Chapter 5: Assessing the impact of beach nourishment on the intertidal food web through the development of a mechanistic-envelope model

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Sarah Vanden Eede and Joke Van Tomme worked together on this chapter in equal measure from the starting idea to the first complete draft (as included in the PhD of Joke Van Tomme). Sarah Vanden Eede was the leading author of the current final draft (more and other analyses, restructuring and rewriting the manuscript) and she will be the contact person once the manuscript has been submitted.

Abstract

Beach nourishment is widely applied as a coastal protection measure because of its reduced ecological impact relative to hard coastal protection. In order to predict expected ecological impact on the sandy beach ecosystem, we developed a simulation model that integrates species envelope-based projections for the dominant macrobenthos species and mechanistic food web modules for higher trophic levels.

Species envelopes are estimated by using Bayesian inference of species' biomass relationships according to the three main determining abiotic variables, i.e. median grain size, total organic matter and the intertidal elevation, obtained from multiple independent sampling campaigns along the Belgian coast. Maximal possible abundances of higher trophic levels, being birds, shrimp and flatfish, are estimated based on their functional and energetic relationships with macrobenthos as an important food item.

After validation, we demonstrate that sediment grain size is the most important factor determining beach-level diversity and production, with strong deterioration after nourishment with too coarse sediment (e.g. >> than 300 µm). Nourishment slope had a smaller impact on the species zonation patterns compared to the sediment grain size. Patterns for higher trophic levels do not follow the decreasing patterns in macrobenthos abundance and biomass.

The advised gradient in sediment grain size for nourishment of fine-grained beaches is defined as 200 – 300 µm. This modelling approach shows that the assessment of ecosystem health needs to include the evaluation of different species richness and biomass variables. Focusing solely on for instance the potential abundance of species from higher trophic levels might lead to deceptive conclusions due to the dominance of opportunistic prey species.

Key words: beach nourishment, species envelope modeling, macrobenthos, fish, birds

1.   Introduction

Coastal ecosystems are strongly threatened by climate change due to changes in sea level rise, erosion, changes in storm and wave regimes, flooding, altered sediment budgets and the loss of coastal habitat (Harley et al. 2006; Jones et al. 2007). In the last hundred years global average sea level has risen by 0.1 – 0.2 m (Houghton et al. 2001). In the past, the adaptive management response for the soft sediment ecosystems such as sandy beaches has been the enhancement of existing sea defences and retreat in areas of low-value land. Furthermore, coastal erosion has become an important issue on sandy beaches over the last decades as globally 70 % of beaches are receding, while 20 – 30 % remain stable and 10 % or less are accreting (Bird 2000).

Sandy beaches are the single largest coastal ecosystem on earth and they are covering 70 % of all continental margins (McLachlan & Brown 2006). They have a multitude of ecosystem functions as they are an important habitat for a variety of flora and fauna, and are concurrently of immense social and cultural importance to humans as prime recreational assets. More people interact directly with beaches than with any other type of shoreline worldwide (Schlacher et al. 2008). Sandy beaches also play an important role in coastal defence by functioning as a natural buffer between sea and land (Brampton 1992; Riddell & Young 1992), thus protecting landward sea defences from scour and wave erosion (Brampton 1992; Riddell & Young 1992).

In the past, the construction of hard structures as a management strategy for coastal defence enhanced beach erosion and destroyed important ecosystem functions (Defeo et al. 2009). Current widely applied defence approaches use beach nourishment to counteract coastal erosion and protect the land from flooding. This is particularly the case on the West European beaches of Belgium and The Netherlands, as these countries are vulnerable to sea level rise and storms due to their low height. Different types of beach nourishment can be executed. The most common types are high-shore, low-shore and profile nourishment (Speybroeck et al. 2005a). Up till now, technical aspects (e.g. easily available sand with coarse grain size and a rather steep and thus more stable beach slope (Finkl & Walker 2002) were dominant in taking management decisions for beach nourishment projects. In the light of international and European legislation, urging towards Integrated Coastal Zone Management (ICZM), attention for the functionality of the sandy beach ecosystem has increased (Schlacher et al. 2008). Although beach nourishment is generally considered as the least harmful beach management option (Hamm et al. 2002; Hanson et al. 2002), it does put a severe pressure on the biota living on, in and around sandy beaches (Speybroeck et al. 2006a). However, well-conceived impact studies are scarce (Jones et al. 2008; Leewis et al. 2012; Schlacher et al. 2012) and especially adequate information to predict the impact of nourishment on the beach ecosystem and to ecologically adjust nourishment projects, is lacking.

Optimizing technical aspects (e.g. characteristics of the sediment used, slope of the nourished beach, nourishment timing) of the nourishment projects is indispensable to maintain an ecologically healthy ecosystem on the beach. Indeed, the ecological characteristics of the beach fauna and flora are very much determined by morphodynamic beach characteristics such as grain size and beach slope (McLachlan & Jaramillo 1995; McLachlan 1996; Defeo & McLachlan 2005). As management of beaches is a multi-faceted and complex endeavour, where the interests of several stakeholders need to be combined, coastal managers need to interact with ecologists to integrate ecological aspects in beach management. Hence, clear and user-friendly management tools are essential in taking interdisciplinary management decisions (Schlacher et al. 2008).

As a good knowledge on the morphodynamics of Belgian sandy beaches is available (Degraer et al. 2003b; Speybroeck et al. 2008a), this beach ecosystem was used to develop a combined mechanistic-niche envelope model to predict the impact of beach nourishment on species richness at different trophic levels. The model builds further on well-established insights that the realised niche of lower trophic levels can be predicted based on three beach parameters, i.e. slope, grain size and organic matter, that are correlated under equilibrium conditions (Degraer et al. 2003b; Speybroeck et al. 2006a). Microphytobenthos and macrobenthos species composition are well documented along the Belgian coast. The importance of macrobenthos as food for birds and fish is also illustrated and quantified (Beyst et al. 1999a; Beyst et al. 1999b; Vanermen et al. 2009) and here mechanistically modelled by applying energy-based trophic interaction rules.

The general objective of this study was to develop a nourishment simulation model for the Belgian beach ecosystem. The simulation model had the aim (1) to predict short-term changes in beach macrobenthos species richness in response to changes in beach profile and grain size following beach nourishment and (2) to elucidate how these changes in community composition potentially feedback on the abundance of dominant species of higher trophic levels (birds, fish and shrimp).

2.   Material & methods

2.1   Model description

For the model description, the 'Overview, Design concepts and Details' protocol (ODD) (Grimm et al. 2010) was followed. This protocol standardizes published model descriptions, making them less subject to criticism for being irreproducible.

