

REVIEW

Beach nourishment: an ecologically sound coastal defence alternative? A review

JEROEN SPEYBROECK^{a,*}, DRIES BONTE^b, WOUTER COURTENS^c, TOM GHESKIERE^a,
PATRICK GROOTAERT^d, JEAN-PIERRE MAELFAIT^{b,c}, MIEKE MATHYS^e,
SAM PROVOOST^c, KOEN SABBE^f, ERIC W.M. STIENEN^c, VERA VAN LANCKER^e,
MAGDA VINCX^a and STEVEN DEGRAER^a

^a*Ghent University, Biology Department, Marine Biology Section, Ghent, Belgium*

^b*Ghent University, Biology Department, Terrestrial Ecology Unit, Ghent, Belgium*

^c*Institute of Nature Conservation, Brussels, Belgium*

^d*Royal Belgian Institute of Natural Sciences, Brussels, Belgium*

^e*Ghent University, Geology Department, Renard Centre of Marine Geology, Ghent, Belgium*

^f*Ghent University, Biology Department, Laboratory of Protistology and Aquatic Ecology, Ghent, Belgium*

ABSTRACT

1. Even though beach nourishment is generally considered as an environment-friendly option for coastal protection and beach restoration, sizeable impacts on several beach ecosystem components (microphytobenthos, vascular plants, terrestrial arthropods, marine zoobenthos and avifauna) are described in the literature, as reviewed in this paper.

2. Negative, ecosystem-component specific effects of beach nourishment dominate in the short to medium term, with the size of the impact being determined by (1) activities during the construction phase, (2) the quality and (3) the quantity of the nourishment sand, (4) the timing, place and size of project, and (5) the nourishment technique and strategy applied. Over the long term the speed and degree of ecological recovery largely depend on the physical characteristics of the beach habitat, mainly determined by (1) sediment quality and quantity, (2) the nourishment technique and strategy applied, (3) the place and the size of nourishment and (4) the physical environment prior to nourishment.

3. The limited information available on indirect and cumulative ecological effects indicates that these effects cannot be neglected in an overall impact assessment. Hence, for ecologically good practice of beach nourishment it is advised (1) to choose nourishment sands with a sediment composition comparable to that of the natural sediment, (2) to avoid short-term compaction by ploughing immediately after construction, (3) to execute the nourishment in a period of low beach use by birds and other mobile organisms, (4) to choose a number of smaller projects rather than a single large nourishment project and (5) to select the nourishment technique with respect to the local natural values.

*Correspondence to: J. Speybroeck, Ghent University, Biology Department, Marine Biology Section, Krijgslaan 281, Building S8, B-9000 Ghent, Belgium. E-mail: jeroen.speybroeck@UGent.be

4. In order to allow an objective, scientifically sound, ecological adjustment of future nourishments, research should aim at (1) taking into account the full sandy beach ecosystem, (2) avoiding strategic imperfections in experimental design and (3) elucidating the biological processes behind impact and recovery of all ecosystem components.

Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: sandy beaches; ecology; beach nourishment; beach replenishment; coastal erosion; coastal defence; ecological impact

INTRODUCTION

Beach nourishment is defined as 'the process of mechanically or hydraulically placing sand directly on an eroding shore to restore or form, and subsequently maintain, an adequate protective or desired recreational beach' (Anonymous, 1984) or as 'deliberately placing an amount of sand on an eroding beach or creating a beach where no beach or only a narrow beach was present before' (Anonymous, 1995). The process may, however, also include offshore deposition of material to build an artificial berm (e.g. Charlier and De Meyer, 1995).

The use of beach nourishment as a standard means of coastal protection is a fairly recent phenomenon. In Europe and North America, the first large projects were executed only about 50 years ago (Anonymous, 1995). In Europe most projects were executed in Spain (over 600 between 1997 and 2002), the Netherlands (200), France (115), Italy (50), the UK and Denmark. Tens of millions of cubic metres of sand have been deposited on the beaches, e.g. six million cubic metres per year in the Netherlands since 1991. Hanson *et al.* (2002) and Hamm *et al.* (2002) offer overviews of the European beach nourishment history.

