereiland) is het meest bekend. Uit de modelsimulaties blijkt dat, bij een ontwerplevensduur van 10 jaar, de voeding van de omliggende kust op lange termijn vergelijkbaar is voor alle drie de varianten van een megasuppletie op de ondiepe vooroever of strand. Voorwaarde is wel dat de suppletie in de actieve zone (niet dieper dan ca 8 à 10 meter) is aangebracht. De drie varianten onderscheiden zich wel in ‘hoe de kustlijnontwikkeling verloopt’ (bijv. hoe de breedte van het strand zich over de tijd ontwikkelt). Ook bij megasuppleties geldt dat suppleren op het strand sneller bijdraagt aan handhaving van de kustlijn. Dit zal in de praktijk geen belangrijk argument zijn, omdat megasuppleties worden aangelegd vanwege hun langetermijneffect, al dan niet in combinatie (zoals bij de zandmotor bij Delfland) het doel om een concreet nieuw (maar wel tijdelijk) landschap te maken. Aangezien de kustlangs verspreiding van megasuppleties langzaam is, zal er ter plekke gedurende lange tijd sprake zijn van (tijdelijke) uitbouw van de kust. Zowel in de simulaties als in de praktijk van de Zandmotor is te zien dat de suppletie in de eerste tien jaar na aanleg nog niet volledig is verspreid. Om een groter deel van de kust te voeden met zandmotoren zullen deze megasuppleties dus op meerdere verspreidingslocaties en met een bepaalde frequentie en bijbehorend volume in de tijd moeten worden uitgevoerd. Dit zal ongetwijfeld gepaard blijven gaan met lokale uitbouw. De modelsimulaties laten zien dat de uiteindelijke kustlangse verdeling van de continue suppletie vergelijkbaar is met dat van een megasuppletie. Het grootste deel van het materiaal ‘hoopt zich echter op’ bij de locatie van verspreiden als dit lozingspunt op dieper water is geplaatst. Zonder aanvullende maatregelen zal dit op termijn een knelpunt vormen voor de aanvoer van zand, zowel via een Cablehopper (beperkte diepgang) als een pijplijn (opstopping).

De ecologische effecten op de vooroever zijn bedelving door vooroeversuppleties (sterfte van bodemdieren en tijdelijke afname foerageergebied) en de kans op langjarige veranderingen in ecotopen.
Om de effecten door bedelving te kunnen kwantificeren is in dit project een methodiek ontwikkeld. Hiervoor is een bedelvingsequivalent, de ‘Bentimeter’ ontwikkeld waarmee het oppervlak met ecologische schade door bedelving (ha) over de tijd wordt berekend. Dieper in het kustprofiel is een hogere dichtheid aan benthos en zijn de soorten minder goed aangepast aan verstoring. Daardoor hebben dieper gelegen suppleties een grote negatieve impact dan suppleties die dichter bij de kust worden aangebracht. Dit is in de resultaten te zien door de relatief lage waarden voor strandsuppleties in vergelijking met vooroeversuppleties. De schaal en terugkeertijd van suppleties speelt een rol in de waarde voor schade door bedelving. Voor kleine suppleties is de benthos bijna hersteld na een suppletiecyclus. Op lange termijn kunnen er wel negatieve effecten zijn (bijv. door verandering van sedimentsamenstelling). Megasuppleties hebben een lage frequentie, maar wel een grootschalige bedelving met langere hersteltijd. De ecotopen veranderen dusdanig dat een herstel naar het systeem zoals het er was voor de aanleg van de suppletie niet wordt verwacht. Continue suppleties zijn een interessant alternatief vanuit het perspectief van bedelving, dat maar op een klein oppervlak plaats vindt. Continue suppleties hebben daardoor de laagste waarde voor ecologische schade gedurende de levensduur van de suppletie. De belangrijkste negatieve impact is de indirecte bedelving door zandtransport door golven nabij de suppletielocatie. Veranderingen in diepte zijn meer gradueel, met de verwachting dat soorten daar beter tegen bestand zijn.

Tenslotte de op langjarige veranderingen in ecotopen. Hiervoor is gekeken negen ecotopen, ingedeeld op diepte en bodemschuifspanning. Met de methode van Van Zanten (2016) is berekend hoe het oppervlak van de ecotopen verandert bij de aanleg van verschillende suppletieconcepten. Megasuppleties hebben de grootste impact op het oppervlak ecotopen. Al bij de aanleg is er een grote verandering, en gedurende de ontwikkeling van de suppletie veranderen de oppervlakten van ecotopen mee. Vooral het oppervlak aan hoger gelegen ecotopen neemt toe. Uit de resultaten blijkt dat beschutte subtidale ecotopen (zoals de lagune op de Zandmotor) alleen voorkomen bij megasuppleties met een beschutte zone, en ze bestaan ook dan alleen tijdelijk. Oppervlaktes van ecotopen in de brandingszone variëren sterk met het suppletieconcept. Reguliere suppleties hebben weinig impact op de oppervlakten van ecotopen. Er zijn weinig veranderingen in diepte en bodemschuifspanning in deze categorie. Na 4 jaar is de diepte en bodemschuifspanning vergelijkbaar met de situatie vóór de suppletie.

1. Introduction

The overall objective of the Top consortia Knowledge & Innovation project Dutch Coastline Challenge (hereafter, TKI-DCC) is to provide building blocks for climate-neutral and scalable coastal maintenance by designing and evaluating concrete coastal maintenance alternatives for the IJmuiden-Texel coastal section until 2035. The project will focus on (1) sustainable and scalable coastal maintenance concepts and (2) sustainable collaboration in the “triangle” (government, private sector, and knowledge institutions) based on smart methods of collaboration and contracting.

Within work package 2 (WP2), the main question is: Which alternative coastal maintenance concepts are available and what is their impact on the physical and ecological system? This question will be investigated on the basis of three tasks:

- Generating a set of alternative nourishment concepts and their potential impact.
- Evaluating the morphological predictive skill of current state-of-the-art modelling.
- Evaluating the morphological and ecological impact of selected coastal nourishment concepts.

This memo is the second of five memos that collectively constitute the deliverables from Work Package 2 (WP2). These memos are (see Figure 1):

- Memo 1 (M1): Description of the inventory of nourishment alternatives. (*in Dutch: Inventarisatie kustonderhoudsconcepten voor de Dutch Coastline Challenge*)
- Memo 2 (M2): Description of the setup of the Delft3D Flexible Mesh model and validation of the hydrodynamics.
- Memo 3 (M3): Evaluation of the morphological predictive skills of the Delft3D FM model based on simulations of the Sand Engine.
- Memo 4 (M4): Morphological and ecological indicators for the Dutch Coastline Challenge nourishment evaluation (M5).
- Memo 5 (M5): morphological and ecological evaluation of nourishment concepts.

Several alternative nourishment concepts are presented (*Memo 1*). To predict the (eco)morphological development of these alternatives, a process-based model is set-up (*Memo 2*) and morphologically validated (*Memo 3*). Multiple indicators are defined (*Memo 4*) and used to evaluate a selection of alternative nourishment concepts (*Memo 5*).

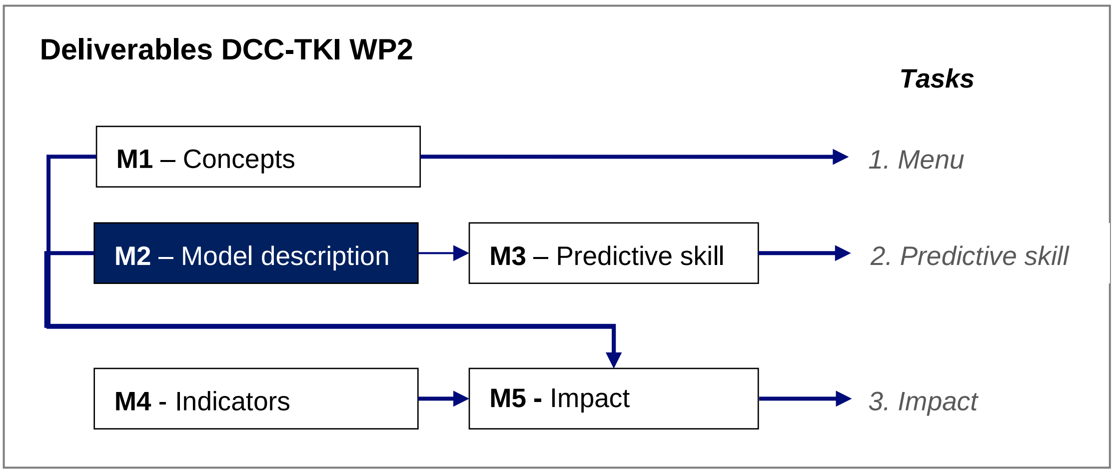


Figure 1 Overview of deliverables (memos) within the DCC-TKI project, relationship with WP2 tasks and interrelationships.

1.1 Scope

A selection of nourishment concepts is evaluated based on numerical morphodynamic simulations. The indicators on which this evaluation is based are described in Technische Universiteit Delft (2023d). This memo presents an evaluation of the most promising nourishment concepts at one location (Egmond aan Zee) for intercomparison. The model allows for intercomparisons at other locations with different conditions and possibly different concepts. However, this was not done within the timespan of this project.

Given the focus of the morphodynamic model and its limitations (Technische Universiteit Delft, 2023c) special attention is paid to nourishments that are intended to feed adjacent beaches and/or are innovative (e.g. mega feeder nourishments and continuous nourishments).

