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)

In deze memo zijn verschillende kustindicatoren beschreven, die binnen het TKI-DCC project worden gebruikt voor de evaluatie van een selectie aan innovatieve onderhoudsconcepten. De indicatoren die hier zijn beschreven zijn gerelateerd aan de morfologische en ecologische ontwikkelingen ten gevolgen van suppletieconcepten, en zijn onderverdeeld in drie groepen kustfuncties: Voorkomen van kusterosie, Ecologie en Recreatie. Indicatoren in verband met kosten, emissies of vergunningen worden verstrekt door andere werkpakketten en vallen buiten deze memo.

Kusterosie
Langs de Nederlandse kust is zand cruciaal voor de bescherming tegen overstromingen in het achterland. Het aanbrengen van suppleties langs de Nederlandse kust heeft twee doelen:

- Dynamisch handhaven van de kustlijn op een tijdschaal van 0 tot 20 jaar;
- Voldoende in evenwicht houden van het kustfundament op langere termijn (>20 jaar)

We gebruiken de gewogen kustlijnpositie (de Momentane Kust Lijn) en het volume in het kustprofiel als indicatoren. Het analyseren van de spatiotemporele evolutie van deze indicatoren geeft inzicht in de verspreiding van het sediment kustlangs. Dat is met name van belang voor geconcentreerde mega suppleties (bv de Zandmotor) en puntlozingen (bv de Kabel hopper). Omdat de kustlijnpositie afhankelijk is van kust dwarse processen, die niet goed worden vastgelegd door het model, zal de nadruk vooral liggen op de longshore distributie van sediment in kustfundering.

Ecologie
De ecologische kwaliteit van ecosystemen hangt af van de diepte van de bodem en de gerelateerde abiotische factoren. Ecotopen zijn ruimtelijk afgebakende ecologische eenheden waarvan de samenstelling en ontwikkeling worden bepaald door abiotische, biotische en antropogene omstandigheden. Aangezien suppleties een sterke invloed hebben op deze factoren, kunnen ecotopen een nuttige indicator zijn voor de evaluatie van de impact van suppleties op de ecologie. De toegepaste ecotoopclassificatie is gebaseerd op een ecotoopsysteem voor de Nederlandse kust opgesteld door Bouma et al., (2005). Het berekenen van het ecotoopgebied voor meerdere tijdstappen geeft inzicht in de ecologische veranderingen over tijd. Bovendien kunnen voedingen een negatieve invloed hebben op de benthische populatie in de kustzone als gevolg van bedelving, waarbij benthische soorten niet kunnen ontstappen aan de sedimentatie. We presenteren een tool die schade aan benthisch leven berekent als gevolg van bedelving; de zogenaamde *Benthimeter*. Met deze tool willen we het begrip van het relatieve effect van voedingsstrategieën op de benthos-populatie verbeteren. Het gemiddelde van deze ecologische schade geeft een indicatie van de totale ecologische schade (ha) gedurende de levensduur van een voeding, wat de directe vergelijking van voedingsconcepten mogelijk maakt.

Recreatie
Suppleties en met name grootschalige suppleties hebben de potentie om extra ruimte te creeeren voor natuurontwikkeling en recreatie, zoals het geval was met de Zandmotor (Huisman, 2021; van Zanten, 2016). Een van de indicatoren is dan ook het toegevoegde strandoppervlak dat geschikt is voor recreatieve doeleinden. Dat kan het aaneengesloten droge oppervlak zijn (bv voor zonnebaden) of luwte gebied met ondiep waterdat geschikt is voor watersporten. Het gemiddelde van deze gebieden in de loop van de tijd maakt de directe vergelijking mogelijk van de impact van verschillende voedingsconcepten op recreatieve waarde.

De indicatoren in deze memo zijn toegepast in de evaluatie van verschillende suppletieconcepten die beschreven is de volgende memo (Technische Universiteit Delft, 2023e).

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:

1) Generating a set of alternative nourishment concepts and their potential impact.
2) Evaluating the morphological predictive skill of current state-of-the-art modelling.
3) 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*).

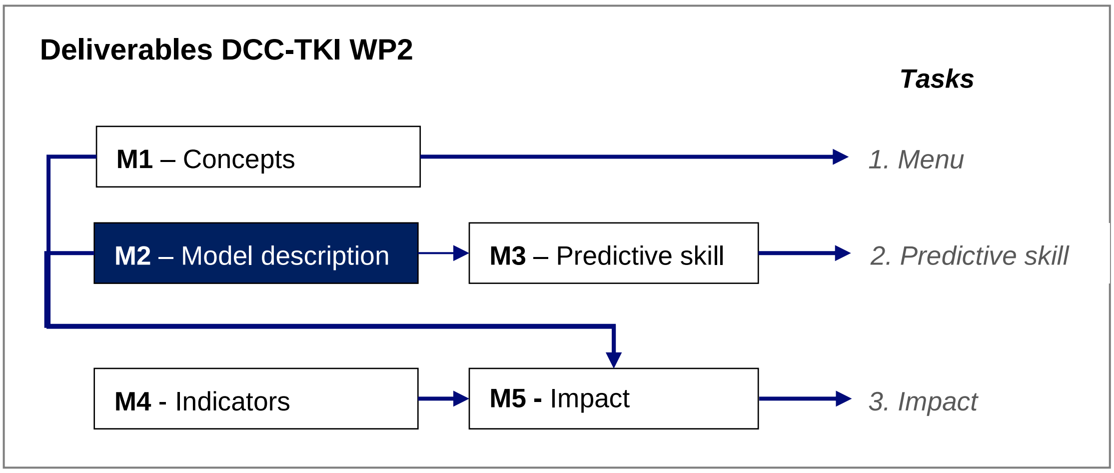

Figure 1 Overview of deliverables (memos) within the DCC-TKI project, relationship with WP2 tasks and interrelationships.