The coastal protection projects in the USA, carried out under the authority of the US Army Corps of Engineers, show a drop in the use of hard structures (breakwaters, dykes, groynes and harbour walls); around 1970 already 80% of all coastal protection measures were through beach nourishment, and this percentage increased from 1970 onwards (Basco, 1999). Beach nourishment has been in use for a much longer time, however, e.g. in California since 1919 (Clayton, 1991), on the US east coast barrier islands since 1923 (Valverde *et al.*, 1999) and on New England beaches since 1935 (Haddad and Pilkey, 1998; Trembanis *et al.*, 1999). From 1970 to 1993, 49 large-scale projects were executed. The total volume of deposited sand amounted to more than 145 million m³, while in 1998, 31 further projects were under various degrees of construction (Basco, 1999). Besides these federally funded projects, many additional projects were conducted at the state or local level.

Awareness of and attention towards problems of coastal erosion in general, and beach nourishment and physical and biological monitoring in particular, has increased over the last decades. As an alternative for 'hard' coastal protection, both positive and negative aspects of beach nourishment are mentioned. Largely in contrast to nourishment, 'hard' coastal protection may lead to increased erosion, often at downdrift locations rather than where the actual construction took place (through longshore transport of the sediment) (Peterson *et al.*, 2000a). An example of a higher risk of erosion is the disappearance of the dry beach section on many beaches along the eastern coast of Belgium after the construction of dykes at the foot of the coastal dunes about a century ago (Charlier and De Meyer, 1995, 2000). Beach nourishment gives rise to smaller changes in the dynamics of both sediment and water, thus a natural equilibrium is reached sooner and more easily, and stays in effect for a longer time (Peterson *et al.*, 2000a). Negative aspects are the higher costs, as a consequence of the need of replenishment every few years, and the lower applicability on beaches with high wave energy (Esteves and Finkl, 1998). Some cost efficiency options are discussed by Raudkivi and Dette (2002).

Nowadays beach nourishment is widely considered as a better alternative than the construction of hard structures to protect a coast against detrimental erosive effects (e.g. Dankers *et al.*, 1983; Adriaanse and

Coosen, 1991; Charlier *et al.*, 1998; Basco, 1999; Brown and McLachlan, 2002; Finkl, 2002; Greene, 2002; Hamm *et al.*, 2002; Hanson *et al.*, 2002).

Owing to the highly dynamic nature of their environment (mainly determined by waves and tides but also winds), the benthic organisms inhabiting the littoral zone of sandy beaches are limited to species with a high tolerance towards several forms of environmental stress. Therefore, according to many authors, nourishment should cause only minor damage to the ecosystem (e.g. Löffler and Coosen, 1995; Anonymous, 2002b; Miller *et al.*, 2002). This high tolerance is, however, not unlimited (Jaramillo *et al.*, 1996; Moffett *et al.*, 1998). Even though beach nourishment is considered as the more ecologically sound option, this form of beach restoration also brings about sizeable changes in the sandy beach ecosystem. In the short term, a large proportion of the resident flora and fauna is destroyed by the addition of a thick layer of nourishment sand. Changes in the beach habitat after nourishment, such as altered beach profile and sedimentology, will influence the rate of recovery of the ecosystem's natural equilibrium.

An impact of such magnitude can be expected to affect the entire beach ecosystem. Nevertheless, most research has been carried out on the intertidal benthic macrofauna (e.g. Rakocinski *et al.*, 1996; Peterson *et al.*, 2000a), while other ecosystem components remain mostly uninvestigated. Also, most studies are short-term investigations of the benthic macrofauna. Little is known of long-term effects, recovery after nourishment or the effects of repeated replenishment at the same site (cumulative effects).

Several strategies (classical or profile nourishment, foreshore nourishment and backshore nourishment) and techniques (rainbow spraying versus carrying the sediment to the beach as a mixture of water and sand under pressure via pipelines) of nourishment can be applied and their specific effect on the ecosystem will be discussed.