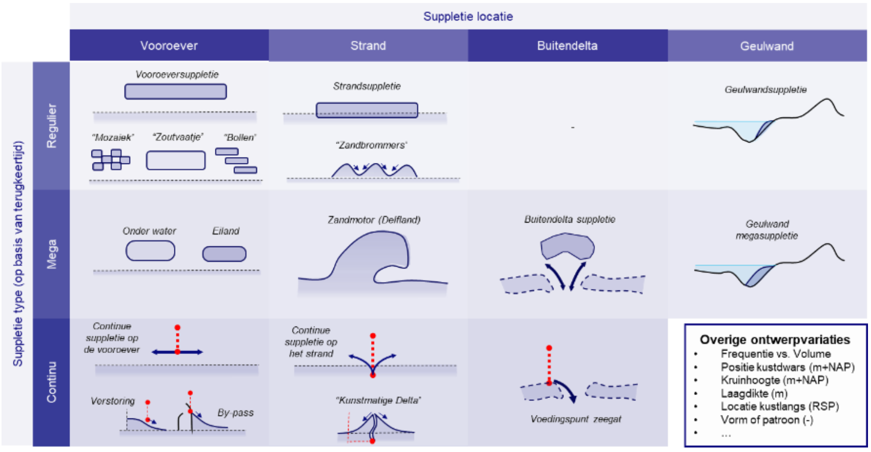


Figure 2 Overview of nourishments concepts within the DCC-TKI project (memo 1)

1.2 Reader

Based on the results of the morphodynamic predictions, a quantitative evaluation has been conducted for the following indicators, as discussed in detail in Technische Universiteit Delft (2023d):

- Preventing coastal erosion (Chapter 3)
- Ecotope surface area changes (Chapter 4)
- Providing recreational area (Chapter 5)
- Burial of ecology (Chapter 6)
- Practical feasibility (Chapter 7)

The main findings are summarised in Chapter 8.

2. Methodology

For the morphological and ecological evaluation of nourishment concepts we examine numerical model results from a calibrated Delft3D Flexible Mesh model. The validation in discussed in Technische Universiteit Delft (2023b).

Our aim is first and foremost to compare nourishments with each other such that we can use the model's capabilities best. Over a period of several months we developed 3 numerical experiments with a group of nourishments. These groups of nourishments had the following categories. Special attention is paid to nourishments that are intended to feed adjacent beaches (e.g. mega feeder nourishments and continuous nourishments):

Set 1: Small nourishments of 0.5 Mm^3 / 4 yrs
Set 2: Nourishments of 2.5Mm^3 / 4 yrs
Set 3: Large scale nourishments of 7.5 million m^3 with a 10 year lifetime

Set 1 focusses on the category 'Regular' nourishments (see Figure 2). Set 2 intends to compare across categories, comparing a regular shoreface nourishment as well as a mega feeder nourishment and continuous nourishment. Set 3 is fully focussed on the mega and continuous categories (see Figure 2).

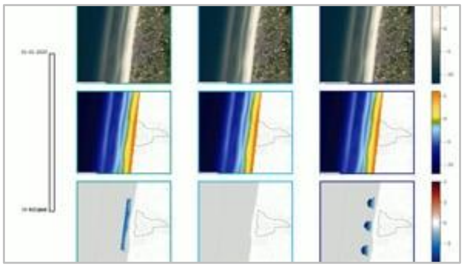
These simulation sets contain nourishments volumes increasing in size and timehorizon. With that we cover the typical beach nourishment volumes as well as the larger shoreface nourishments implemented thus far at Egmond (see Workpackage 1). As the Delft3D FM software developed simultaneously with the DCC timeline and advancing insight, the settings for these 3 simulation sets are not fully similar.

The morphological and ecological effects of nourishments are evaluated in terms of indicators outlined in Technische Universiteit Delft (2023d).

2.1 Overview of simulations

This section provides an overview of all the simulations that are carried out and accompanying underlying assumptions and model settings.

Set 1: Small nourishments of 0.5 Mm^3 / 4 year
The first set of simulations consists of small local nourishments (see Video 1 and Table 1). The objective of this set is to explore the development of a range of small-scale nourishments in their goal to counter local erosion. The considered concepts have a design lifetime (and simulation period) of 4 years and a nourishment volume of 0.5 Mm^3 (=0.125 Mm^3/year), which is based on historic beach nourishment volumes placed near Egmond.

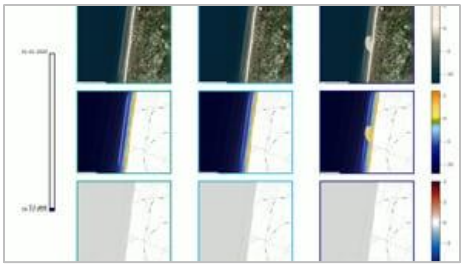


Video 1 Animation of simulation results for 4-year morphological development of three beach-type nourishments (left-to-right; regular, continuous, sand groynes) at Egmond. May also be accessed directly by going to https://vimeo.com/768646347

The simulations were carried out early in the DCC project with a slightly altered model set-up compared to the definitive model settings used in set 3. The boundary conditions are not compressed, and consequently seasonality is not included. In these simulations the longshore transport is underestimated, and only relative comparison between the nourishment concepts is examined.

Set 2: Nourishments of 2.5 Mm^3 / 4 year

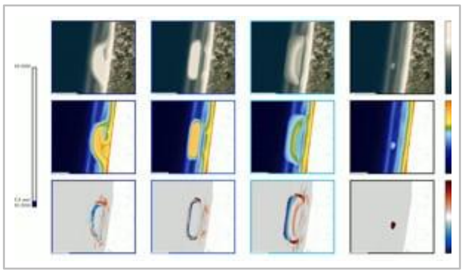
The second set of simulations consists out of larger-scale nourishments with volumes that are sufficient to lift the entire profile with the sediment deficit. This relates to the coastal foundation approach (see Video 2 and Table 1). The objective of this set is to compare the feeding functionality of three fundamentally different concepts. The design volume (=0.625 Mm^3/year) is based on historic shoreface nourishments carried out at Egmond. The concepts are simulated for the first 4 years (consistent with Set 1) although they may be planned for longer lifetimes. For a fair comparison between these concepts, the entire lifetime must be simulated. Unfortunately, this was not possible due to high computational times and model instabilities. Despite the fact that direct comparison between these simulations is not possible given the varying lifetimes, the simulation results can still provide insight into the key differences between these concepts concerning morphological behaviour. The same model set-up is applied as for the small-scale nourishments (§0).



Video 2 Animation of simulation results for 4-year morphological development of three nourishments (left-to-right; shoreface, continuous, mega) near Egmond. May also be accessed directly by going to https://vimeo.com/768648467

Set 3: Large scale nourishments of 7.5 million m^3 with a 10-year lifetime

The final group of simulations involves larger size nourishments with a time horizon that spans 10 years. The objective of these simulations is to quantify the longshore spreading of different (feeder-type) nourishment concepts. All nourishments have an anticipated design lifetime of 10 years and a total nourishment volume of 7.5 Mm^3 (± 0.15 Mm^3). These simulations were performed with the final model set-up (Technische Universiteit Delft, 2023b; 2023c), whereby the real-time (‘brute force’) boundary conditions have been applied for tides, wind, surge, and waves. Hence, these simulations include seasonality and storms in the longshore spreading.



Video 3 Animation of simulation results for 10-year morphological development of three (of the four) feeder nourishments (left-to-right; peninsula, island, submerged) and one continuous nourishment (right; cable hopper) near Egmond. May also be accessed directly by going to https://vimeo.com/767600512.

2.2 Overview of considered concepts

The table below summarizes the three different sets of nourishments considered during modelling. Note that comparisons between the three sets is not directly possible due to the different volumes applied and expected lifetimes of the concepts. Comparisons are done within a set.

Table 1 Overview of all the numerical simulations carried out for the morphological and ecological evaluation.

Simulation set	Added Volume	Simulated Period	Nourishment concepts
Set 1: Small nourishments of 0.5 Mm^3 / 4 yrs 2 km zone of interest	0.125 Mm ^{3}/ yr *or* 0.5 Mm^3 / 4 yr	4 year	Beach nourishment
			Shoreface nourishment [1]
			Continuous nourishment
			Sand Groynes
Set 2: Nourishments of 2.5Mm^3/4 yrs 10km zone of interest	0.625 Mm^3 / yr *or* 2.5 Mm^3 / 4 yr *or* 10 Mm^3 / 16 yr	4 year	Continuous
			Shoreface nourishment
			Mega nourishment [2]
Set 3: Large scale nourishments of 7.5Mm^3/10 yrs 10km zone of interest	0.75 Mm^3 / yr *or* 7.5 Mm^3 / 10 yr	10 year	Peninsula (mega)
			Island (mega)
			Submerged (mega)
			Cable hopper (continuous)

[1] This concept is not included in Video 1.

[2] The nourished volume equals 10 Mm^3 which is based on the sediment demand for ~16 year, although the simulation period is only 4 year.

Nourishment implementation
To include nourishment concepts in the model, the base bathymetry is modified. This is manually done in an iteratively manner as the dredging- and dumping functionalities in the Delft3D FM model caused issues in combination with grid. The initial bathymetries were specified as follows:

Simulation set 1 (Figure 3):

- Beach nourishment. Volume 250 m^3/m ; Alongshore length 2000m, Bed level at placement area prior to nourishment: from –3 to 1 m NAP
- Shoreface nourishment. Volume 250 m3/m; Alongshore length 2000m, Bed level at placement area prior to nourishment: from –6 to -4 m NAP
- Continuous nourishment. Volume 0.125 Mm ^{3}/ yr at one location, Bed level at placement area prior to nourishment: at 0 m NAP
- Sand Groynes nourishment. Alongshore length 3x 400m, Bed level at placement area prior to nourishment: from –3 to 1 m NAP. Three sandy outcrops at 900 m apart in the alongshore direction

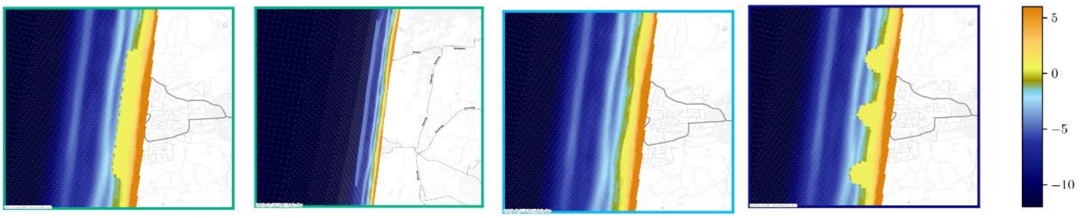


Figure 3 Initial bathymetries for set 1 (beach, shoreface, continuous, groynes).