1.1 Scope

The aim of this memo is to define and describe the nourishment performance indicators for the morphological and ecological impact of different nourishment concepts. The performance indicators are subdivided over three main coastal functions: coastal safety, ecology, and recreation.

The quantification of these indicators is done using a numerical model, Delft3D FM. Aspects that cannot be quantified sufficiently with the numerical model will be evaluated using expert judgment in Workpackage 5 (‘integratie en afwegingskader’).

Note that indicators related to costs, emissions, or licensing, are examined by other Dutch Coastline Challenge Workpackages and are out of scope for this memo.

1.2 Reader

This memo starts with outlining the approach (chapter 2). Next the indicators are described grouped per coastal function: coastal safety (chapter 3), ecology (chapter 4 & 5), and recreation (chapter 6).

In the beginning of each chapter the relevance quantifying the coastal function will be discussed (i.e. the ‘why’ of the quantification) followed by the definition of the indicators (i.e. the ‘what’ of the quantification). Next a methodology section will show how the indicator can be derived from the model data (i.e. the ‘how’ of the quantification) and an example will be given to illustrate the data that results from the quantification procedure.
Chapter 7 summarizes the work with the conclusions and outlook.

2 Approach

To establish the mmorphological and ecological indicators we use the following approach:

1. Generate a longlist of potential indicators through an initial inventory.
2. Select indicators that can be (partly) quantified with the model, based on model skill, importance and the overall aim of the DCC project.
3. Establish a method per indicator to compute the indicator from the model results and demonstrate the method.

2.1 Longlist of indicators for morphological and ecological impact

As a first step an initial inventory by the DCC team has resulted in a longlist of morphological and ecological indicators that can be relevant for the evaluation (Table 1). These can be grouped in the three main coastal functions: coastal safety, ecology, and recreation.

Table 1 Overview of all indicators deemed relevant during inventory

Coastal function / (indirect) ecosystem service	Indicator	Abiotic factors (from model)
Coastal safety (Ch3)	Longshore feeding range (m)	Longshore distribution of volume in coastal profile from shoreface to dune (m^3)
	Local erosion (ha)	Coastline position
	Dune volume (m^3)	-
Ecology (Ch0 & Ch5)	Benthic population (ha)	Burial (cm/month)
	Habitat provision (ha)	Environmental conditions: • Shear stress (N/m2) • Water depth (m)
	Dynamic dunes (%)	Aeolian flux towards the foredune ($m^3/m/yr$)
	Turbidity (-)	-
Recreation (Ch0)	Disruption due to construction (%)	-
	Sunbathing (-)	Beach area (m)
	Swimmer safety (-)	Currents (m/s)
	Watersports	• Water depth (m) • Wave height (m) • Currents (m/s)

2.2 Delft3D Flexible Mesh Model to quantify indicators

Indicators are to be quantified with a Delft3D Flexible mesh model. This numerical model plays a key role in the quantification of the indicators. Since the model is reasonably well capable of predicting longshore morphological development of large-scale interventions (Technische Universiteit Delft, 2023c), it will be employed to extract some of the coastal performance indicators (e.g. the longshore feeding capability of nourishment concepts, table 1). However, the process-based model has several limitations, amongst the most important are:

1) Subaerial processes are not included, meaning the evolution of the dry beach and dunes are not included.

2) Cross-shore processes are not described well, resulting in unrealistic cross-shore development, such as flattening of the breaker bars.

Because of these limitations, the results on indicators need to be interpreted with care. The role of the model to quantify indicators for concepts that are heavily dependent on cross-shore transport, such as shoreface nourishments, will be limited. Additionally, no indicators related to beach or dune development (beach width, dune volume, fluxes, dynamics, etc.) will be quantified.

3 Indicators for mapping changes in coastal erosion

3.1 Relevance

Along the Dutch coast, sand in the coastal system is crucial for hinterland flood protection. The Dutch coast is maintained using a dynamic conservation strategy, also referred to as dynamic preservation (Lodder & Slinger, 2022). Nourishments are applied along the Dutch coast to achieve two main objectives:

1) Dynamically maintaining the *coastline* at its 1990 position
2) Maintain the sediment budget within the *coastal foundation* (i.e. the area between the landward edge of the dunes and the 20 m depth contour of the North Sea)

Over the last decades, studies (e.g. Stive et al., 2013; Brand et al., 2022) have shown that “regular” nourishment concepts can provide coastal safety by feeding the coast. Regular nourishments are placed relatively close to target areas, which makes the longshore feeding capacity less relevant for these types of nourishments. More innovative concepts, such as feeder-type nourishments (mega- or continuous nourishments), have a stronger dependency of longshore spreading. Therefore, morphological predictions of the longshore spreading of the sediment are useful for the evaluation of feeder-type nourishments.