This paper aims at providing a complete ecosystem-encompassing perspective of the ecological effects of beach nourishment. Whereas the majority of past research has focused on macrobenthic infauna, a more complete ecosystem approach offers much higher scientific value. Therefore, together with sedimentology and hydrodynamics, five major beach ecosystem components were taken into account in this review: microphytobenthos (benthic micro-algae), vascular plants, terrestrial arthropods, marine zoobenthos and avifauna (Figure 1). As referred to in this paper, microphytobenthos consists of benthic micro-algae inhabiting the top layer of the beach sediment. The vascular plants considered are those growing on the dry part of the beach including the dune foot, while terrestrial arthropods encompass insects and other arthropods inhabiting the strand line and the dry part of the beach, including the typical wrack fauna that depend for their survival on stranded seaweeds or other wrack-dependent organisms. Marine zoobenthos comprises the marine benthic fauna, including those organisms living in the sediment (infauna) and larger than 1 mm. The avifauna consists of shorebirds and other birds depending on sandy beaches for nesting, foraging and/or resting.

The impact of nourishment is apparent at two different sites: the 'borrow site' where the nourishment sediment comes from, together with adjacent indirectly impacted sites, and the 'target site' or 'nourishment site' (beach, foot of coastal dunes and/or foreshore), together with adjacent sites impacted indirectly through sediment transport (longshore transport but also aeolian transport). Within the scope of this paper only the nourishment site will be discussed and we refer, for example, to Hall (1994), Newell *et al.* (1998), Greene (2002) and Nelson (1993) for assessments of effects at the borrow site. In particular this paper offers an overview of the available knowledge on the ecological impact of beach nourishment on the beach ecosystem.

ECOLOGICAL EFFECTS OF BEACH NOURISHMENT

The ecological effects of nourishment can be divided into three main groups: (1) effects related directly to aspects of the nourishment project — the construction; (2) effects related to quality characteristics of the

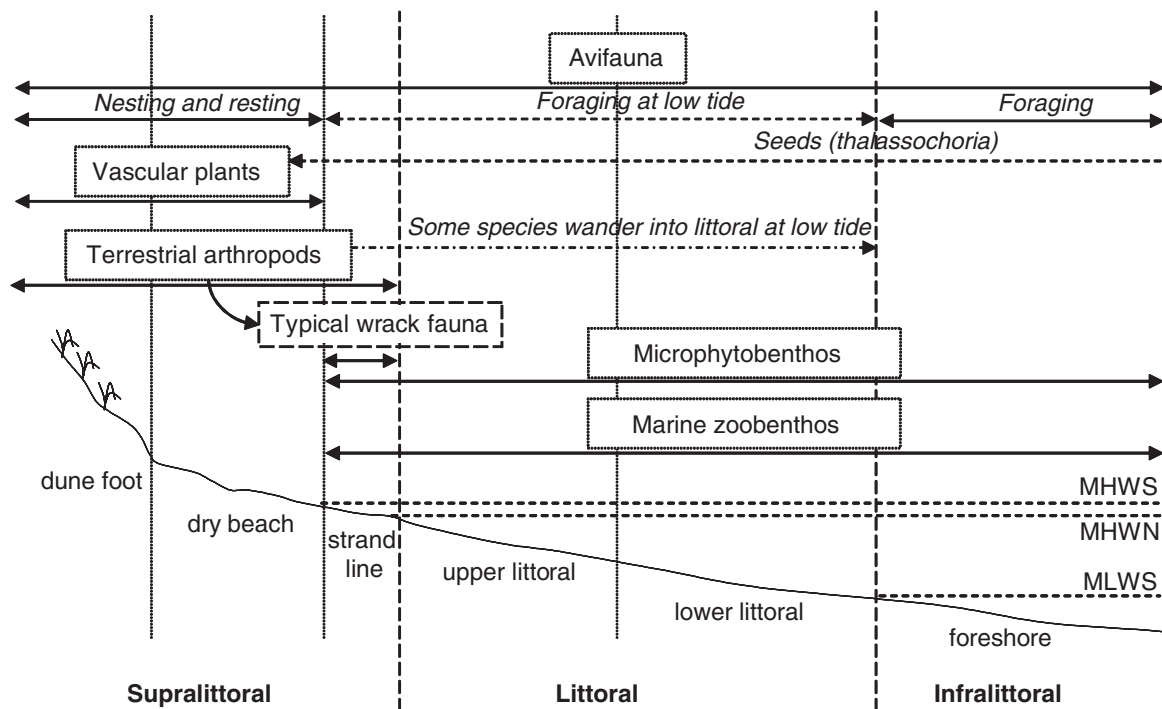


Figure 1. Scheme of the sandy beach ecosystem in the biological components considered in this paper. Supralittoral = here consists of strand line, dry beach and dune foot; littoral = intertidal zone; infralittoral = zone below MLWS; MHWS = mean high water level at spring tide; MHWN = mean high water level at neap tide; MLWS = mean low water level at spring tide. See text for further explanation.