Simulation set 2 (Figure 4):

- Shoreface nourishment. Volume 280 m^3/m; Alongshore length 9000m, Bed level at placement area prior to nourishment: from –6 to -4 m NAP
- Continuous nourishment. Volume 0.625 Mm^3 / yr split over two outflow locations 5500 m apart in the alongshore direction. Bed level at placement area prior to nourishment at –4 m NAP.
- Mega nourishment. Volume 6000 m^3/m (max); Alongshore length 3000m, Bed level at placement area prior to nourishment: from –6 to 3 m NAP.

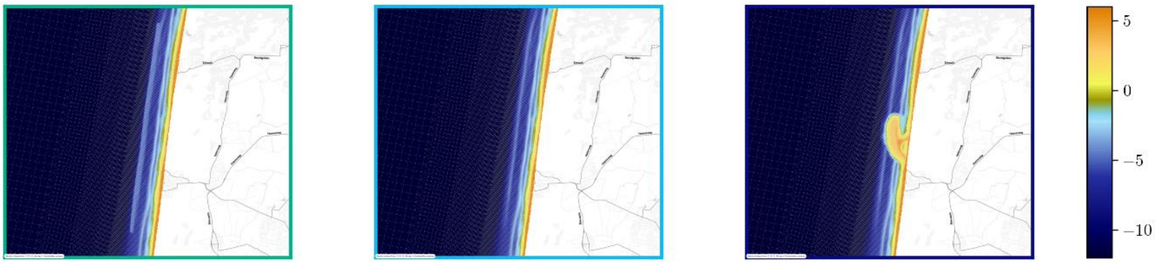


Figure 4 Initial bathymetries for set 2 (shoreface, continuous, mega)

Simulation set 3 (Figure 5).

- Peninsula feeder nourishment. Volume 6000 m^3/m (max); Alongshore length 2000m, Bed level at placement area prior to nourishment: from –6 to 3 m NAP, crest level: 5 m NAP
- Island mega nourishment. Volume 4000 m3/m ; Alongshore length 2000m, Bed level at placement area prior to nourishment: from –6 to -3 m NAP, crest level: 3 m NAP
- Submerged mega nourishment. Volume 3500 m3/m ; Alongshore length 2500m, Bed level at placement area prior to nourishment: from –6 to -2 m NAP; crest level: -1 m NAP
- Continuous nourishment. Volume 0.75 Mm^3 / yr at one location; Bed level at placement area prior to nourishment at –4 m NAP

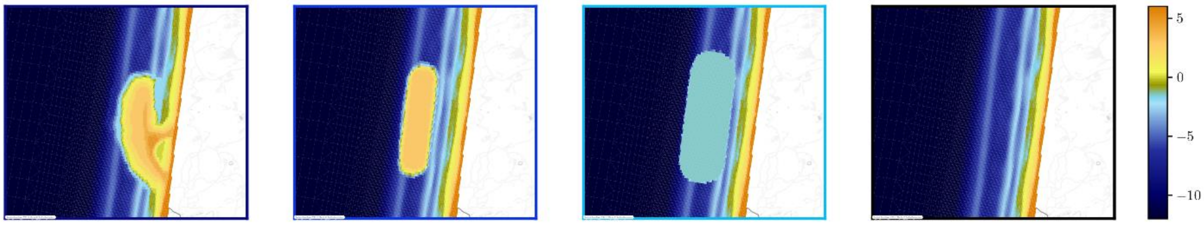


Figure 5 Initial bathymetries for set 3 (Peninsula, island, submerged, continuous)

All simulations were done with a grainsize D50 of 250 µm.

2.2 Quantifying impact

Each indicator is quantified for each concept in space and time (where appropriate) using the model output data. These are grouped in the following classes: 1) preventing coastal erosion, 2) ecotope surface area changes, 3) providing recreational area and 4) burial of ecology
An additional indicator (practical feasibility) is been added to discuss the feasibility of the cable hopper continuous nourishment concept. The methodology to obtain these indicator data is described in the Technische Universiteit Delft (2023d) of the DCC project

3. Preventing coastal erosion

The morphodynamic results in relation to maintaining coastal safety have been analysed on the following indicators:

- Longshore spreading (2.1)
- Impact on shoreline position (2.2)

3.1 Longshore spreading

For the longshore spreading, the change in profile volume m^3 per m alongshore in the active coastal zone (-20 m waterdepth to 3 m above) has been used as indicator. This volume change ΔV is quantified with respect to the simulation results without a nourishment (see Technische Universiteit Delft (2023d) for more details on this procedure). This longshore spreading is discussed per set of nourishment simulations below.

Simulation set 1. Small nourishments of 0.5 Mm^3 / 4 yr

The following findings can be derived from the model results, shown in Figure 6 and Figure 7:

The model simulations show a much smaller lateral dispersion of sediment for the shoreface nourishment alternative (Figure 6, top left), compared to the beach nourishment alternatives. Dispersion of the shoreface nourishments only occurs at the lateral edges of the nourishment, whereas the beach nourishment erodes along the entire nourished stretch. The dispersion of nourished sand is mostly symmetrical for the concepts. The shoreface nourishment shows slightly more dispersion on the north side, following the direction of net annual longshore sediment transport.

The sand groynes concept shows remarkably similar dispersion as the regular beach nourishment after 4 years (Figure 7, blue and light green lines), although having different initial topographies. The initial shape was found to only influence the initial morphodynamic response up to ~1 year (not illustrated here).

The continuous nourishment concept shows a concentrated accretion of the coast while the dispersion is limited. The concentrated salient development most likely reduces the local sand transport and hence the dispersion; the waves and currents are significantly affected by this coastal advancement, interrupting the longshore transports.

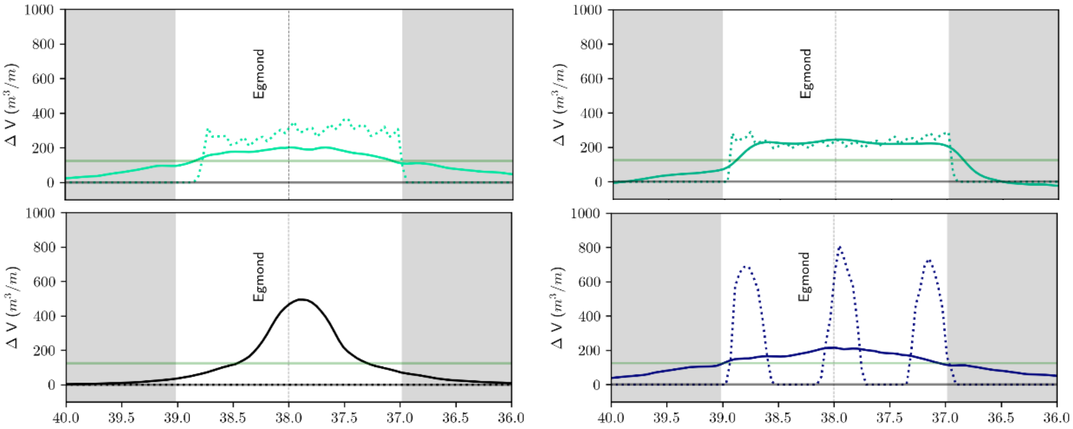


Figure 6 Longshore spreading of sand for four nourishment alternatives in simulation set 1 after 4 years (top-left: Beach nourishment, top-right: Shoreface nourishment, bottom-left: continuous nourishment, bottom-right: Sand Groynes). The dotted lines indicated to state directly after construction and continuous lines indicate the state after the design lifetime of 4 year. Horizontal axis is the distance to Den Helder (in km).

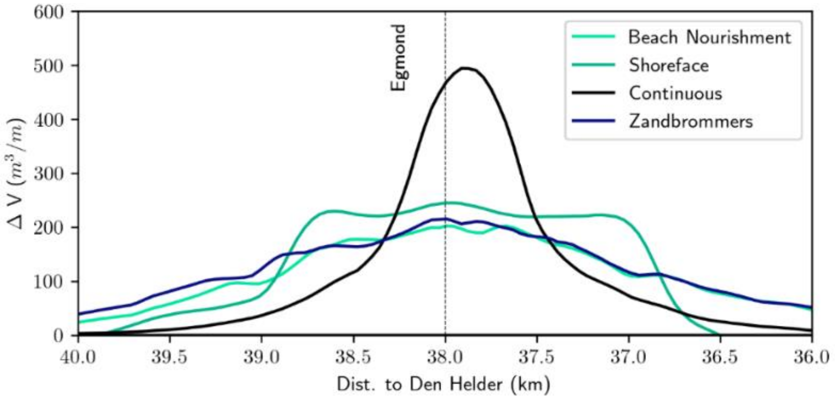


Figure 7 Alongshore distributios of profile volume after four years of morphological evolution as obtained for Simulation set 1.

Simulation set 2: Nourishments of 2.5Mm^3 / 4 yrs
In this set of nourishments, the mega nourishment concept cannot be directly compared to the other concepts due to the different design lifetime and hence volume. Nevertheless, the following findings can be derived from the model results, shown in Figure 8 and Figure 9:

- Where the shoreface has a direct impact sediment volume in the profile in the zone within 2 km of the centre of the nourishment, the continuous and mega feeder nourishment concepts require time to spread and positively impact the volume change ΔV and in that way increase their area of influence.

- The feeding behaviour of the continuous and mega nourishment initially shows a relatively fast dispersion while the feeding rate slows down significantly after the first year. This means that for these concepts the area of influence (i.e. where the nourishment requirement is fulfilled) has grown fast in the first 1 - 2 years, becomes constant after a few years. Thereafter the area of influence only grows very gradually.