2.2 Species envelopes

A species envelope is defined as the set of environmental conditions at locations where a species is known to occur, thereby assuming that on other locations with similar conditions, the species will also be present. This approach has been hugely successful, also in marine systems (Snickars et al. 2013) in other applications like climate change research, despite the caveats of such an approach for predicting large scale species ranges (Guisan & Zimmermann 2000; Bahn & McGill 2012). Earlier research elucidated either linear or quadratic relationships among the abundance or biomass of the main macrobenthos species with abiotic parameters (Beyst et al. 2002; Degraer et al. 2003b; Speybroeck et al. 2006a). Species envelopes for these taxa were derived from data collected on 23 intensively sampled beaches along the Belgian coast, during different seasons within the period 1997 – 2011 (Degraer et al. 2003b; Speybroeck et al. 2003; Speybroeck et al. 2005b; Welvaert 2005; Van Ginderdeuren et al. 2007; Vanaverbeke et al. 2008; Vanden Eede et al. 2008; Vanden Eede & Vincx 2010, 2011b) (see also Appendices – Chapter 5 – appendix A).

2.3 Entities, state variables, and scales

Model entities

The model consists of three major modules, one determining the abiotic conditions of the beach, a second module modelling predicted (changes in) abundance and biomass of macrobenthos according to their envelopes and a third one predicting the maximum abundance of the most important species from higher trophic levels. For the macrobenthos, the abundance and biomass of the eleven most dominant species were taken into account. These dominant species comprised the polychaetes *Nephtys cirrosa* and *N. hombergii*, *Capitella capitata*, *Spio filicornis*, *Pygospio elegans*, *Eteone longa* & *Scolelepis squamata*, the amphipods *Bathyporeia pilosa* and *Bathyporeia sarsi* and the isopods *Eurydice pulchra* and *E. affinis*. The most important species from higher trophic levels included the gulls *Larus canus* and *L. ridibundus*, the waders *Calidris alba* and *C. alpina*, the shrimp *Crangon crangon* and juvenile flatfish (mainly *Pleuronectes platessa*).

State variables

Three state variables determine the species richness and abundance of macrobenthos along sandy beaches: median grain size (*MGS*), total organic matter (*TOM*) and elevation (*h*) relative to the lowest tide, being 0 m TAW, i.e. the vertical level of reference in Belgium (McLachlan & Jaramillo 1995; Degraer et al. 2003b; Veloso et al. 2003). The slope of the beach (*α*) determines the submergence area and availability of prey for higher trophic levels (figure 1). The available biomass of species belonging to the

lower trophic levels are input variables for estimating abundance of species from higher trophic levels and species richness (S).
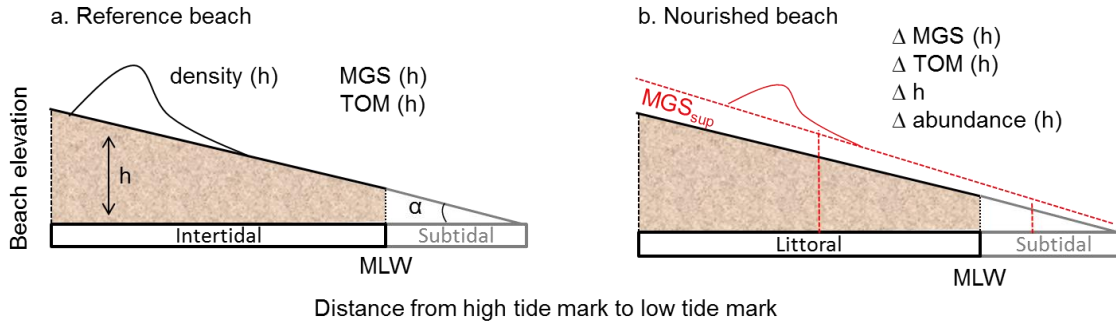

a. Reference beach

b. Nourished beach

Δ MGS (h)
Δ TOM (h)
Δ h
Δ abundance (h)

density (h)   MGS (h)
               TOM (h)

MGS_{sup}

Beach elevation

h

α

Intertidal   Subtidal

Littoral   Subtidal

MLW

MLW

Distance from high tide mark to low tide mark

Figure 1: Schematic overview of the principal state variables. MLW: mean low water level

Scales

The model predicts the biomass, abundance and species richness of the macrobenthos and maximum carrying capacity for foraging predators at the scale of 1 m^2, according to the local conditions of the beach state variables. These estimates are interpreted along the intertidal transect and, when summed, at the beach level.

2.4   Process overview and scheduling

According to the input data on the beach profile after beach nourishment (changes in height according to the distance from the low water mark and grain size of the nourished sand), the model first estimates the local *TOM.* Based on the beach state variables and input data on macrobenthos niche properties, local abundance (number of individuals.m^{-2}) of macrobenthos is estimated and subsequently converted to biomass (g AFDW.m^{-2}) (appendix 1). Total availability of chlorophyll a (mg.m^{-2}) is estimated without conversion. More detailed information on the source of the input data and sampling strategies can be found in appendix 1.

This basic envelope modelling is used for both the reference situation, with *MGS* estimated according to *h* since earlier work has demonstrated the prevalence of such grain sorting mechanisms (Short 1991) and for nourished beaches with a predefined *MGS.* These envelope models are subsequently projected on the supplemented beach profile (changes in *h*, *α* and *MGS*), with *TOM* inferred from its previously derived relationship with *MGS.* In a second phase, estimated macrobenthos biomass is integrated into functions to determine the maximum local abundance of higher trophic levels, according to available biomass of prey species and availability according to tidal frequency. The model is stochastic with parameters for species envelopes and beach characteristics estimated from prior statistical distributions.

For each beach condition, 10 000 simulations are performed to estimate mean values and variance of species and predation pressure from higher trophic levels.

The model has been successfully evaluated and validated by three data sets from two beaches (of which data were not used to create the envelope model) for the dominant macrobenthos species that were sampled in an identical way as described in Degraer *et al.* (2003). Abundance of the dominant species, biomass (g total ash free dry weight (AFDW)) and species richness from the samples were subsequently compared with simulated data (average values and 95 % confidence intervals for 10 000 simulations) according to the sample location *h* and grain size *MGS* (see Appendices – Chapter 3 – appendix A).

2.5   Design concept

Basic principles

The model integrates envelope modelling approaches to estimate abundance and biomass of lower trophic levels into mechanistic modules to quantify maximum available biomass for higher trophic levels. The model allows a biotic evaluation of local beach nourishment impact on species richness by comparison of pre-nourishment and post-nourishment states. As currently, recolonisation processes are not well-known, no lag effects are incorporated in the model. The predicted state of the beach subsequently assumes equilibrium in species dynamics according to the envelope.