nourishment sediment; and (3) effects related to the quantity of the nourishment sediment (Figure 2). Aspects of all three groups affect the biota through impacts on their habitat. The size of the effects is also influenced by (1) place, time and size of the nourishment project and (2) the chosen nourishment technique and strategy. Indirect and cumulative effects are discussed separately.

Differential ecological effects of beach nourishment related aspects

Activities during construction

During the construction phase of the beach nourishment, disturbance of the fauna can occur, which can be both visual and auditive, e.g. shorebirds abandoning their nests (Peterson and Manning, 2001). Temporary noise overload during construction (associated with the use of pumps, bulldozers, outlet pipes etc.) (Anonymous, 2002b) may cause disturbance to foraging birds. The use of bulldozers may destroy the primary dune vegetation and increases the degree of compaction of the beach sediment with many smaller vehicles causing more damage than fewer but larger ones (Anonymous, 1989). This can affect vascular plants (and associated terrestrial arthropods) living on the dry parts of the beach. Furthermore, some pollution may occur due to exhaust gases, fuel leaks etc.

Although no data are available on the subject, it seems likely that the microphytobenthos and the marine zoobenthos are only affected to a minor degree by the activities of the construction phase of the nourishment project per se; nevertheless, it is possible these benthic organisms are affected by increased compaction brought about by bulldozers and other equipment installed on the beach.