- The concentrated nourishments seem to be able to impact the local transport gradients in such a way that the dynamics of the nourishment reduce significantly. Due to the surplus of sand, locally the coastal zone has the freedom to grow towards a local ‘equilibrium’, by local reorientation of the coastline leading to reduction of the wave-driven transports. In this way, it finds a more stable geometry and it tends to be self-stabilising.

- As these models are forced with ‘averaged’ conditions, it can be argued whether the shape of the concentrated nourishments is able to withstand storm events. Simulations for Set 3 will indicate the robustness of these concentrated nourishment concepts for storm events, as there the models are forced with real-time conditions.

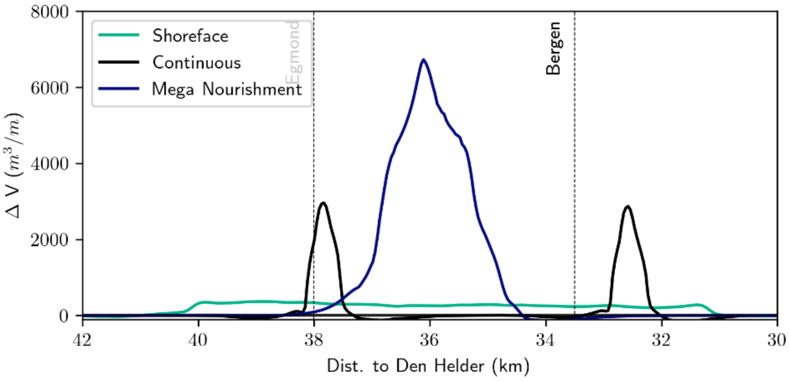


Figure 8 Comparison of the longshore volume in the coastal foundation after the design lifetime of 4 year.

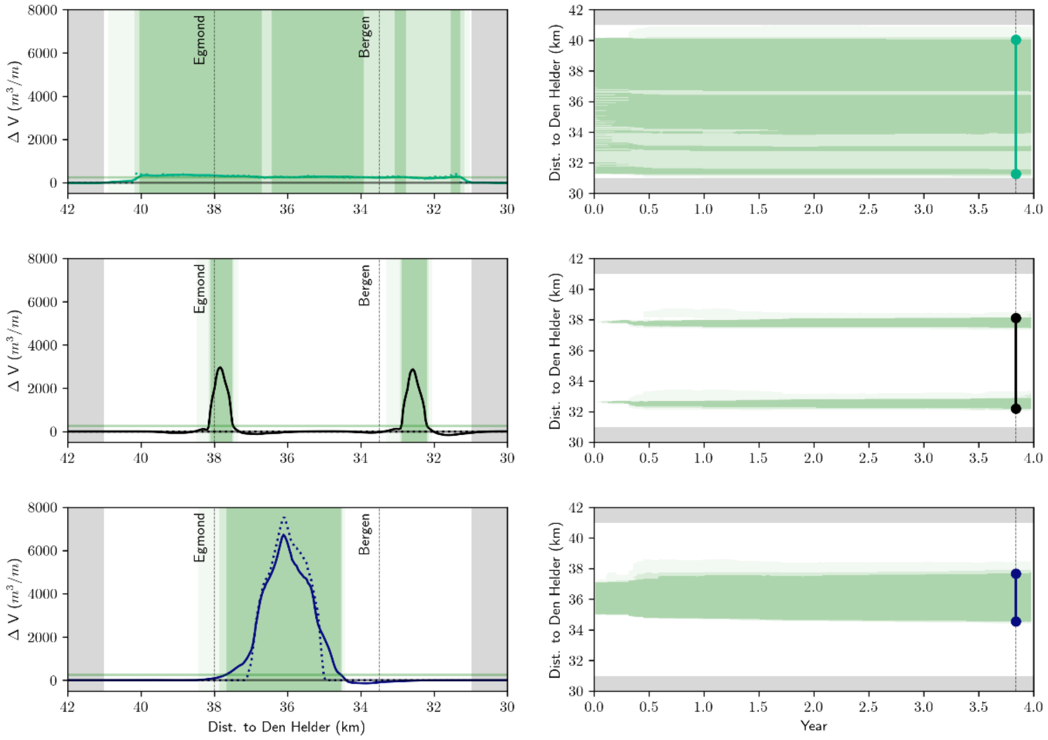


Figure 9 Longshore spreading of sand in the coastal profile for the three nourishment concepts in simulation set 2 (top: shoreface; middle: 2 continuous; bottom: mega nourishment). (left panels) Alongshore distribution of ΔV just after implementation of the nourishment (dotted line) and after nearly 4 years of development (continuous line). The threshold indicating uniform redistributed sediment is given by the green horizontal line. The dark, intermediate and light green patches indicate if profile volume exceeds respectively 100%, 50% or 5% of the value of uniform redistribution. (Right panels) The development over time is shown by stacking the impact zone over time.

Large scale nourishments of 7.5 million m^3 with a 10 year lifetime

To design the feeder nourishment dimensions (i.e. volume, size, location), it is assumed that each nourishment concept contains enough sediment to account for the total sediment demand over a coastal stretch with a 10 km length over a lifetime of 10 years (~7.5 million m^3 / 10 year). For analysis purposes we assume that the nourished volume should be uniformly distributed over the 10 km coastal stretch, resulting in a positive volume change of ~750 m^3/m. This threshold value serves as an indicator for a 100% adequately fed part of the coast and is indicated by the darkest green patch in Figure 11. So, the green hatches indicate areas where the nourishment requirement is fulfilled relative to the baseline prediction.

The dispersion is presented for four feeder nourishment concepts (see Figure 10 and Figure 11).

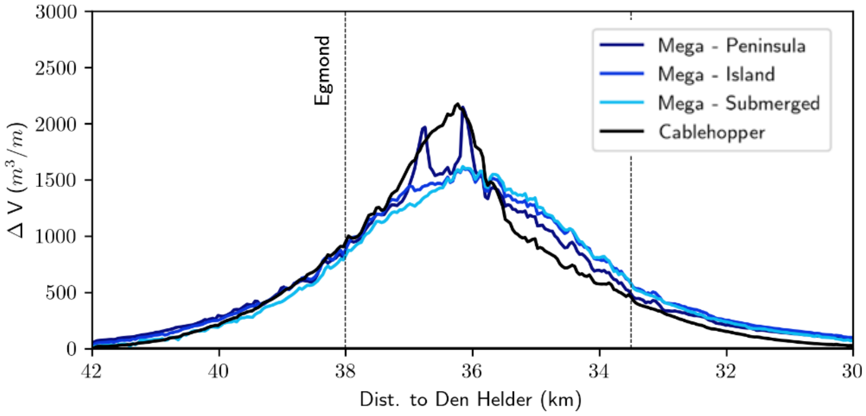


Figure 10 The range of influence (alongshore length in km) for four feeder-type nourishment concepts after the design lifetime of 10 years.

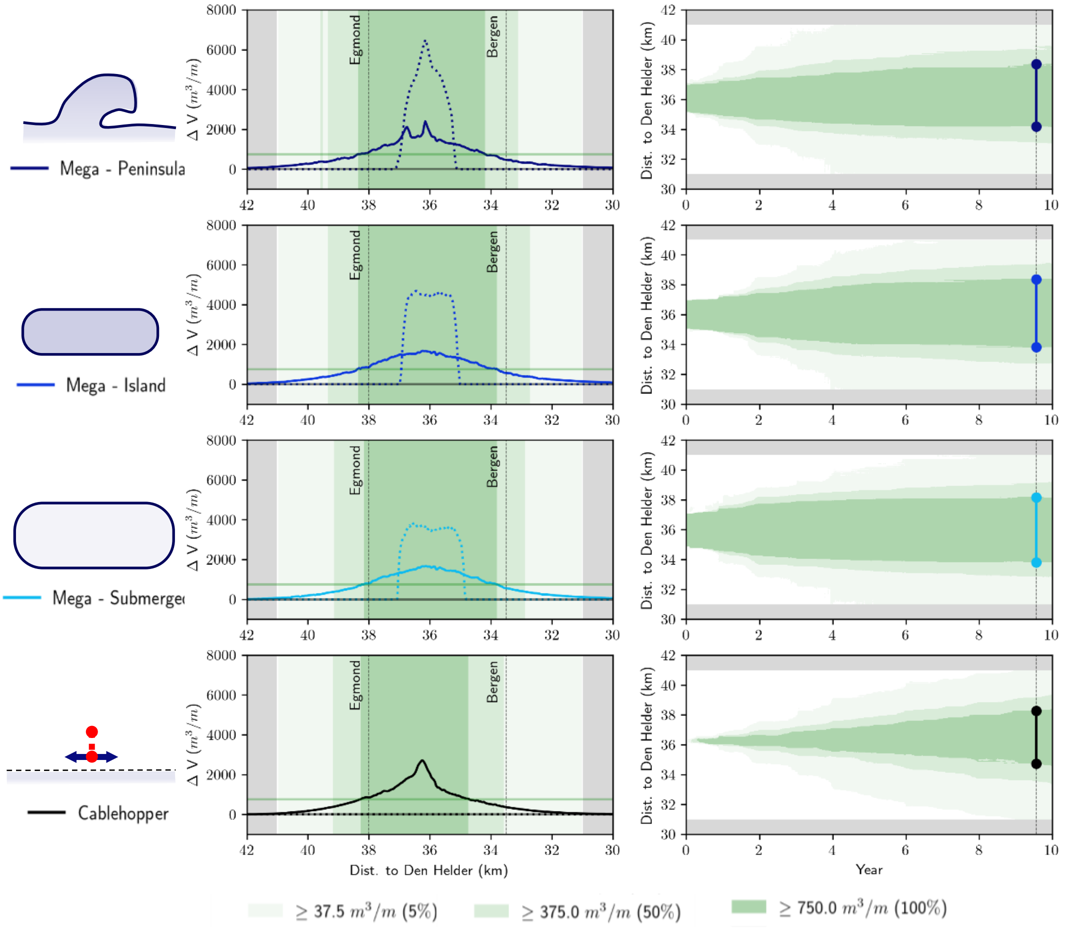


Figure 11 Longshore spreading of sand over the coastal foundation for the four feeder nourishment concepts of simulation set 3. (left panels) Schematic of the nourishment concept in the row. (Middle) Alongshore distribution of ΔV just after implementation of the nourishment (dotted line) and after nearly 4 years of development (continuous line). The threshold indicating uniform redistributed sediment is given by the green horizontal line. The dark, intermediate and light green patches indicate if profile volume exceeds respectively 100%, 50% or 5% of the value of uniform redistribution. (Right panels) The development over time is shown by stacking the impact zone over time.