Interactions

Sand grains are sorted according to their elevation on the beach (Short 1991) with coarse grains deposited at higher locations. Total organic matter is positively correlated with the median grain size. Beach nourishment alters the height and the profile of the beach and it initially induces an unsorted, often coarser, sand grain distribution. Emerging abundances and biomass of prey items will eventually impact higher trophic levels, but no implicit interactions due to predation and interspecific competition are modelled. The input data for the prey items in this model are derived from non-disturbed beaches, so niche properties are assumed to reflect realized niche dimensions.

2.6   Submodel structure

Macrobenthos envelopes

We estimated niche dimensions for eleven dominant macrobenthos species (Appendices – Chapter 3 – appendix B) in relation to three abiotic input variables. As earlier work clearly indicated Gaussian niche dimensions, niche envelopes were modelled by second-order polynomial Poisson regression models because prior information evidenced both linear and quadratic responses according to the abiotic input variables (Degraer et al. 2003b). Parameter estimates were obtained by Bayesian estimation using a Monte-Carlo Markov chain (MCMC) procedure in WinBugs v. 1.4. (Spiegelhalter et al. 2003).

Macrobenthos biomass

The obtained regression coefficients (Appendices – Chapter 3 – appendix B) are used to estimate species abundances according to implemented beach characteristics in the main simulation model. Parameters were sampled from the obtained regression distributions kernels N(,SD) but constrained within the 95 % credibility interval. The eventual abundance estimates are subsequently transformed towards biomass (gram ash free dry weight, g AFDW) by earlier determined conversion factors ((Speybroeck et al. 2006b; Vanden Eede et al. 2013, in prep.); Appendices – Chapter 3 – appendix C).

Modelling trophic relationships

Macrobenthos – epibenthos

Previous work has demonstrated the importance of intertidal habitat for residing epibenthos foraging on macrobenthos (Kuipers & Dapper 1984; del Norte-Campos & Temming 1994; Beyst et al. 1999a; Koot 2009). Along Belgian beaches, epibenthos is dominated by *Crangon crangon* (95 %), while the other 5 % constitutes of juvenile flatfish, mainly *Pleuronectes platessa* (Beyst et al. 2001b). We experimentally quantified the maximum proportion of prey consumed by either *C. crangon* or juvenile flatfish. These values are used to estimate the maximum local predation pressure by epibenthos based on the available macrobenthos abundance. Because predation pressure is additionally time constrained, and only possible under submergence, the total available biomass at a certain elevation along the beach (*h)* for higher trophic levels is described by the following function:

$$\text{Biomass}_{available}\ (h) = \ _{x\text{->}i}\sum [\text{biomass}(h)*(1\text{-}h/h_{max})*\text{Predation pressure}_x] \qquad (eq.1)$$

with x = preyed species from the macrobenthos, *h_{max} the height of the beach at high tide* and [biomass] = g AFDW.m^{-2}

The caloric value of macrobenthos equals 23 kJ/g AFDW (Beukema 1997), so the available energy for higher tropic levels is

$$E_{available}(h) = biomass_{available}(h) * 23 \qquad \text{with [energy] = kJ} \qquad \text{(eq.2)}$$

From this available source of energy, the maximum number of *C. crangon* (constituting 95 % of the epibenthos), able to feed on this biomass at height *h* is based on their daily energetic needs ($NEI_{crangon}$), being 16 % of their total body mass (del Norte-Campos & Temming 1994). Based on the average biomass of a single *C. crangon* of 0.0175 g AFDW (Beukema 1992) and a mean average caloric value of 4.768cal/mg AFDW ≈ 20kJ/g AFDW (Szaniawska 1983; Zwarts et al. 1996), $NEI_{crangon}$ = 0.056 kJ; the maximum abundance of *C. crangon* at location *h* can be calculated as follows:

$$Crangon_{max}(h) = (E_{available}(h)*0.95)/NEI_{crangon} \qquad \text{(eq. 3)}$$

Similarly, the *NEI* for juvenile flatfish is estimated to be 10 % of the body mass (Lockwood 1984), so the maximal abundance of flatfish at location *h* can be calculated as follows:

$$Flatfish_{max}(h) = (E_{available}(h)*0.05)/NEI_{flatfish} \qquad \text{(eq. 4)}$$

with $NEI_{flatfish}$=0.188 kJ

These estimates should be regarded as ceiling values for higher trophic levels, since it assumes immediate consumption under laboratory conditions, though mimicking natural prey abundances.

Waders

Two wader species, *Calidris alba* and *C. alpina*, feed predominantly on macrobenthos along Belgian beaches. Although both species show some differences in foraging behaviour, they both feed on the same prey and therefore we treat them as being one functional group. Both species were found to forage about 25 % of their total residential time on all macrobenthos species (Speybroeck 2007; Vanermen et al. 2009). According to Vanermen et al. (2009), waders along soft sanded beaches only forage from two hours before till four hours after low tide. This implicates that foraging is not possible at the high littoral (upper quartile of the beach). At the low littoral, foraging is possible twice a day for six hours, resulting in a daily foraging time of 12 hours in the low littoral and thus a foraging time of 0.50 (eq. 5).

This leads to maximal foraging time at a certain height (*h*) as follows:

$$\text{Foraging Time}(h) = -0.25+0.75*h_{rel} \qquad \text{(eq. 5)}$$

with h_{rel} the relative proximity to the low water level (being 1 when at 0 m TAW, being 0 at high water) and Foraging Time (*h*)=0 when eq.6 yields values <0.

The availability of prey is additionally dependent on the slope of the beach since this affects the depth of the prey burrowing into the sediment, with prey unavailable for waders when the water table exceeds 40 cm beneath the surface (Stienen, personal communication). Foraging possibilities are theoretically maximal on flat beaches and minimal when beach slopes exceed 21° (a zone of less than 1 m available at

the water line). Taking into account continuous changes in biomass availability (foraging time) for the central and lower littoral, a caloric value of macrobenthos of 23 kJ/g AFDW and a daily energy uptake for small waders (NEI_{waders}) of on average 224 kJ/day (Kersten & Piersma 1987; Castro et al. 1989; Speybroeck 2007), potential wader pressure can be calculated as follows:

$$\text{Wader pressure } (h) = \text{foraging time* biomass } (h)*(1-\alpha/21°)*23/NEI_{waders} \qquad \text{(eq. 6)}$$