3.2 Indicator description

We use the coastline position and the profile volume in the coastal foundation zone as indicators to determine whether a nourishment concept is capable of providing coastal safety. Analyzing the spatiotemporal evolution of these indicators provides insight into the longshore spreading, and hence feeding capacity, of nourishment concepts. Since the coastline position is depending on cross-shore processes, which are not resolved well by the model, the main focus will be on the longshore distribution of sediment in coastal foundation.

Profile volume in the coastal foundation zone
The coastal foundation is defined as the active coastal zone, stretching from the landward side of the dunes to the 20 m depth contour (Lodder & Slinger, 2022). The coastal foundation will be expressed as a volume V (m^3/m). The sensitivity of volume in the coastal foundation to the cross shore behavior is limited. Since the mentioned model limitations can affect the accuracy of cross-shore predictions, the volume of the coastal foundation is a suitable indicator that only focusses on the longshore feeding capability.

Coastline position
The position of the coastline in the Netherlands is calculated using a volume-based approach. This Momentary Coastline, or MCL (Hillen et al., 1991), is determined by calculating the volume between a landward and seaward boundary. The landward boundary is defined where the bed level crosses the dune foot (+3 m NAP). The seaward boundary is defined as the location where the bed level crosses the Mean Low Water minus height h. The vertical distance between the Mean Low Water level and the dune foot is defined as the height h (m). The MCL position is calculated by dividing the MCL volume by the total vertical elevation (= $2*h$). The overall calculation method is visualized in Figure 2 (left).

The Mean Low Water level varies in longshore direction, and therefore also the elevation of the seaward boundary. In our domain of interest, the seaward boundary varies between -4.5 m NAP (IJmuiden) to -4.68 m NAP (Callantsoog) in North Holland and between -4.74 m NAP (Den Hoorn) and -4.94 m NAP (De Koog) at Texel (Hillen et al., 1991). For consistency, a constant value of the seaward boundary is chosen. As most of our analysis is based on the Egmond-Bergen zone, the elevation of the seaward boundary is set to -4.58 m NAP.

When the bed level crosses the land- and/or seaward boundary multiple times, this approach is not applicable. Such situations can occur if the crest of a nourishment or breaker bar extends into the MCL-domain (>-4.58 m NAP) or even extends above the dune foot reference height (>3 m NAP). To take these situations into account, an adjustment has been made to the approach (van Zanten, 2016), which is shown in Figure 2 (right). In these cases, also the volume within the MCL-domain in disconnected parts of the coast are included in the volume.

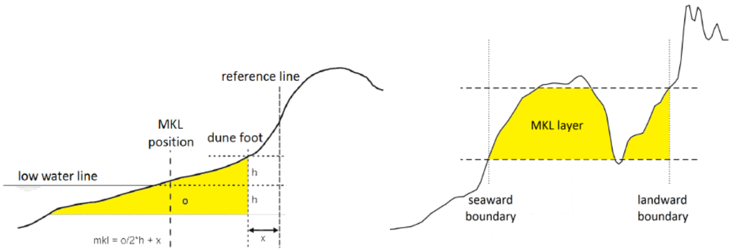

Figure 2 Conceptual presentation of the volume-based approach to compute the coastline position, left (Hillen et al., 1991) *and an adjusted procedure in case of multiple crossings of the sea- and landward boundaries, right* (van Zanten, 2016)*.*

3.3 Method

The procedure for the computation of the coastline and profile volume in the coastal foundation consists out of several steps. The computed bed level is provided on a two-dimensional grid by the process-based model, with a weekly (morphological) output frequency. Within our domain of interest, all cross-shore positioned rows of cells in the two-dimensional grid were considered as separate one-dimensional transects. Based on the definitions described in §3.2, the coastline position and volume of coastal foundation are calculated for each individual transect.

Next, we construct timeseries of the change with respect to the setting prior to the nourishment and corrected for the autonomous response of the model. This is done for the coastline position *MCL* and profile volume *V* and illustrated in the in the equations below for the profile volume in the coastal foundation zone.
Timeseries of the absolute profile volume change are given by:

$$\Delta V_{concept,T} = V_{concept,T} - V_0$$

Where:

$\Delta V_{concept,T}$: Profile volume change in the coastal foundation (m^3/m)
$V_{concept,T}$: Profile volume in the coastal foundation at timestep *T* (m^3/m)
V_0 : Profile volume in the coastal foundation at before any nourishment (m^3/m)

The initial bed levels based on observations are not necessarily in balance with the forcing condition in the model schematization. Examples of this are small alongshore shoreline undulations that are removed by the model or a cross shore profile with sandbars which is converted to a smooth profile over time.
This means that model results also include morphological changes due to adjustments to the forcing (i.e. irregardless of the nourishment). Especially the shoreline position is affected by this autonomous response. The results of the nourishment scenarios are corrected for this autonomous response. This is illustrated in the equations below for the profile volume in the

coastal foundation zone.

$$\Delta V_{ref,T} = V_{ref,T} - V_0$$

$$\Delta V_{corr,T} = \Delta V_{concept,T} - \Delta V_{ref,T}$$

Where:

$\Delta V_{reft,T}$:	Volume change in the coastal foundation in the autonomous situation (m^3/m)
$\Delta V_{corr,T}$:	Corrected volume change in the coastal foundation (m^3/m)
$V_{ref,T}$:	Volume in the coastal foundation at T in the autonomous situation (m^3/m)
V_0 :	Volume in the coastal foundation at T=0, before any nourishment (m^3/m)

The resulting timeseries of $\Delta V_{corr,T}$ and $\Delta MCL_{corr,T}$ (*derivation similar but not shown here*) are used to evaluate the nourishment performance. They are referred to as ΔV and ΔMCL from hereon.