From these results we find that the area of influence for feeder-type nourishments is limited. Longshore spreading is essential for feeder-type nourishments. The model results indicate that the longshore spreading is not fast enough to feed the entire coastal stretch (10 km; defined for calculating the nourishment volume) within the chosen time period of 10 years Model results indicate that the length of the influence zone only reaches an alongshore length of ~4 km after 10 years, if we consider a threshold of 750 m^3/m relative to the baseline prediction. More specifically, the area of influence is not increasing significantly anymore after 6 – 8 years for the island, submerged and peninsula mega nourishments. Consequently, feeder-type nourishments are not expected to be able to adequately feed large coastal stretches as a standalone solution.

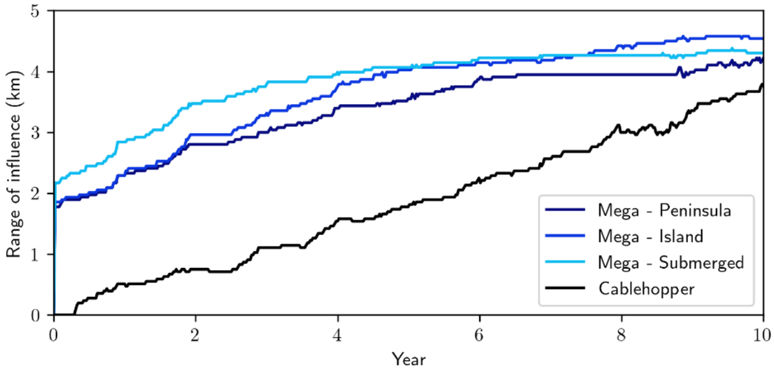


Figure 12 Range of influence over time for four feeder-type nourishment alternatives

We conclude that the cross-shore placement less relevant on decadal timescale
From a volume perspective, the computed morphological spreading of three cross-shore variations on mega nourishments (island, submerged, peninsula) is not significantly different on the long-term (~5 year). The initial response (first couple of years) however does show differences (see Figure 11) and in this first period we also observe local erosion at lateral sides (see next section).

3.2 Influence on shoreline position

Besides the sediment volume over the full coastal profile we also examined the shoreline position. The shoreline position is taken here through a volume based approach (Technische Universiteit Delft, 2023d). We refer to this position as the MCL (or Momentane KustLijn MKL in dutch) and it is in meters. The MCL is directly related to the current policy objectives of maintaining a minimum cross-shore position of it (van Koningsveld and Mulder, 2004).

From the simulations of the small scale nourishments we see that beach nourishment and sand groynes concepts show a large and similar increase in MCL over a distance of more than 4 km (see Figure 13). Note that as both nourishments are placed high in the profile, a similar distribution is found for the volume change in the coastal profile and MCL (this section). The impact of the continuous nourishment is restricted to an area of ~3 km in the four years simulated with a large seaward MCL position around the disposal location.
The impact of the shoreface nourishment on the MCL is very small after 4 years. Note that a complex net balance of onshore and offshore transports will determine how this shoreface nourishment will behave over time. These complex interactions are not well resolved in depth-averaged process-based models like Delft3D and XBeach. For this, expert judgment, based on observed behaviour at various locations along the Dutch coast is needed.

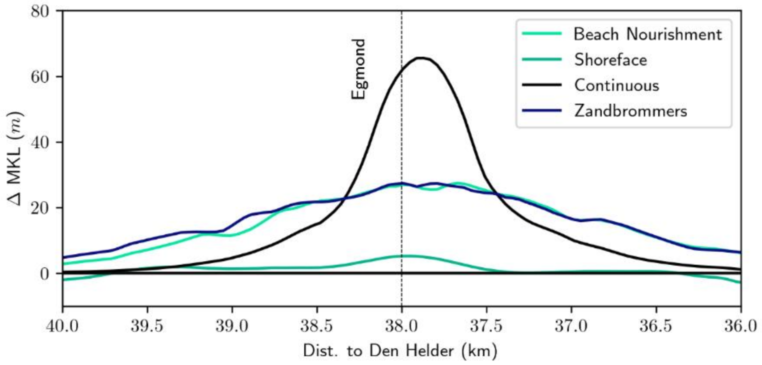


Figure 13 The increase of the MCL (m) after the design lifetime of four year for four shoreline nourishments.

Larger scale nourishments can potentially cause local erosion for a period of time, due to nourishment-induced effects. The shape and dimensions of the nourishment could cause large gradients in longshore transports, that may result in (temporary) erosion of the beach area leading to shoreline retreat. This could occur both updrift and downdrift of the nourishment, caused by the bi-model wave climate. An example is displayed in Figure 14 showing local loss of sand volume from the MCL zone after several months after placement of the four considered mega-nourishments concepts.

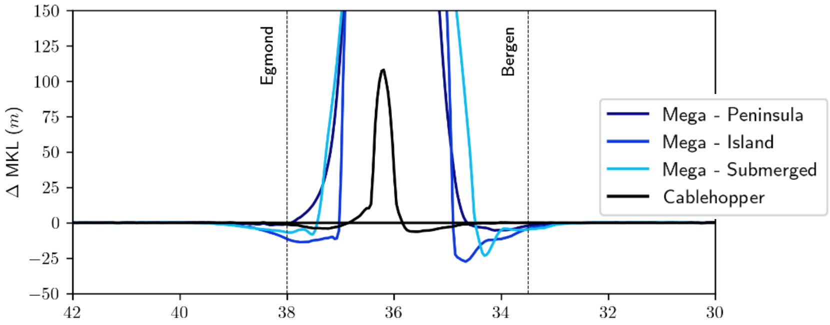


Figure 14 Change of MCL (m) for four feeder-type nourishments after several months of development. The negative MCL changes directly adjacent to the nourishment location indicate local erosion.

Model results indicate that the cross-shore position of the nourishment in the profile strongly influences the amount of local erosion. We observe different response for the island, peninsula and submerged alternatives (Figure 15) as well as different values for the integrated erosion area magnitudes (Figure 16). The main finding of this analysis is that after placement or during the development of larger scale interventions local erosion can temporally occur, resulting in not fulfilling the MCL criteria and/or the beach width. Whether the local erosion is leads to unacceptable impacts, should be judged for each nourishment design, and depends on the considered locations.

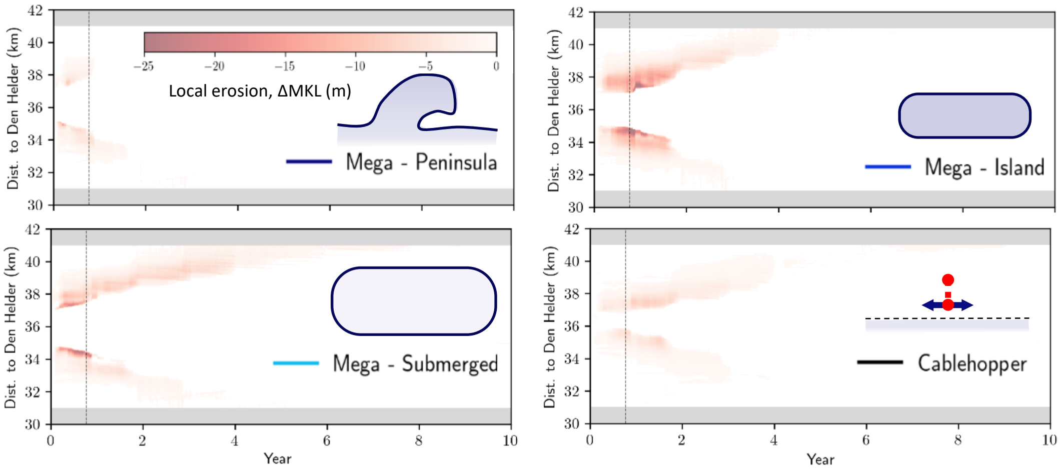


Figure 15 Local erosion as a result of nourishment construction, directly adjacent to the nourishments. The negative shoreline changes (erosion) are indicated by the red patches.

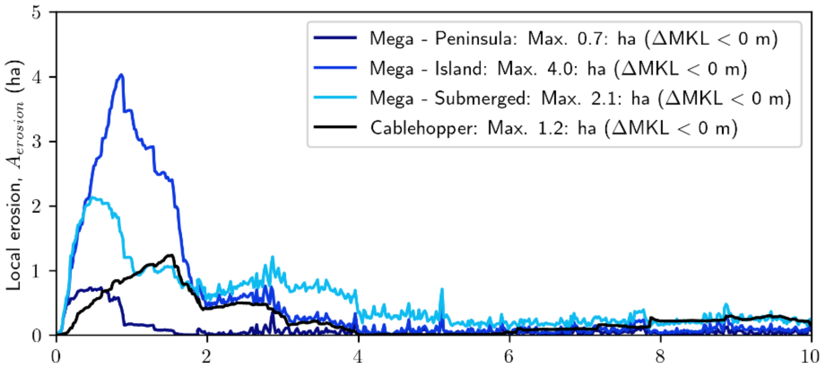


Figure 16 The total erosion of the MCL integrated over space. The horizontal axis is in years.