Small-sized gulls

Larus canus and *L. ridibundus* are the principle gull foragers on beaches. They feed on polychaetes and *C. crangon* (Speybroeck 2007). Prey availability within the littoral food web is maximal at low tide and concentrated in beach pools. Because the lack of any insights into this pool formation and temporal patterns in gull foraging behaviour, we assume polychaetes and *Crangon* biomass to be available after submergence.

$$\text{Biomass}_{avialable} (h) = \text{biomass}_{polychaeta} + \text{biomass}_{crangon} \qquad \text{(eq. 7)}$$
$$= {}_{x->i}\sum \text{biomass}_x (h)*(h/h_{max})$$

with x = species polychaetes and *C. Crangon*

Given caloric (cal) values for polychaetes and *C. crangon* of respectively 23 kJ/g AFDW and 20 kJ/g AFDW, and the average daily energy need of small *Larus* species ($NEI_{gulls)}$) of 607 kj (Ysebaert & Meire 1989), the potential maximum number of foraging gulls is:

$$\text{Gulls } (h)= {}_{x->i}\sum ((\text{Biomass}_{available})_x * \text{cal}_x)/ NEI_{gulls} \qquad \text{(eq. 8)}$$
with x respectively polychaetes and *C. crangon*

Although several bird species are also known to feed on stranded wrack material, this trophic link was not incorporated in this model due to the difficulties of quantifying stranded wrack on beaches.

2.7   Model application & research strategy

The nourishment model was applied on a typical Belgian beach. Two of the thee parameters predicting the realised niche of lower trophic levels, e.g. slope and grain size, are technical aspects of the nourishment projects and can be optimized accordingly. The relative importance of each parameter is tested under realistic conditions, by keeping the other parameter constant. Initially, the influence of altered beach profile and nourishment slope was simulated for the fauna on the beach. While maintaining the natural sediment grain size (ranging from 139 to 285 µm), three beach profiles were tested: the natural beach profile (t0) a nourishment profile of 18° (s1) and a nourishment profile of 33° (s2) (figure 2). After nourishment, average macrobenthos abundances can be higher, lower or equal to

the abundances before the nourishment and this response differs between species. We predicted the effects on macrobenthos abundance per dominant species, total macrobenthos biomass and predation pressure of higher trophic levels including avifauna and epibenthos (fish and shrimp), present on the beach. Subsequently, the effect of varying sediment grain sizes used for nourishment was simulated for the afore-mentioned fauna: 200 – 500 µm with increments of 50 µm. In this case, the nourishment profile did not deviate from the natural beach profile (t0). Predictions of the effects on macrobenthos and on higher trophic levels were made, identical to the ones made for different beach profiles.
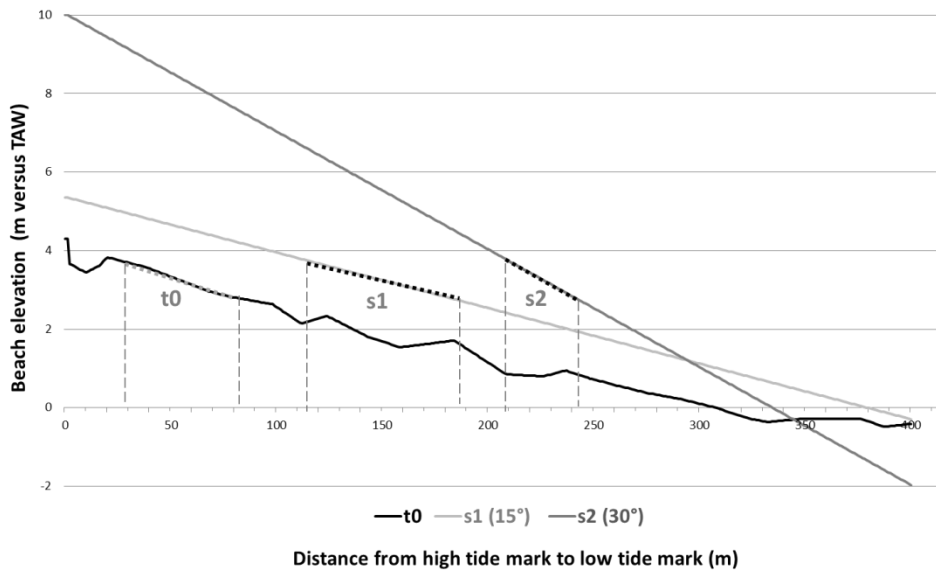

Figure 2: Different nourishment profiles and the exemplary shift of habitat on the beach due to nourishment. t0: natural beach profile; s1: nourishment profile of 18°; s2: nourishment profile of 33°. X-axis: across-shore beach distance from a fixed point above high tide mark (left) towards low tide mark (right). Y-axis: relative beach elevation (m versus TAW), calculated by the M2-reduction model (Van Cauwenberghe et al. 1993)

The t0 situation, frequently depicted in the following figures and tables, encompasses the macrobenthos situation on this typical Belgian beach prior to nourishment impact effects. This t0 simulation is based on the information of 23 intensively sampled beaches along the Belgian coast, during different seasons within the period 1997 – 2011. In these simulated pre-nourishment conditions, sediment is in equilibrium and well-sorted across the shore (with coarser sediment on the upper shore and finer sediment on the lower shore). Conversely, the simulated t1 situation is characterized by a uniform sediment grain size.

3.   Results

3.1   Influence of altered beach profile and nourishment slope

An important consequence of beach nourishment, coinciding with the steeper beach slope, is the shift in intertidal beach area (figure 2) and consequently the decrease in species abundance (table 1), except for *Bathyporeia pilosa* and chlorophyll a, which is a measure for the microphytobenthos. The macrobenthos species abundance (table 1), the total macrobenthos biomass and the trends for the higher trophic beach levels (figure 3) did not differ between nourishment profile types s1 (15°) and s2 (30°) used on a single beach. The chlorophyll a levels and the abundance of *Bathyporeia pilosa*, *Nephtys cirrosa* and *Scolelepis squamata* increases slightly when a steeper slope is applied (s2: 30°) while the opposite is true for *Bathyporeia sarsi* and *Eurydice pulchra* (table 1).