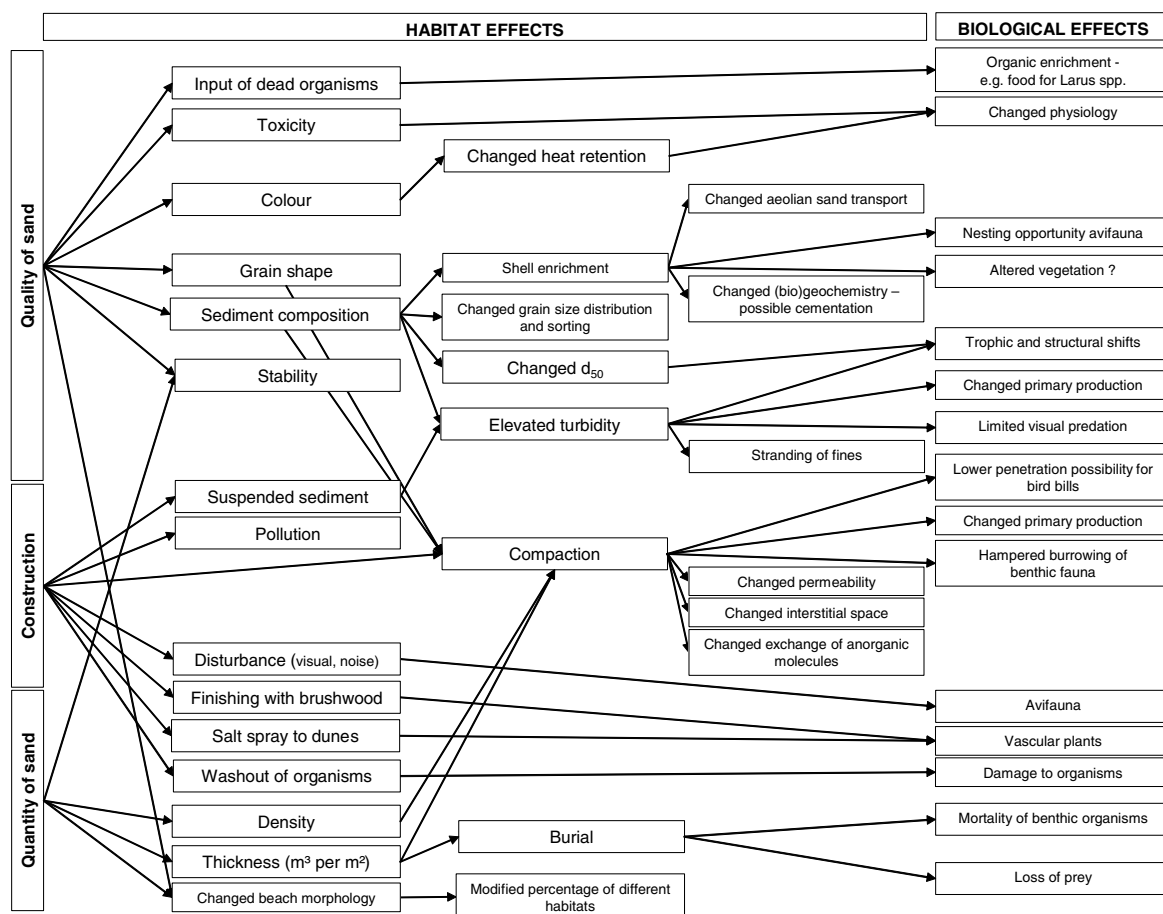


Figure 2. Integrated network of the ecological effects of beach nourishment. The scheme is a tentative summary resulting from the compiled literature data and consultation of all authors, each of them expert in a specific ecosystem component. Effects at the borrow site are not considered.

Quality characteristics of the nourishment sediment

Beach nourishment is characterized by a number of aspects related to the quality of the fill sediment: (1) sediment composition (proportion of shells or other coarse matter, proportion of fines, grain-size distribution), (2) beach morphology and beach profile, (3) presence of toxic substances and/or dead organisms and (4) sediment colour.

Sediment composition

● Shells and other coarse matter

If the fill sediment contains a high proportion of shells, shell fragments may become dissolved. Subsequently, sometimes a solid floor of shells is formed through cementation. Cementation is a process of lithification, in which chemical precipitates (in the form of new crystals) form in the pores of a sediment or rock, binding the grains together. Thus, a solid shell layer is formed and this causes a drop in the natural aeolian (van der Wal, 1998) and hydrodynamic sand transport. A shell lag layer may also be left by

winnowing out of sand by the wind without subsequent cementation. This layer too, can reduce aeolian sand transport. Sand dispersion by winds is an important factor for the development of dunes and vegetation on beaches (McLachlan, 1991). Frequent input of wind-dispersed sand is essential for the viability of European beachgrass or 'marram' (*Ammophila arenaria*) (van der Putten and Peters, 1997) because it inhibits growth of fungi and nematodes that can damage its roots.

Coarse materials in fill sediments also affect invertebrates. Den Hollander and Van Etten (1974) showed that beetles of the genus *Bledius* do not live in sand too rich in shells because of their digging behaviour. Peterson *et al.* (2000a) noted a slower recovery of a *Donax* (intertidal clam) population after nourishment with sediment containing a high percentage of shell fragments.

On the other hand a certain percentage of shells can create favourable nesting conditions on the dry beach for some birds, such as the Kentish plover (*Charadrius alexandrinus*) (Melvin *et al.*, 1991). During nature restoration projects in the Dutch Delta area, the natural succession of vegetation seemed to be slowed down considerably when the nourished surface contained a lot of stones or pebbles and thus this surface remained suitable as a nesting habitat for shorebirds for a longer time (Stienen and Schekkerman, 2000).

No specific results are available on how high concentrations of coarse material may affect microphytobenthos.

Given the apparent contrasting impact of coarse material on some nesting birds on the one hand and most other ecosystem components on the other, the use of a fill containing high concentrations of shells or other coarse material should depend on the actual or desired natural values of a certain beach. Aeolian sand transport may possibly often even be greater after nourishment, but it would depend on the characteristics of the chosen fill sediment.

• Fines

Fines are fine materials like mud (mineral clay and silt) and particulate organic matter. High proportions of these can cause a temporary increase in turbidity of both interstitial water and adjoining water masses. However, this increase disappears quite rapidly owing to wave action (Van Dolah *et al.*, 1992). Fine particles, which can contain a considerable amount of organic matter and contaminants, are rapidly moved further offshore (Naqvi and Pullen, 1982). Thus, elevated turbidity is mostly not regarded as an ecological problem in the nearshore zone of high energy beaches. Furthermore, the foreshore biological communities possess a natural resilience towards shifts in turbidity, being a natural phenomenon (Van Dolah *et al.*, 1994; Anonymous, 2001, 2002b) and turbidity levels caused naturally during storms most likely exceed those arising from nourishment.