3.4 Illustration

We illustrate the type of results for the indicators for mapping changes in coastal erosion with an example of the change in profile volume ΔV for a mega nourishment of about 7.5 million m^3 placed between Egmond and Bergen. For this particular concept, the nourishment volume was designed to feed 10 km of coast for 10 year.

The longshore distribution of sediment within the change in coastal foundation ΔV is shown in Figure 3. This indicator provides insight into the alongshore feeding of the coast and its influence zone (Figure 3).
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 the spreading. In the simulation shown, the nourishment is not fully redistributed over the coastal stretch and little sediment volume gains are found several kilometres. Only for a small (~40%) part of the alongshore stretch the profile volume exceeds the ~750 m^3/m (Figure 3, darkest green patch). Similarly we can examine where sediment volume equals 50% (i.e. ~375 m^3/m) or 5 % (~37.5 m^3/m) of this value of uniform redistribution (Figure 3, intermediate and light green patch respectively).

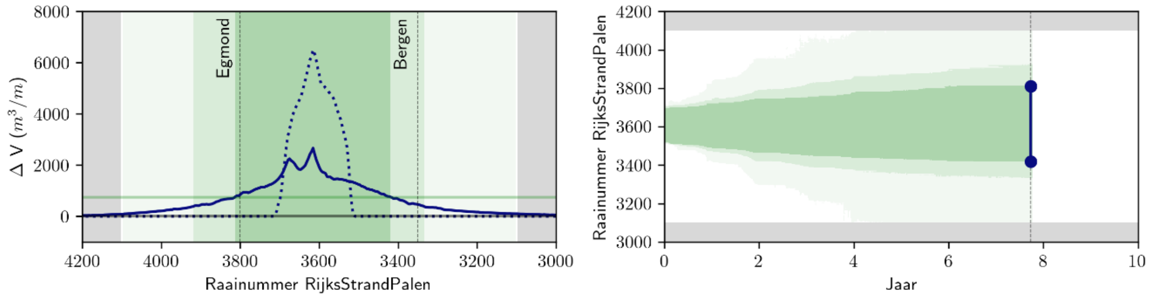

Figure 3 Left) The longshore distribution of sediment in the coastal foundation (left panel) just after implementation of the nourishment (dotted line) and after appr. 8 years of development (continuous line). The threshold indicating uniform redistributed sediment is given by the green horizontal line. The dark, intermediate and light green patches indicate if profile volume exceeds respectively 100%, 50% or 5% of the value of uniform redistribution.
(Right) The development over time is shown by stacking the impact zone over time. Raainummer RijksStrandPalen is the alongshore coordinate with a distance 100 representing approximately 1 km.

4 Indicator for mapping changes in ecotopes

4.1 Relevance

The ecological quality of ecosystems largely depends on the depth of the seabed and the related abiotic factors. Ecotopes are spatially delimited ecological units whose composition and development are determined by abiotic, biotic, and anthropogenic conditions on site. Since nourishments have a strong influence on these abiotic conditions, ecotopes can be a useful indicator for the evaluation of the impact of nourishments on the ecological quality.

4.2 Indicator description

The ecotope area is examined following the approach of van Zanten (2016). The ecotope classification used in that assessment is based on an ecotope system for the Dutch coast (Bouma et al., 2005) where the coastal system is divided into nine ecotopes (Table 2) Ecotope classifications can be based on all kind of abiotic conditions, such as salinity, nutrient availability, or sediment characteristics, however, our model only provides us with hydrodynamic and morphological information. Therefore, we chose to apply an existing ecotope classification that is based on bathymetric and hydrodynamic conditions.

In the ecotope classification by Bouma et al., (2005), the hydrodynamic conditions are based on current velocities (m/s), however, in a recent application by van Zanten (2016) this has been translated to hydrodynamic stresses (N/m^2). Since stress is a direct model output, for the sake of simplicity, we adopted the approach by van Zanten (2016). Eventually, the ecotope classification limits are determined by the bed level elevation (m NAP) and the bed shear stress τ as a result of hydrodynamic forcing (N/m^2), see Table 2.

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	$h \leq -0.95$	$\tau > 4$
2	Seaward side of the surfzone	$h \leq -0.95$	$2 < \tau \leq 4$
3	Nearshore	$h \leq -0.95$	$1.2 < \tau \leq 2$
4	Offshore	$h \leq -0.95$	$0.3 < \tau \leq 1.2$
5	Sheltered subtidal	$h \leq -0.95$	$\tau < 0.3$
6	Exposed lower intertidal	$-0.95 < h \leq 0$	$\tau > 0.1$
7	Exposed upper intertidal	$0 < h \leq 1.2$	$\tau > 0.1$
8	Sheltered intertidal	$-0.95 < h \leq 1.2$	$\tau \leq 0.1$
9	Supratidal	$h > 1.2$	-

The supratidal zone hosts many opportunities for development of various dune habitats (grey dune, dune slack, green beach, embryonal dune). These different dune habitats are not considered in detail but combined in the class ‘supratidal beach’.