Table 1: Simulated chlorophyll a (mg.m^{-2}) and abundance (number of individuals.m^{-2}) of the dominant species on a typical Belgian beach for the pre-nourishment (t0, median grain size: 218.31 µm and slope: 15°) and post-nourishment situation, using different slopes: s1 (15°) and s2 (30°); mean ± SE (based on 10 000 simulations)

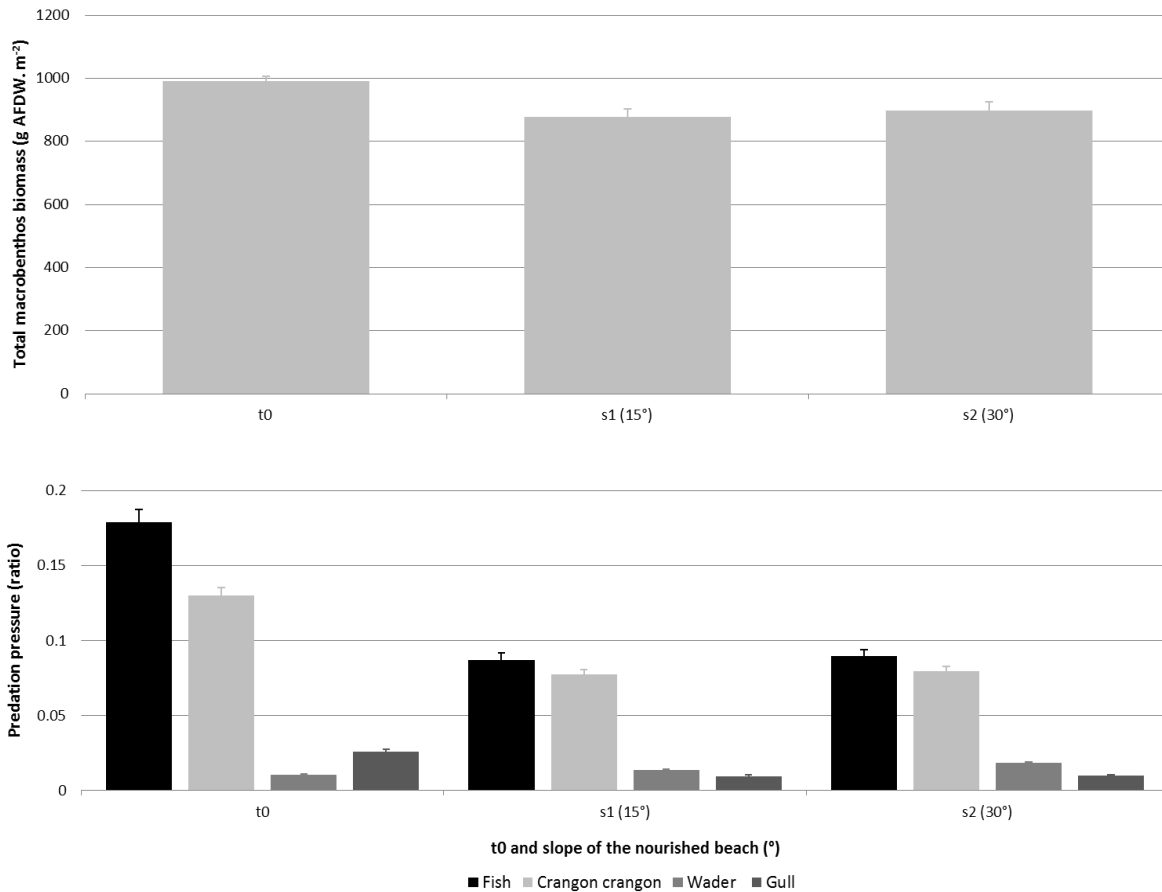| Slope	chlorophyll a (mg.m^{-2})	*Bathyporeia pilosa*	*Bathyporeia sarsi*	*Eurydice Pulchra*	*Nephtys cirrosa*	*Scolelepis squamata*
t0	2.03 ± 0.01	111.5 ± 9.3	323.8 ± 7.7	7.4 ± 1.0	47.0 ± 1.4	178.9 ± 10.2
s1 (15°)	3.05 ± 0.02	242.9 ± 15.4	283.0 ± 7.0	3.7 ± 0.4	26.1 ± 1.0	59.5 ± 5.2
s2 (30°)	3.07 ± 0.02	287.8 ± 16.1	263.5 ± 6.8	2.6 ± 0.5	34.4 ± 1.2	60.1 ± 5.4

Figure 3: Simulated macrobenthos biomass and potential predation pressure of higher trophic levels on a typical Belgian beach. X axis: t0 and slope of the nourished beach (°); Y-axis: *above:* total macrobenthos biomass (g AFDW.m^{-2}) and *below:* potential predation pressure (ind.m^{-2}); mean ± SE (based on 10 000 simulations)

3.2 Influence of the used sediment (grain size)

The average simulated abundance of the species after nourishment is similar to pre-nourishment conditions when the grain size of the used sediment resembles natural conditions (200 – 250 μm). However, when nourishment sediment differs in grain size from natural beach sediment, species abundances will respond more profoundly to this habitat transformation. The chlorophyll a pattern (measure for the microphytobenthos) and macrobenthos patterns are given in table 2. The microphytobenthos, the amphipod *Bathyporeia pilosa* and the polychaete *N. cirrosa* show a clear negative trend when beaches are nourished using sediment with a median grain size of 300 μm or coarser (table 2). For the amphipod *Bathyporeia sarsi*, this negative trend starts from 350 μm onwards (table 2). *Eurydice pulchra* and *Scolelepis squamata* are not negatively but positively influenced by nourishment using sediments with a medium grain size of (more than) 300 μm (table 2). However, this

coarse sediment is not naturally occurring along the Belgian coastline (Vanden Eede & Vincx 2011b; Vanden Eede & Vincx 2011a).

Table 2: Simulated chlorophyll a (mg.m^{-2}) and species abundance (number of individuals.m^{-2}) on a typical Belgian beach for the pre-nourishment (t0, median grain size: 218.31 µm) and post-nourishment situation, using different sediment grain sizes; mean ± SE (based on 10 000 simulations)

Grain size (µm)	chlorophyll a (mg.m^{-2})	*Bathyporeia pilosa*	*Bathyporeia sarsi*	*Eurydice pulchra*	*Nephtys cirrosa*	*Scolelepis squamata*
t0	2.03 ± 0.02	111.5 ± 9.3	323.8 ± 7.7	7.4 ± 1.0	47.0 ± 1.4	178.9 ± 10.2
200	3.05 ± 0.02	242.9 ± 15.4	283.0 ± 7.0	3.7 ± 0.4	26.1 ± 1.0	59.5 ± 5.2
250	2.32 ± 0.01	225.8 ± 14.8	311.2 ± 7.6	12.5 ± 1.4	12.7 ± 0.6	302.8 ± 13.7
300	1.59 ± 0.01	162.9 ± 12.1	309.4 ± 8.0	20.0 ± 2.5	4.7 ± 0.3	553.4 ± 19.1
350	0.98 ± 0.01	82.4 ± 7.3	125.4 ± 4.8	17.5 ± 2.8	1.7 ± 0.2	524.7 ± 19.0
400	0.82 ± 0.01	0.0 ± 0.0	117.0 ± 5.2	41.0 ± 4.8	0.7 ± 0.1	423.6 ± 17.6
450	0.55 ± 0.01	0.0 ± 0.1	30.9 ± 2.5	47.2 ± 5.5	1.4 ± 0.2	424.3 ± 18.8
500	0.42 ± 0.01	0.0 ± 0.2	79.8 ± 4.5	32.8 ± 4.5	1.8 ± 0.3	468.3 ± 20.4