4. Ecotope surface area changes

We quantify the evolution of ecotope surface area using two abiotic indicators: bed level elevation (or depth) and shear stress (N/m^2), as shown in Figure 17. Together these provide a first assessment of the boundary conditions for specific habitats (e.g. intertidal ecology). We differentiate between nine ecotopes zones in this study (Table 1).

Table 2 Overview of the ecotope classification and limits based on bed level height and shear stress. Obtained from van Zanten (2016)

	Ecotope	**Bed level elevation** (m NAP)	**Bed shear stress** (N/m^2)
1	Surfzone	$h \le -0.95$	$\tau > 4$
2	Seaward side of the surfzone	$h \le -0.95$	$2 < \tau \le 4$
3	Nearshore	$h \le -0.95$	$1.2 < \tau \le 2$
4	Offshore	$h \le -0.95$	$0.3 < \tau \le 1.2$
5	Sheltered subtidal	$h \le -0.95$	$\tau < 0.3$
6	Exposed lower intertidal	$-0.95 < h \le 0$	$\tau > 0.1$
7	Exposed upper intertidal	$0 < h \le 1.2$	$\tau > 0.1$
8	Sheltered intertidal	$-0.95 < h \le 1.2$	$\tau \le 0.1$
9	Supratidal	$h > 1.2$	-

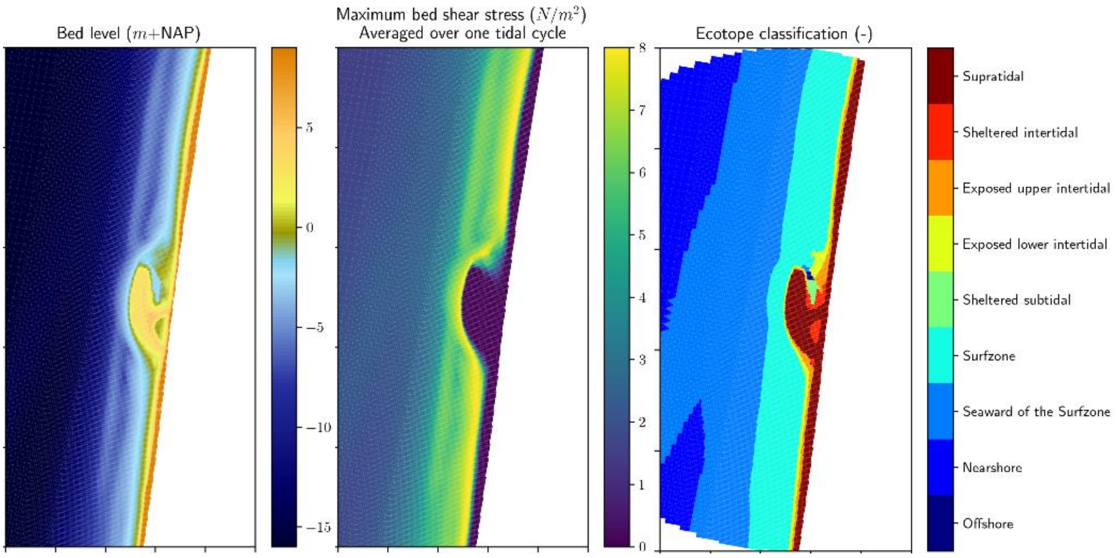


Figure 17 Illustration of the ecotope surface area method. (left) Bed level with respect to NAP (center) Flow velocities in m/s and (right) classified ecotope areas based on the abiotic indicators.

Our abiotic indicators can be used in combination with (expert judgement on) biotic controls to examine the ecological response to different nourishment concepts. In reality, the ecological response to nourishments is slower than the hydro- and morphodynamic response. This time lag is not considered in the analysis.

Ecotope surface areas are computed for each year in the morphological simulation (Figure 18). These results are aggregated by averaging the ecotope surface area changes over the simulation period in Table 3, Table 4 and Table 5 for simulation sets 1,2 and 3 respectively. These averages reflect gains and losses over the lifetimes of nourishments.

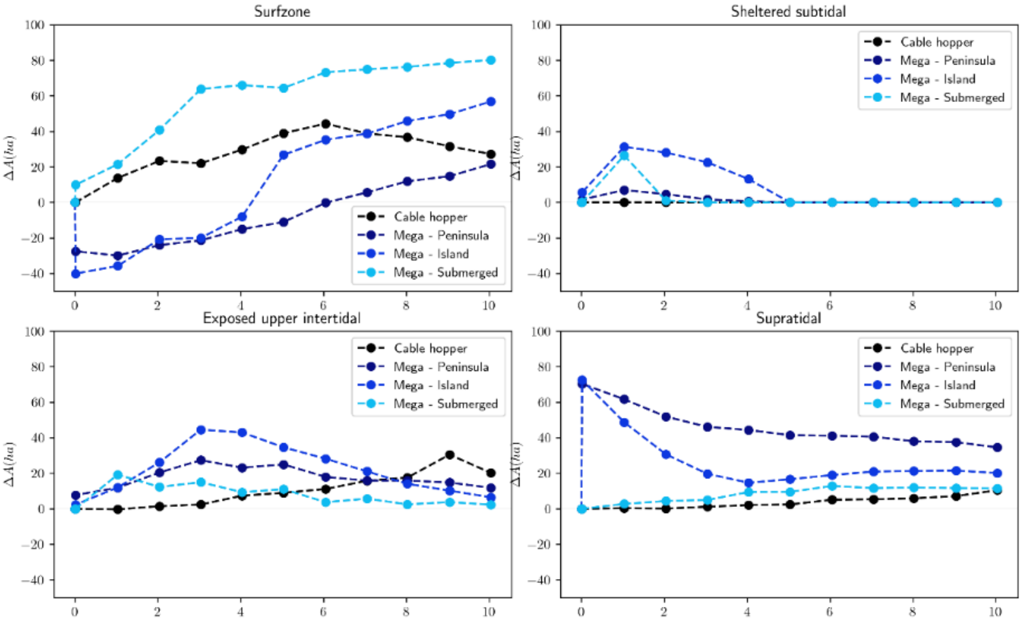


Figure 18 Temporal evolution of ecotope surface areas for ecotopes surfzone (top left), sheltered subtidal (top right), exposed upper intertidal (bottom left) and supratidal (bottom right). Results for simulation set 3: large scale nourishments of 7.5 million m^3 with a 10 year. The horizontal axes represent years.

From these results, the following findings can be derived:

- Sheltered subtidal ecotope surface area (similar to the lagoon of the Sand Engine Kijkduin) is only available for mega feeder nourishments that include a sheltered lee side. Such sheltered zones exist for only part of the nourishment lifetime (Figure 18, top right).

- Surfzone ecotope surface area varies strongly with the nourishment concept. The placement and evolution of a submerged mega nourishment provides a large increase in surfzone ecotope surface area (Figure 18, top left).

- For regular nourishments (Simulation set 1) the impact on the surfaces areas is low (< 15 ha). These simulations do not show large scale changes to topographical and bathymetric situation and other abiotic conditions. As these smaller scale nourishments are quickly absorbed into the coastal system the situation after 4 years is very similar to initial situation. Note that, although ecotope surface areas change is limited, there may still be ecological impacts.

- Mega nourishments impact the ecotope surface area most. The implementation of the large nourishment body results in a large initial change (see Figure 18) followed by substantial changes as the nourishment develops. In particularly the zones higher up the profile (e.g. supratidal or intertidal zones) increases (Table 5). In contrast, subtidal area size is reduced as these are converted to different (i.e. shallower) ecotopes.

Table 3 Average changes in ecotope surface areas ∆ **A** *over the simulation period (4 years) for set 1.*

∆ A (ha)	Regular			Continuous
	Beach	Sand Groynes	Shoreface	Continuous
Offshore	0.0	0.0	0.0	0.0
Nearshore	6.8	-1.1	-0.9	5.2
Seaward of surfzone	-6.8	0.9	-1.8	-5.2
Surfzone	-13.1	-13.2	2.6	-9.4
Sheltered subtidal	0.0	0.0	0.0	0.0
Exposed lower intertidal	0.0	0.1	0.0	0.1
Exposed upper intertidal	10.6	10.3	0.1	5.7
Sheltered inter	2.5	2.7	-0.1	2.4
Supratidal	-0.1	0.2	0.0	1.3

Table 4 Average changes in ecotope surface areas ∆ **A** *over the simulation period (4 years). Results from Simulation set 2. Note that the added volumes are different in the concepts and the simulation period is only part of the lifetime of the mega nourishment.*

∆ A (ha)	Shoreface	Continuous	Mega
Offshore	0.0	0.0	4.0
Nearshore	-12.5	-17.5	-52.4
Seaward of surfzone	-20.1	36.2	40.5
Surfzone	32.3	-29.2	-104.8
Sheltered subtidal	0.0	0.0	5.7
Exposed lower intertidal	-0.1	10.9	8.2
Exposed upper intertidal	0.4	-0.2	6.2
Sheltered inter	0.0	-0.1	16.0
Supratidal	0.0	-0.1	76.6

Table 5 Average changes in ecotope surface areas ∆ **A** *over the simulation period (10 years) for 4 different nourishment concepts of Simulation set 3. Timeseries for several ecotopes are displayed in Figure 18.*

∆ A (ha)	Continuous	Mega		
	Cable Hopper	Peninsula	Island	Submerged
Offshore	-1.1	-1.9	0.5	-1.5
Nearshore	-0.4	-1.1	-3.4	-12.3
Seaward of surfzone	-57.7	-76.7	-91.1	-79.5
Surfzone	25.5	-6.3	10.7	54.1
Sheltered subtidal	0.0	1.3	8.4	2.3
Exposed lower intertidal	18.1	16.0	24.1	22.1
Exposed upper intertidal	9.6	16.0	20.2	7.1
Sheltered inter	2.6	10.4	5.1	0.2
Supratidal	3.4	42.3	25.5	7.6

5. Recreation

The added beach area is computed as an indicator for changes in recreational value of the beach after implementation of the nourishment. We examine herein the temporal evolution of the added beach areas (Figure 20 and Figure 21) as well as the average values during the computation (given in the legends of Figure 20 and Figure 21). Since the findings from simulation sets 1 to 3 overlap we present only results from simulation set 1 and 3 here.