4.3 Method

For the quantification we need the bed level elevation and the shear stress. The bed level elevation is directly provided by the model. Acquiring the hydrodynamic bed shear stress requires additional hydrodynamic computations and post processing. The bed shear stress depends on the hydrodynamic forcing and is therefore highly variable in the morphodynamic computations with bruteforce forcing. In order to obtain consistent results, the bed shear stress must be computed for a fixed set of hydrodynamic conditions.
Here we used the same dominant wave condition as van Zanten (2016) is used: $H_s = 1.48$ and $\Theta = 232^o$ N (SW).

The bed shear stress computations are based on the yearly bathymetries obtained from the long-term morphodynamic simulations. For each yearly bathymetry (for each alternative), a fixed dominant wave condition is imposed during one tidal cycle, resulting in one ecotope map per year. The bed shear stress is then computed by taking the average bed shear stress over one tidal cycle.

The numerical model is validated on both hydrodynamics (Technische Universiteit Delft, 2023b) and morphological development (Technische Universiteit Delft, 2023c). The relevant hydrodynamic conditions (water levels and wave heights), and the large-scale long-term morphological behavior are reproduced well by the model compared to measurements. Since these two abiotic conditions are the only input into this classification system, it is reasonable to assume that the predicted ecotope outcome, based on the currently chosen classification, is realistic. However, it must be noted that the number of given abiotic conditions is of course limited. There are many more factors that could influence the spatial ecotope distribution, such as morphological features (Holzhauer et al., 2020). Besides, we focus on one single wave condition, neglection periods with calmer conditions and extreme events or seasonality entirely. Additionally, we have to be aware that ecology may not directly respond to the changing abiotic conditions. Benthic life on the shoreface is known to take several years to fully recover after a major intervention (Baptist et al., 2009a). This means that, after an intervention, the surface area of ecotopes calculated using instant adjustment is likely to be overestimate ecological recovery.

The methodology outlined above results in an ecotope map, a spatial pattern of the different ecotopes. Subsequently, the ecotope surface area A for can be calculated for each of the nine classes in Table 2.

Similar to the erosion indicators (section 3.3), the autonomous response of the model is removed from the results to focus on the impact of the nourishment concept. The resulting indicator as ΔA (ha/year) maps the changes in ecotope surface area relative to the pre nourishment situation and in comparison, to simulation without a nourishment, averaged over time.

4.4 Illustration

We illustrate the type of results for the changes in ecotope surface area with an example of a mega nourishment of about 7.5 million m^3 placed between Egmond and Bergen.
The different bed levels and shear stress result in a mosaic of the different ecotopes (Figure 4).

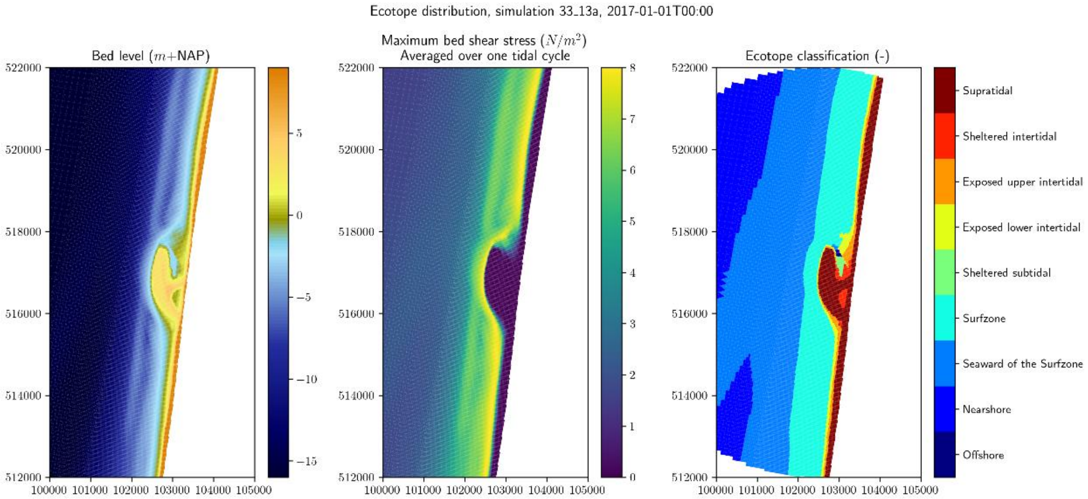

Figure 4 Ecotope map of a mega nourishment. Axes are in the Dutch Coordinate System in meters.

The temporal evolution of the ecotope area ΔA shows how the implementation of a nourishment and the subsequent redistribution of sediment can change ecotopes (Figure 5).

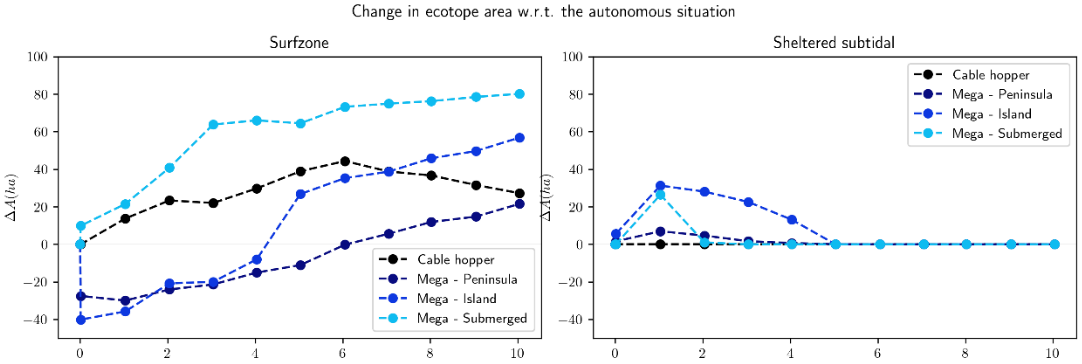

Figure 5 Temporal evolution of ecotope surface areas for the ‘surfzone’ (left) and ‘sheltered subtidal’ (right) ecotopes. Colored lines represent the results for 4 different nourishment concepts.