Figure 4 shows that after nourishment using sediment with a median grain size from 300 µm onwards, macrobenthos species richness on the beach decreases. Nourishment with sediment characterized by a median grain size of 350 µm will cause a decrease in macrobenthos species richness by 30 % compared to the t0 situation. There seems to be no apparent species richness loss when fine sediment is used (200 and 250 µm) (figure 4).
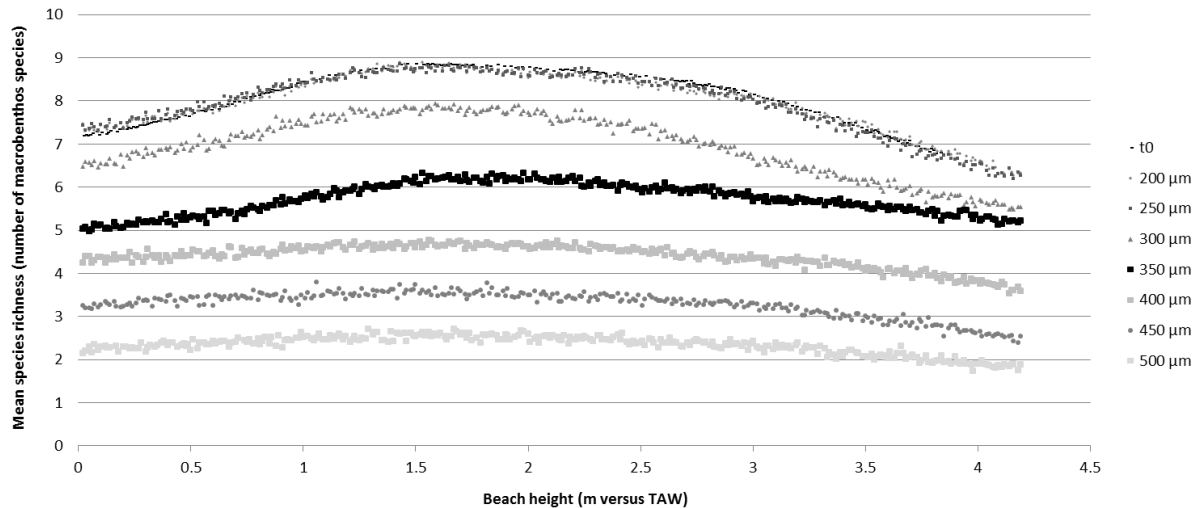

Figure 4: Expected species richness on a typical Belgian beach before (t0, median grain size: 218.31 µm) and after nourishment with different sediment grain sizes (µm). X-axis: beach height (m versus TAW); Y-axis: mean species richness (number of macrobenthos species)

The species richness results (figure 4) are contrasted by the biomass results (figure 5). While the maximum macrobenthos species richness was found at a median grain size of 200 – 250 µm, the maximum total macrobenthos biomass was found at 300 µm. The total biomass after nourishment with 350 µm was comparable to the biomass in the t0 situation, but from 350 µm onwards, there was a decrease in total macrobenthos biomass. At 400 µm, total biomass was similar to the situation at 200 µm and from 400 µm onwards, there was again an increase in total macrobenthos biomass towards conditions comparable to the t0 situation (figure 5). The effects of beach nourishment on higher trophic levels can be completely linked to the evolution of total macrobenthos biomass after nourishment with different types of sediment. For shrimp, juvenile flatfish and birds, there is a maximum potential predation pressure (number of individuals.m^{-2}) at 300 µm, followed by first a decrease and then again an increase in presence on the beach at increasing coarser grain sizes (figure 5).
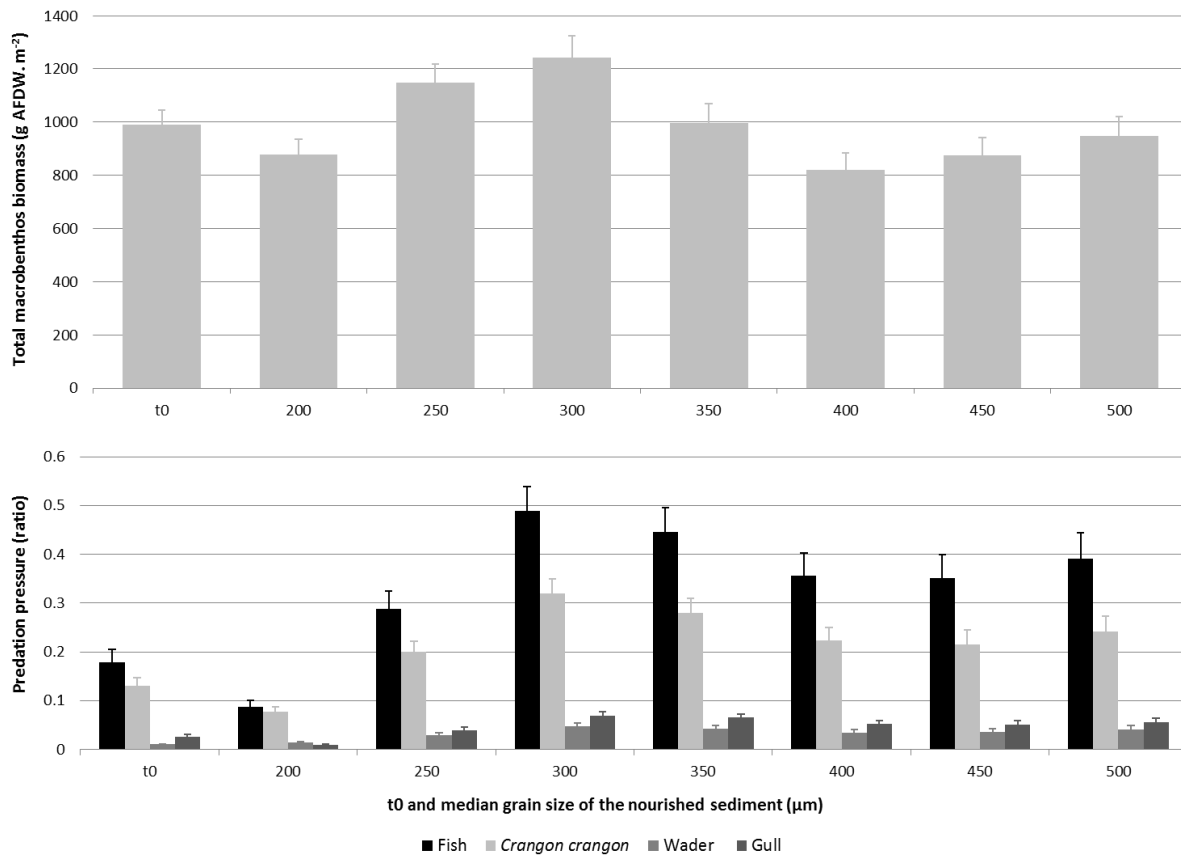