Surface area for recreation
For the determination of recreational surface area, we exclude subaerial zones that are not accessible from the main beach such as an island (Figure 19). For simulations in which large sand bodies are intermittently connected to the shore this results in a period with large fluctuations in beach surface area (e.g. Figure 21, blue line)

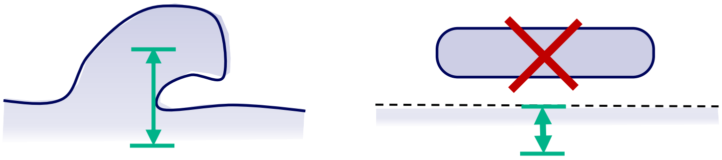


Figure 19 Schematic to clarify that subaerial parts of detached sand bodies (i.e. islands) are excluded from the calculated beach surface area.

Smaller nourishments of 0.5 Mm^3 / 4 yr (simulation set 1) have a minor impact (<10 ha) on the beach surface area (Figure 20). The limitations of the model setup prohibit strong conclusions due to schematisation of cross-shore sediment transport. However, the model data shows clearly that concepts where sediment is deposited on (or very close to) the beach provide temporary gains in beach surface area, whereas the shoreface alternative shows limited beach area gains.

The more innovative sand groynes nourishment layout initially provides less beach area compared to beach nourishments as sand is placed in concentrated humps. Within 2 years these differences decrease in magnitude and over a 4-year period the average gained beach areas vary by roughly 10 % (9.9 ha vs 8.9 ha, Figure 20).

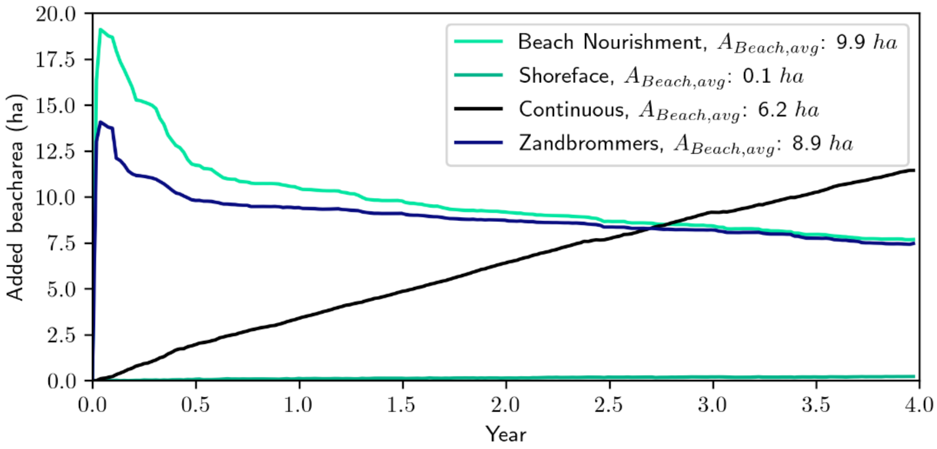


Figure 20 Temporal evolution of gained beach area for shoreline nourishment concepts (Simulation Set 1)

The beach area gains for larger scale (feeder type) nourishment concepts vary strongly. Depending on the type of nourishment, temporally large area suitable for beach visitors may vary by 80 ha. The peninsula concept shows the largest beach area gains, with on about 60 ha gained on average over the 10 years simulated (Figure 21). An island nourishment concept also shows large beach surface area gains (up to 40 ha), but this requires the island to weld first onto the beach after which it will be accessible for pedestrians. Results show that for submerged mega nourishment changes in beach surface area can also be expected but not as significant as other two. For continuous nourishments (Cable hopper concept) beach surface gains are on average smaller, but surface area builds up over the nourishment period which could be favourable for the development of new recreational purposes (Figure 21).

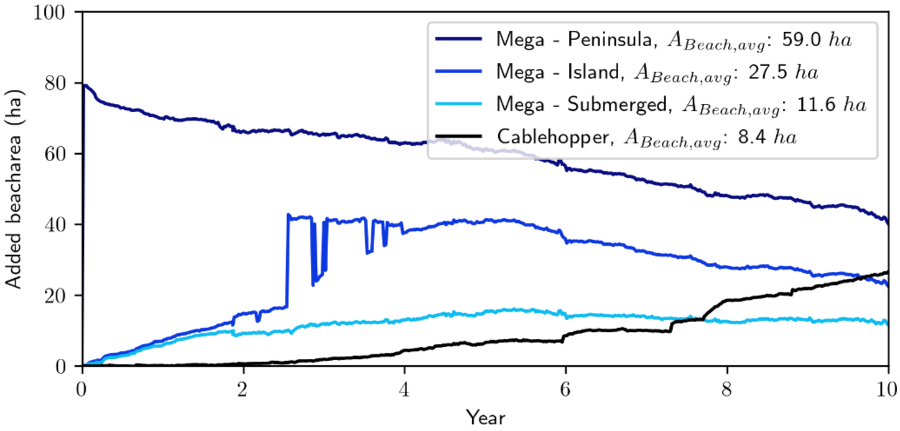


Figure 21 Temporal evolution of gained beach area for feeder nourishment concepts (Simulation Set 3)

Water sports
Large sandy interventions open up possibilities for inclusion of other types of recreational area which are not captured by surface area only, e.g., water sports in a lagoon feature. For water-based activities that require a sheltered environment the peninsula concept is most promising, although the island concept may also create a large lagoon like feature over time. This behaviour is less predictable. Smaller nourishments are capable of sustaining existing recreational value and functions but are less suitable for creating new (unique) recreational functions.

Safety
Large sandy interventions can impact the safety of beach visitors. Strong erosion of protruding beach nourishment can result in scarps because of artificially steep slopes (see Sand Engine) or increased currents due to new morphological features. These effects are currently hard to simulate with a numerical model. For shoreface nourishments the impact on swimmer safety if limited and there is ample experience with these types of nourishments. For the peninsula, island and submerged feeder concepts this is harder to predict as these may affect or create rip currents.

6. Burial of ecology

Burial and recovery of benthic life is assessed over the lifetime of the nourishment. The burial consists of the initial burial for concepts that are implemented once or ongoing burial for continuous nourishments. On top of this, burial due to (enhanced) sediment transport arising because of altered morphological behavior.
The burial is compensated for by recovery of the benthos. Different species respond differently to the implementation of a nourishment. Results discussed here are based on two ecological classes. These two selected classes have a different species density distribution over water depth and respond differently to burial (Gielen, 2023).

Burial and recovery combined provide a first estimate of the ecological damage over time (Figure 22) and the ecological damaged averaged over time are shown
Results of the burial method (the 'Benthimeter') are preliminary and serve as input for a wider examination of impacts on ecology. Qualitative results should be combined with expert judgement to assess the response of benthic life on nourishment burial. Values in the upcoming tables should not be taken as the sole metric of the impact.

Table 6.

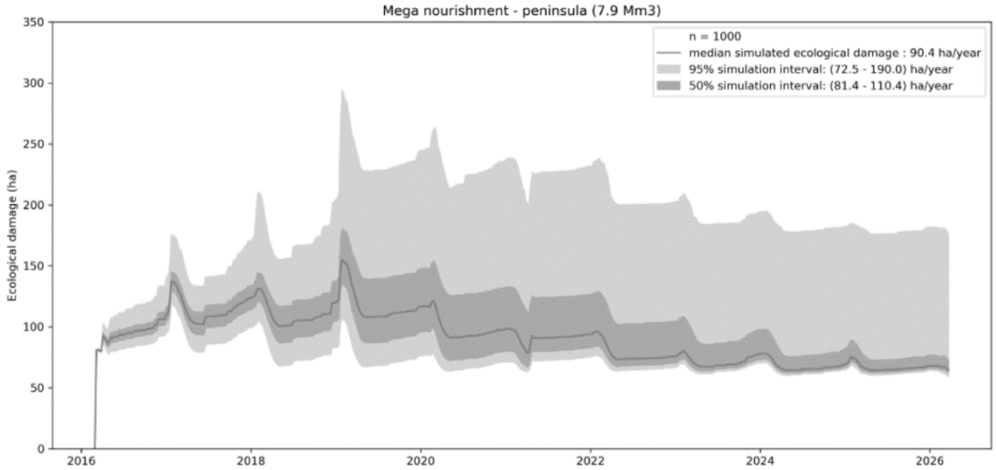


Figure 22 Timeseries of 10 years of ecological damage from burial and recovery of benthic species. Results shown for a peninsula mega nourishment (Simulation set 3). Gray shades provide an estimate of the uncertainty range, determined by systematically varying key input parameters. Annual fluctuations in the damage are the result of the recovery (during spring) and burial in winter.

Results of the burial method (the 'Benthimeter') are preliminary and serve as input for a wider examination of impacts on ecology. Qualitative results should be combined with expert judgement to assess the response of benthic life on nourishment burial. Values in the upcoming tables should not be taken as the sole metric of the impact.