5 Indicator for mapping changes in burial of benthic life

5.1 Relevance

Nourishments can have a negative impact on the benthic population in the coastal zone as a result of an abundance of sedimentation, burying benthic species. In this respect we separate *direct* impact as a result of dumping sand during the construction of the nourishment and *indirect* impact as a result of burial due to (enhanced) sediment transport arising because of altered morphological behavior.

5.2 Indicator description and method

We developed a tool (the *Benthimeter*) to examine the relative effect of nourishment strategies on the benthos population. This is a multi-faceted problem that cannot solely be done using a morphodynamic model. We can however use the results of the morphodynamic model to assess the burial depths and rates. From these data we damage to benthic life due to 1) burial, 2) recovery over time, and 3) a maximum carrying capacity depending on depth and seasonality. The key input for this model is the bed levels and the change in bed levels (see Figure 6). In the current setup we calculate this benthic burial and response for 2 types of species.

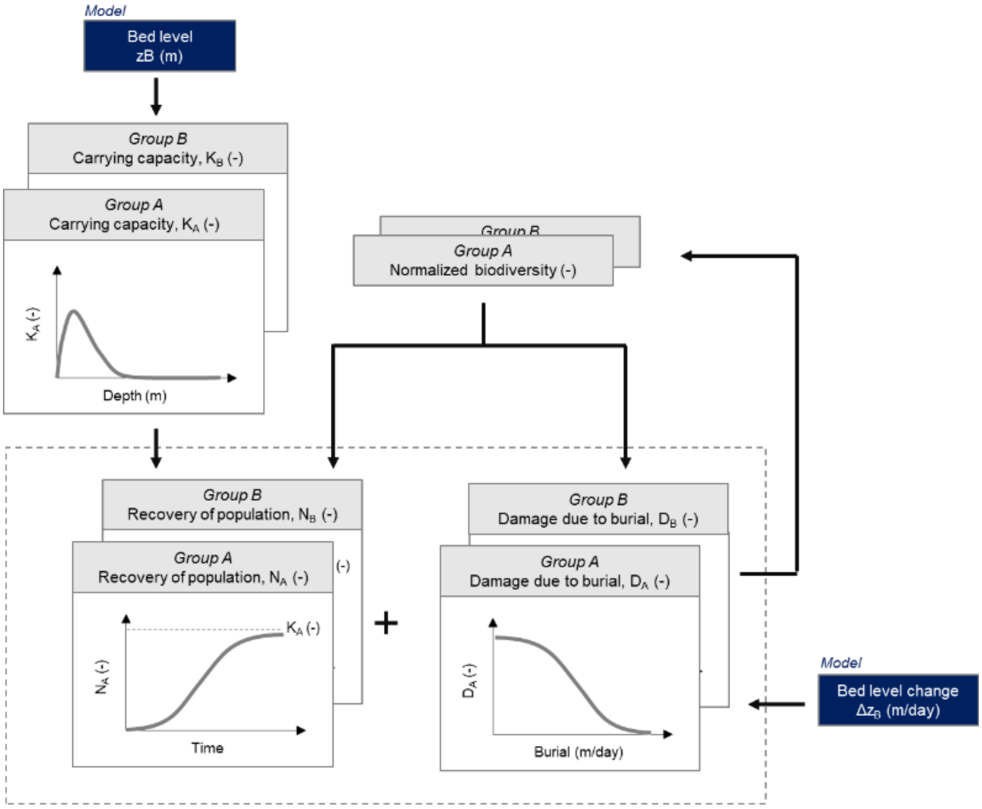

Figure 6 Flowchart of the steps within the Benthimeter to estimate the benthic response to burial

The development of the Benthimeter is part of the MSc graduation work of Chris Gielen. For a complete description of the used literature, applied methodology and results, see Gielen (2023). The Benthimeter eventually computes the ecological damage over time (ha) which is spatially integrated. Averaging this ecological damage and compared to a computation without a nourishment, this gives an indication of the total ecological damage (ha) over the lifetime of a nourishment, which allows for the direct comparison of nourishment concepts.

5.3 Illustration

We illustrate the type of results for the burial of benthic life with an example of a mega nourishment of about 7.5 million m³ placed between Egmond and Bergen. The methodology contains several parts that are subjected to uncertainty (e.g. the response curve of species to the burial, Figure 6). To address the uncertainty, we varied the parameters in the Benthimeter to obtain 1000 different simulations of the response of the benthic life.

The results from of the Benthimeter are a spatial distribution of the normalized benthic diversity for multiple timesteps (Figure 7). For the damage to the benthic population, or reduction of the normalized benthic diversity, two causes can be distinct: 1) damage by direct burial and 2) change of carrying capacity due to a new bed level elevation. The results show variations on an annual timescale. This is the response to the winter season where sediment is mobilized by storms.