Figure 5: Simulated macrobenthos biomass and potential predation pressure of higher trophic levels on a typical Belgian beach. X axis: t0 (median grain size: 218.31 µm) and median grain size of the nourished sediment (µm); Y-axis: *above:* total macrobenthos biomass (g AFDW.m^{-2}) and *below:* potential predation pressure (ind.m^{-2}); mean ± SE (based on 10 000 simulations)

4.   Discussion

Beach nourishment is known to alter the morphodynamic state of the beach due to the significant changes in beach slope and sediment. Our modelling approach indicates that the grain size of the sediment, used for beach nourishment, is the dominant factor in determining the effects on the ecosystem. The gradient for median grain size of nourishment sediment on dissipative West European beaches is advised to be 200 – 300 µm, in order to reduce the impact effects as much as possible.

The evaluation of the beach ecosystem health by total macrobenthos biomass or by the presence of socially or economically important species, like some birds and fish, can be deceptive as generalist species (cfr. *Scolelepis squamata*) can become very abundant on a beach impacted by nourishment. Hence, the combination of different variables (species richness, biomass) is advisable to estimate the effects of nourishment on the beach ecosystem. Finally, the development of the nourishment model in this study is only a first step and the refinement and enhancement of the model relationships should greatly contribute to a better ecosystem-based nourishment approach in the future.

4.1   Assessing ecological impact

Envelope models are widely used in ecological assessment studies. These models assume that species show no dispersal limitations and have constant niches. Moreover, biotic interactions are expected to be incorporated in the models as input data are gathered from field situations where these interactions determine the distribution patterns of species (Araújo & Peterson 2012). In the nourishment context, envelope models are thus highly usable and have advantages over models predicting processes on a larger spatial scale (such as climate models). The nourishment model developed in this study is based on a large set of input data, was validated and assumes realistic and highly likely short term responses.

Influence of the beach profile and slope
Beach erosion combined with increasing economic and human development along the coast, is resulting in coastal squeeze. To counteract this evolution, beach nourishment is aiming at coastal relaxation. This management measure however has ecological implications for the sandy beach ecosystem. The model simulations indicated a decrease in total macrobenthos biomass on the beach (figure 4) as a result of the steeper nourishment slope leading to a narrower intertidal beach (difference between t0 and s1 or s2).

On a smaller scale, when different nourishment slope types were taken into account on one specific beach, the nourishment model showed that particular nourishment slopes could positively influence the microphytobenthos and even favour specific species. This possibility to compare species responses to different slopes makes this model especially useful for management purposes, aiming at protecting

species or habitats. Indeed, by positively influencing abundance of macrobenthos, through the use of specific beach slopes enlarging the habitat of dominant prey species (such as high-shore nourishment, positively influencing *Bathyporeia pilosa* in the high-intertidal), the presence and abundance of higher trophic levels such as birds or fish can also be positively influenced. In this context, the knowledge that intermediate beaches with steeper beach slopes are unfavourable for epi- and hyperbenthos (Beyst et al. 2001b), should be taken into account when developing nourishment slopes.

Influence of the used sediment (grain size)

The nourishment sediment is of vital importance to predict the effects of nourishment on the beach ecosystem (Speybroeck et al. 2006a). The dominant role of sediment grain size was supported through the results obtained by testing different beach slopes and sediment grain sizes. Indeed, most of the modelled macrobenthos species did not respond to the different slope type but only to the grain size of the sediment used. Coarse sediments (median grain size of 300 µm or coarser), not naturally occurring on Belgian beaches, negatively influenced the microphytobenthos, the amphipods *Bathyporeia pilosa* and *Bathyporeia sarsi* and the polychaete *N. cirrosa* (table 2). However, these coarse sediments positively influenced the polychaete *Scolelepis squamata*, resulting in an increase in total macrobenthos biomass and an increase of the trophically linked birds and fish present on the beach. The polychaete *Scolelepis squamata* is a generalist and cosmopolitan species both thriving on fine-grained as well as coarse-grained beaches (Dauer 1983; Hartmann-Schröder 1996). Although the polychaete is restricted to the upper-intertidal zone on Belgian beaches, its distribution on other beaches worldwide is more spread over the entire beach. Currently, the reason(s) for these different spatial distribution patterns remain unknown and no clear sediment preference for this species could be found. The high biomass of *Scolelepis squamata* after nourishment further confirms its broad sediment tolerance range.

Opposite to the calculated abundance and biomass patterns, the overall species richness was simulated to decline when coarse sediment was used for beach nourishment. The contrasting abundance, biomass and species richness' patterns clearly show that macrobenthos or avian biomass, as single descriptors to evaluate the health of an ecosystem, are insufficient and can lead to wrong conclusions concerning ecosystem health. We therefore advise to use a combination of species richness, abundance and biomass indices to monitor the ecological impact of nourishment on sandy beach ecosystems.

Furthermore, it is precarious to conclude that the effect of nourishment using coarse sediment is harmless for higher trophic levels in general, due to the afore-mentioned uncertainties in the model concerning these higher trophic levels.

4.2   Strengths and weaknesses of the model

The model predicts if the habitat after nourishment is considered suitable for the most dominant members of the sandy beach community, although the predicted species may in practice be absent because of other anthropogenic impacts, such as tourism or natural temporal variability (Brown & McLachlan 2002; Defeo & McLachlan 2005; Defeo et al. 2009; McLachlan et al. 2013). The model however gives a prediction without taking into account the nourishment period, the nourishment method and the techniques used. After a nourishment event, both the beach slope as well as the characteristics of the beach sediment will evolve towards pre-nourishment conditions (Speybroeck et al. 2006a). Although some data show that macrobenthos recovers completely within short time frames (Gmelig Meyling & De Bruyne 1994; Slim & Löffler 2007), these statements are not based on peer-reviewed information or well-developed monitoring. Furthermore, the post-nourishment evolution is depending on several nourishment-specific (e.g. high-shore versus profile nourishment) but also ecosystem-dependent features (erosion-susceptibility of the beach ecosystem, recolonising capabilities of the sandy beach species). Nevertheless, personal observations during post-nourishment monitoring indicate a rapid recolonisation of the infauna due to the rather small scale of the current nourishment, so no lag effects are currently incorporated in the model. A further examination of the temporal and spatial post-nourishment processes, based on a scientifically based monitoring, is however essential to extend and refine the predictions of the model for a longer time period and for more large-scaled nourishment projects. These predictions on the beach evolution after nourishment will also be highly important for the frequency of repeated nourishment and this repeated nourishment will in turn have an effect on the evolution of the beach after nourishment.