Table 6 Average damage to benthic life over the simulation period (10 years), expressed in representative hectares. Results from Simulation set 1, 2 and 3. Values in brackets indicate the 95% confidence interval from the input parameters of the Benthimeter module

	Damage (ha/year)	
Set 1: Small nourishments of 0.5 Mm^3 / 4 yrs		
Beach	6.2	(5.4 - 7.9)
Sand Groyne	8.0	(6.3 - 12.2)
Shoreface	15.9	(9.9 -26.3)

Continuous	2.6	(2.5 - 3.0)
Set 2: Nourishments of 2.5Mm3 / 4 yrs Be careful, since these concepts are not directly comparable, there are no colours assigned to the values.		
Shoreface	77.7	(51.5 - 113.1)
Continuous	22.4	(16.1 - 36.8)
Mega	105.6	(87.9 - 130.2)
Set 3: Large scale nourishments of 7.5 million m^3 with a 10 year lifetime		
Peninsula (mega)	102.2	(72.6 - 198.8)
Island (mega)	115.3	(81.2 - 215.7)
Submerged (mega)	115.1	(80.9 - 200.0)
Cable hopper	52.7	(41.5 - 84.8)

Results have a clear sensitivity to the positioning of the nourishment in the cross-shore. Higher up in the profile benthic life is less abundant, and species accustomed to deeper waters are less resistant to large bed level changes. This is reflected in low damage values for beach nourishments compared to shoreface nourishments (6.2 ha vs 15.9 ha,
Results of the burial method (the ‘Benthimeter’) are preliminary and serve as input for a wider examination of impacts on ecology. Qualitative results should be combined with expert judgement to assess the response of benthic life on nourishment burial. Values in the upcoming tables should not be taken as the sole metric of the impact.

Table 6 simulation set 1).

Results also show an effect of the scale of the nourishment and its related return frequency. For the smallest nourishments the recovery is (nearly) complete after a nourishment cycle. A residual damage that builds up as long-term effects may be present but is not examined here. In contrast, mega nourishments do not have a frequent disturbance but one substantial burial with longer recovery time. Due to the large surface area of mega nourishments the lateral migration of species is also envisioned to be smaller. It is not expected that we see full recovery during lifetime due to changed abiotic conditions (see H2), i.e. shoreface transformed into supratidal beach.

Continuous nourishments are an interesting alternative from the perspective of the burial as dumping takes place in a relatively small area. Continuous nourishment strategies therefore have the lowest damage values over their lifetime (see Table 6). Most impact for these nourishment types is by indirect sedimentation (i.e. sediment that is redistributed by wave action in the vicinity of the dumping location). Bed level variations are more gradual, making it more likely that species can coop with this. This contrasts the behaviour seen for regular and mega nourishments, which are mainly affected by direct burial as a result of dumping.

7. Practical feasibility of cable hopper

The concept of the cable hopper, placing large volumes of sand at a single location, is new. This evaluation report shares some findings on the morphological evolution at the disposal location which relevant for the evaluation of the practical feasibility.

To schematize the cable hopper process, we chose a size of the disposal area as 7500 m^2 (~40 m cross-shore x 800 m longshore). This could in reality be different (larger or smaller). A continuous disposal rate is prescribed in the model and limited workability during winter period (more extreme weather conditions) is not included in the cable hopper disposal frequency.

The model results show that the bed levels at the disposal location (nearshore end of the cable) will vary in time with an average depth of about 2 meters (see Figure 23). The cable hopper requires a water depth of 5 m for its operation. This means that during large part of the considered period there will not be sufficient depth for the cable hopper to reach the most nearshore point. The bed level variation seems to be dominated by wave forcing and hence seasonality, which is an important consideration to include in a feasibility assessment of the cable hopper concept.

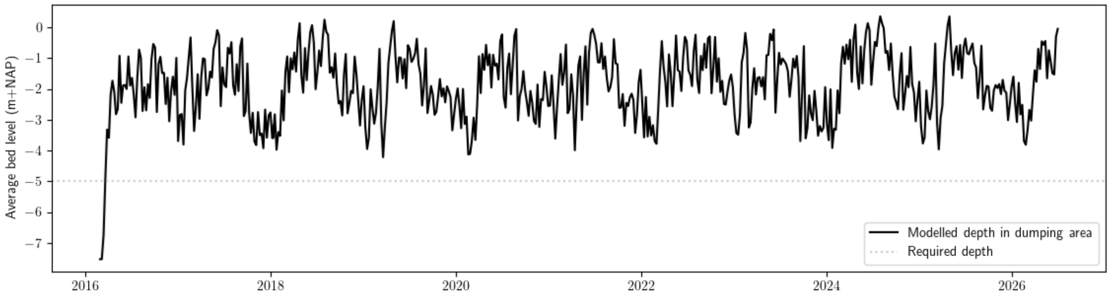


Figure 23 Computed 10-year time series of bed level variations at the disposal location of the cable hopper. Horizontal axis is in years.

These results show that the practical feasibility of the cable hopper concept can be limited. For a rapid redistribution of the added sediment a shallow location would be preferred, but at these locations one rapidly has limited draft for the vessel.

There are different optimisations that could be considered, for instance:

- Aligning the dumping phase with tidal currents could increase spread of sediments and thus improve workability.
- Or, a potential pipeline solution that may pump onto the beach.

8. Conclusions

We evaluated several nourishment concepts to examine the impact on morphological response, recreational impact, and ecology. We tested alternatives with a short lifetime (e.g. beach nourishments of 200 m^3 per meter alongshore) to large scale feeder concepts (e.g. offshore island of 7.5 Mm^3).

Results show that different alternatives outperform others depending on which aspect prevails for stakeholders. As an example, if adding recreational space is of prime importance then the ‘peninsula’ large scale feeder concept provides the most area gains. Such large-scale interventions are however also resulting in severe burial of benthic life and changes in ecotope areas. Our results for continuous nourishment concepts show a much better performance for these ecological aspects.

The longshore spreading of large-scale feeder-type nourishments is limited and stagnates over time. After the design period of 10 years, the zone affected by both the mega- and continuous nourishments, and thus the feeding capacity, is very similar (~4 km). As a result, these concepts are ill-suited to feed continuous stretches of coast with just a few nourishments. On the other hand, the long timescale of the redistribution also means that large-scale replenishments can be a robust solution for erosive hotspots (e.g. at beach towns). The cross-shore placement of large-scale feeder-type nourishments in the profile has only a limited impact on the longshore feeding capacity at the end of the lifetime, as long as sediment is placed in the active zone (i.e. roughly above the depth of closure). The trade-off between efficiency (costs and emissions) and adding added value (new habitat types and recreational opportunities) is therefore decisive in the choice of the cross-shore location.

Large-scale interventions can cause local erosion on the adjacent coast, resulting in a temporary retreat of the coastline of tens of meters. This can be a danger to local coastal safety and other coastal functions, such as (permanent) beach structures. The problem seems to be most significant in the case of an offshore island, while erosion is somewhat more limited for alternatives with a more gradual coastline, due to natural development (continuous replenishment) or designed as such (peninsula).

Benthic life in shallow water is better adapted to dynamic conditions compared to species in deeper water, making replenishments in shallow areas (or on the beach) potentially less impactful than replenishments in deeper parts. As a result, nourishments alternatives higher in the coastal profile come out better from the evaluation for the impact on benthic life than replenishments in deeper water.
Continuous replenishment can have a reduced negative impact on benthic life, as the size of the direct influence zone is limited, and the gradual secondary sedimentation deviates less from natural conditions than the large-scale burial associated with traditional nourishment concepts.

Finally, we examined the morphological response at the disposal location of the continuous nourishment concept. Our results show that limited spreading of sand can be a bottleneck for the required depth of disposal vessel (>5 m) and therefore the practical applicability of the concept. Since the distribution is dominated by wave-driven transport, the sediment is only activated when the disposal location is sufficiently shallow.

Recommendations

The current memo utilises a numerical model to examine different nourishment concepts. The quantitative results display the impact of design and strategy choices. Current knowledge gaps and numerical approaches as listed in previous memos have impact on these results.

We note several elements that require attention, that are described more elaborately in other memos, but are summarized here:

Cross-shore sediment transport and cross-shore profile response is challenging for most numerical models (see also Technische Universiteit Delft (2023c)). A better model skill for this cross-shore behaviour would increase our confidence in the landward feeding that is calculated by the models. Several nourishment concepts are strongly dependent on the cross-shore transport (hump like nourishments, islands, etc..). Additional bed level data and concurrent hydrodynamic forcing should be collected (through pilot studies) to provide more insight into the nourishment behaviour of these concepts.
The current evaluation and modelling setup do not include dune development and dune ecology. We recognize that nourishment concepts can influence dune formation and dune landscapes (e.g. the Sand Engine). We recommend that this is taken into account in future studies, using the newly developed subaerial models (e.g. AeoLis) and coupled subaerial and subaqueous modelling approaches (e.g. CoCoNut), see also Technische Universiteit Delft (2023c).

We use two indicators to map the ecological impact, leaving other aspects unquantified (e.g. impacts of increased turbidity). Especially for alternative sediment disposal strategies this yields to unknowns. Our work is based on ecological responses measured at previous nourishments, but these do not include nourishments primarily tailored to reduce negative impacts (e.g. mosaics, thin layering). Pilot studies on these more innovative designs will have to show if these can be effective.
Furthermore, we quantify the ecological impact by evaluating the abiotic drivers. The relation between morphodynamics and ecology at nourishments is however still subject of research. Future work on the relation between abiotic model outcomes and the biotic response (habitats and benthos) and the human valuation of these (beach area for recreation) would be needed to finetune design alternatives (Technische Universiteit Delft, 2023d).

We included some innovative concepts in this study, amongst others the cable hopper concept of a continuous nourishment. More elaborate research into the characteristics of this concept is needed. In its current implementation there are many unknowns, affecting the practical feasibility of the concept. There are unknowns about the longshore and cross-shore deposition range of the vessel, the frequency and regularity of the disposal of sediment related to the workability depending on weather conditions, an accurate minimal required depth. Besides other possibilities, such as tuning the dumping to the tidal moment to allow for further spreading in suspension, are not explored yet.
We have not focussed on pipeline solutions yet. Due to high energy consumption, costs, and emissions (Workpackage 3), the concept was not included from this evaluation. Nevertheless, pipelines could still be feasible for some specific applications where the sediment needs to be frequently applied on a high elevation (dry beach) and/or where pipeline structures with a limited length are possible. Examples of such applications are local erosive hotspots near a harbour or sediment bypass systems. Testing such applications in real-life could provide operational and practical know-how, and insight in the morphological behaviour and ecological response. Such knowledge could be beneficial for smaller scale implementations, or in case of future scenarios where technical developments make larger scale applications feasible.

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