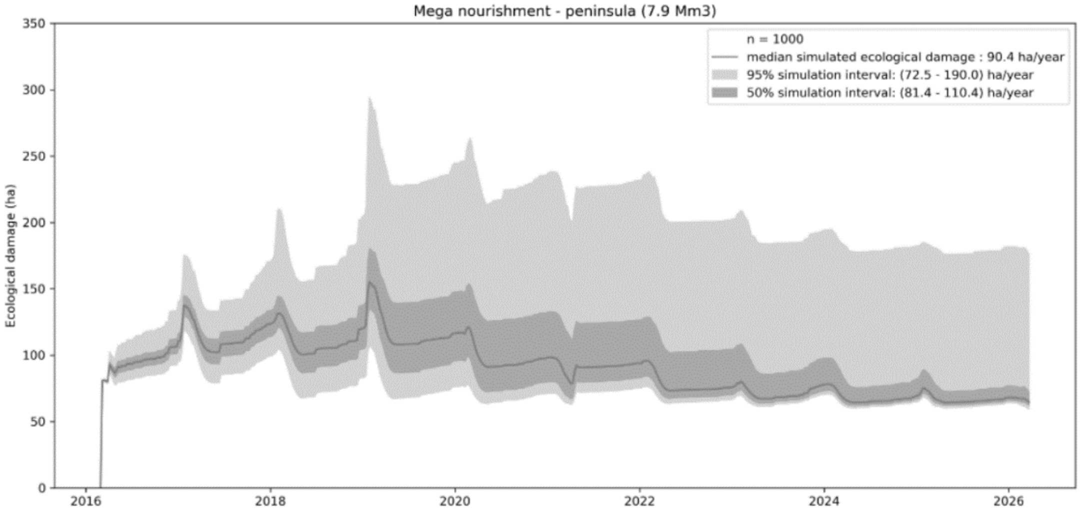

Figure 7 Illustration of the ecological damage integrated over space (ha) over time. The grey bands indication the uncertainty related to variations in model input parameters.

6 Indicators for mapping changes in recreational area and swimmer safety

6.1 Relevance

Nourishment concepts have potential benefits to recreational user functions in the form of (new) recreational areas for swimming, surfing and beach recreation, as was the case with the Sand Engine (Huisman, 2021; van Zanten, 2016). Especially large-scale interventions can also have an unexpected impact on the (swimmer) safety of visitors. Multiple indicators will be presented in this chapter that allow for the evaluation on the impact of nourishment concepts on the recreational value of the coast.

6.2 Indicator description

Recreational beach area
Beach area can increase as a result of the implementation of (beach) nourishments or indirectly through the longshore or cross-shore redistribution of nourished sands. This newly created beach area can be visited by recreationists for sunbathing, walking, and sporting activities. It must be noted that a wider beach is not always favorable for recreational value since the walking distance towards the waterline should not be too long. Only limited studies have been conducted on the optimum beach width for recreational purpose (e.g. Todd et al., 2016), so the translation from beach area to recreational value is still open for discussion. The minimal beach width during high tide could additionally be used as an indicator for stakeholders, such as beach club owners. However, due to the limited cross-shore spatial resolution in the model and a lack of subaerial processes, we deem the model’s predictive skills not sufficient to provide accurate estimates of such indicators.

Sheltered watersports area
A sheltered waterbody can serve for water-based activities, such as kitesurfing. An example of this is the lagoon in the Sand Engine, drawing many kitesurfers over the last years (Huisman, 2021). For the watersports we will focus on kitesurfing only.

Swimmer safety
Large-scale interventions can cause safety issues for recreational beach users due to the potential occurrence of unnatural morphological features leading to scarp formation, strong currents and the presence of large intertidal bars. For instance, certain dynamics can cause the formation intertidal bars in the form of islands and spits that can become closed off from the mainland during high tides which can trap recreational beach users. Additionally, strong currents can arise due to the presence of these morphological features, endangering swimmer safety.

6.3 Method

Recreational beach area

The dry beach area, or supratidal beach, is defined based on the same limits as for the ecotope classification of supratidal beach (bed level h > 1.2 m NAP, see Ch4). An additional requirement is that the area must be accessible from the mainland by foot over duration of the entire tidal cycle (i.e. omitting islands or shallow sand bars). Therefore, the supratidal beach needs a continuous connection with the mainland with a minimum height of 1.2 m NAP.

Sheltered watersports area

For beginning kitesurfers, calm conditions in shallow waters are favorable, so the hydrodynamic stress and bed level are used determine the area suitable for kitesurfing. Both the *sheltered subtidal* and *sheltered intertidal* ecotopes from Ch4 ($h \leq -0.95$ m NAP & $\tau < 0.3$) are used here as an indicator of the sheltered area suitable for watersports.

Recreational safety

To quantify recreational (swimmer) safety, morphological features and flow velocities with a very high spatiotemporal resolution are needed. Since these are not available from the current modelling approach, we cannot quantify these in great detail, meaning that expert judgement will play a big role.

6.4 Illustration

We illustrate the type of results for gained beach area for recreation with an example four nourishment concepts of about 7.5 million m^3 placed between Egmond and Bergen.
The added beach area suitable for recreational is shown in Figure 8. Averaging these areas over time enables the direct comparison of the impact of different nourishments concepts on recreational value.