As the sandy beach food web is complex and all species interactions are not yet elucidated, the predictive effect of the nourishment impact on higher trophic levels should be regarded as an assessment of the potential rather than realistic predictions. One of the main predictions of the model showed a positive effect on both the total macrobenthos biomass as well as on the potential presence of predators after nourishment using coarse sediment. However, it should be kept in mind that the model simulated the potential presence of a restricted but relevant set of species belonging to the higher trophic levels solely based on macrobenthos productivity. The increase in total macrobenthos biomass, following nourishment with coarse sediment, can be exclusively attributed to the increase of the generalist polychaete *Scolelepis squamata*. Furthermore, the predators incorporated in the model were strongly linked to this polychaete as main food item and therefore their potential presence was simulated to be relatively high. Nevertheless, the latter result needs careful consideration, as firstly, these predators also feed on other sources that were currently not incorporated in the model (such as stranded wrack material (De Meulenaer 2006) and secondly, the potential presence of predators is not linked in the current model to abiotic variables such as beach morphodynamics or hydrological

conditions although they may affect the presence of epibenthos and hyperbenthos (Beyst et al. 1999a; Beyst et al. 2001a; Beyst et al. 2002).

Although on other beaches worldwide other species occur, their taxonomic position and trophic relationships are very similar to those of the species considered here (McLachlan et al. 1996a; Defeo & McLachlan 2005) and therefore the model can be valuable for sandy beach ecosystems worldwide. In addition, when invasive species will recolonise the nourished and morphodynamically altered beach or when keystone species disappear, a complete ecosystem shift is possible (Schlacher et al. 2008; Mumby et al. 2012; Perry et al. 2013).

4.3 Synthesis and applications

Beach nourishment in practice occurs with a sediment grain size from 200 μm onwards. Based on the results of the model, we distinguish three groups of beach habitat, based on the most important variable according to the model, grain size of the sediment: (1) 200 – 250 μm; (2) 300 μm and (3) ≥ 350 μm. In figure 6, an overview of the beach nourishment effects for these different habitats is given.

The different ecosystem components included in the model are evaluated. As long as the used sediment resembled the sediment in pre-nourishment conditions, the ecosystem did not change. The use of coarse sediment (sediment grain size ≥ 300 μm) for nourishment had a negative effect on macrobenthos species richness. Due to the differences between simulated patterns of total biomass and species richness, the importance of these variables should however be carefully considered.

Furthermore, it could be stated that beach nourishment with a sediment grain size of 300 μm is most favourable for higher trophic levels based on the results of this model. Nevertheless, this result is largely depending on the strong correlation of the used predators with the generalist polychaete *Scolelepis squamata* and is likely to change when more predators and additional trophic and abiotic links are included in the model. Due to these uncertainties regarding the presence of higher trophic species, the gradient in sediment grain size that is advised to be used for nourishment of natural fine-grained beaches is established as 200 – 300 μm.
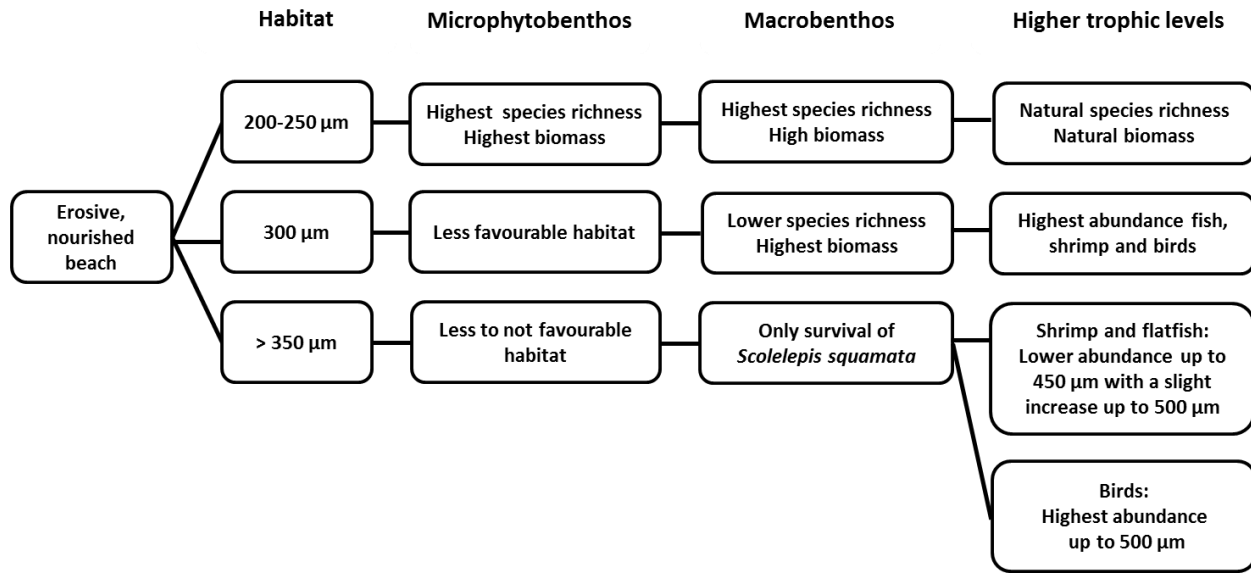
Habitat	Microphytobenthos	Macrobenthos	Higher trophic levels

Erosive, nourished beach

- **200-250 µm** → **Highest species richness / Highest biomass** → **Highest species richness / High biomass** → **Natural species richness / Natural biomass**
- **300 µm** → **Less favourable habitat** → **Lower species richness / Highest biomass** → **Highest abundance fish, shrimp and birds**
- **> 350 µm** → **Less to not favourable habitat** → **Only survival of *Scolelepis squamata*** → **Shrimp and flatfish: Lower abundance up to 450 µm with a slight increase up to 500 µm** / **Birds: Highest abundance up to 500 µm**

Figure 6: Schematic overview of beach nourishment impact on the beach ecosystem, based on the nourishment model simulations

5. Acknowledgements