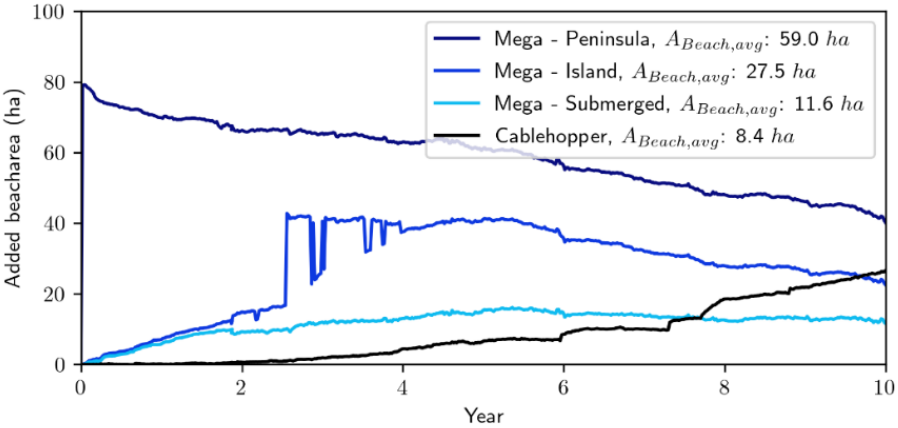

Figure 8 Temporal evolution of gained beach area for four different nourishment concepts. Note that we only use the added beach area which is accessible (i.e. emerged parts of nourishments offshore are excluded). The intermittent connection of the island alternative with the shore results in strong fluctuations in this line.

7 Summary and recommendations

In this memo we presented multiple morphological and ecological indicators that will support the quantitative evaluation of a selection of nourishment concepts steered by the assessment framework developed in WP5. These indicators are related to the following coastal functions:

- Safety against flooding,
- Ecotope surface area,
- Burial of benthic life, and
- Recreation

These indicators form the basis of the evaluation of nourishment concepts discussed in Technische Universiteit Delft (2023e). The indicators are calculated based on hydro- and morphodynamic information generated with a dedicated Delft3D-FM DCC model (Technische Universiteit Delft, 2023b; 2023c).

The quantification of indicators is limited by model limitations and knowledge gaps, i.e. relations between biotic and abiotic conditions or valuation of morphological behavior for recreational values. In order to improve the evaluation of coastal interventions, the quantification of coastal performance indicators need to be improved.

Preventing coastal erosion
For quantifying the feeding capacity of nourishment concepts, we focused on the longshore feeding only and used the distribution of sediment over the entire coastal foundation as an indicator, in order to prevents inaccurate predictions related to cross-shore behavior would affect the results. As a result, it was not possible to directly compare nourishments concepts driven by cross-shore processes with concepts driven by longshore processes. Moreover, we were unable to say much meaningful about the impact on the coastline. To improve this, the implementation of improved cross-shore behavior in the model, either based on data assimilation or an empirical relationship, is recommended.
Besides, no evaluation on the influence on dune development or beach width is done, due to the lack of Aeolian processes in the model. Implementation of or coupling with aeolian processes is necessary to extend the evaluation outside of the marine domain.

Ecology
The evaluation of ecotope area is based on two abiotic conditions, that could be directly derived from the model. In reality, ecotope distribution and the quality of ecology is depending on a very complicated combination of many conditions, making it virtually impossible to fully predict ecotope development related to abiotic development in future evaluations. However, it has been proven that the existence of certain morphological features are important in explaining the distribution of benthic species communities (Holzhauer et al., 2020), and therefore the ecotope distribution. Implementing the behavior of morphological features into the quantification of ecotope distribution could improve predictions. If this is desired, also the description of the development of morphological features (breaker bars) must be improved in the model (see above). For the validation of such an approach, the ecotope distribution could be monitored after the construction of a (large-scale) nourishment, to see whether the relations between abiotic conditions and the ecological value are correct and to measure the time ecosystems need to adept to the newly enforced abiotic conditions.

The same accounts for the response of benthic communities to direct and indirect burial. Much of the relations between benthic life and the abiotic conditions from the model (i.e. the relation between burial and survival rate) are surrounded by a lot of uncertainties. Improving our knowledge on these knowledge gaps can improve the quantification of benthic response to nourishment construction. This could be done by conducting high frequency monitoring experiments on the benthic response to varying burial depths at varying bed levels and monitoring the recovery on a spatial scale over time (including seasonality, recovery due to migration vs. local recovery, etc.).

Recreation

In this analysis, the additional of recreational value is purely based on the development of areas fulfilling certain abiotic conditions (bed level elevation or hydrodynamic stress). The actual human valuation of these areas is not considered.

Relying solely on physical results does not make it possible to attach value to recreational value of certain areas. For this, more research is needed on the appreciation that recreationists have for certain types of beaches and the type of recreation that can occur here. For example, a very wide beach (>500 m) can serve specific recreation perfectly well (e.g. dog walking, blowkarting), while other types of recreation, such as swimming or sunbathing, are reported to prefer narrower beaches.

Moreover, many of the developments are temporary in nature, potentially also affecting their valuation. For instance, preference may be given to a permanent lake where water sports can be enjoyed as opposed to one that is blown shut after a few years.

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