Prolonged nourishment and/or erosion of the fill sediment can, however, indirectly influence turbidity-sensitive plants and animals. As it may offer protection against visual predators in an environment with little natural refuge, elevated turbidity might temporarily be advantageous for surf zone fish (Beyst *et al.*, 2002), but an eventual oxygen deficit will consequently affect breathing and embryonic development (Goldberg, 1989; Anonymous, 1995). Turbid waters can also limit the penetration of light through the water (decreasing phytoplankton and benthic algal productivity), can lower underwater visibility for visual predators such as fish, crabs and birds, and can hamper the feeding and breathing of polychaetes and bivalves (e.g. *Donax* species) (Essink, 1999).

Intertidal amphipods *Bathyporeia pilosa* and *B. sarsi*, both common species of north-west European sandy beaches, in laboratory experiments were shown to have a clear preference for low levels of fines (ca. 1%) (Rivas Higuera, 2003). For *B. pilosa* this was also shown in field data (mud content greater than 2% (Khayrallah and Jones, 1980)). A high level of fines in fill sediments can result in a slow recovery of macrobenthic organisms (Saloman and Naughton, 1984; Gorzelany and Nelson, 1987; Rakocinski *et al.*,

1996), owing to limited juvenile survival (as demonstrated for *Donax*, *Scolecipis squamata* (Reilly and Bellis, 1983)). Aggregations of fines, such as clay balls, in the fill sediment can cause a long-lasting input of fines and thus can elevate turbidity long after the actual nourishment event (e.g. 7 years (Hume and Pullen, 1988; Goldberg, 1989)).

Silt accumulation may positively stimulate microphytobenthos growth, probably because of higher nutrient concentrations (van de Koppel *et al.*, 2001), but deposition of thicker layers of fines will, at least temporarily, have a negative effect on microphytobenthos populations.

- Grain-size distribution

Grain size, beach profile, beach morphology and the morphodynamic type of the beach are related parameters. Grain-size distribution strongly influences the structure and functioning of the ecosystem (e.g. benthic community structure) (McLachlan, 1983; Degraer *et al.*, 2003; Rodil and Lastra, 2004) and therefore it is an important aspect in the evaluation and prediction of the ecological effects of beach nourishment. For reasons of stability after nourishment (and less frequent need for replenishment) and to minimize the amount of sand needed, nourishment is mainly conducted using sands with a median grain size higher than that of the original sands (Dean, 1987; Raudkivi and Detté, 2002). The role of changes in grain size often cannot be investigated independently from changes in beach morphology and in the hydrodynamics. The role of changes in grain size often cannot be investigated independently from changes in beach morphology and in the hydrodynamics. McLachlan (1996) studied a beach on which grain size was artificially increased while tidal range, wave energy and turbidity remained constant. As a consequence, the beach's morphodynamic state evolved from dissipative to intermediate. Changes in grain size and slope could both separately be correlated with a decreasing species richness and macrobenthic abundance. Thus, in this study, grain size and beach morphology were assessed independently. Eventually, the local *Donax* species disappeared. Other research also related changes in median grain size with a decreased abundance of benthic macrofauna and a structural shift in the benthic communities (e.g. Rakocinski *et al.*, 1996; Peterson *et al.*, 2000a; Peterson and Manning, 2001). The common north-west European sandy beach amphipod *Bathyporeia pilosa* prefers sediments with a median grain size of 150–220 µm (Khayrallah and Jones, 1980); a range which is well below conventionally used median grain sizes of fill sediment.

Through changes in grain size and grain shape, nourishment can cause changes in sediment density and set off an augmented compaction of the sediment (Anonymous, 1989). Effects of compaction are manifested through changes in the interstitial space, the capillarity, the water retention, the permeability and the exchange of gases and nutrients (Anonymous, 1989). The penetration of bills of wading birds, and vertical locomotion of the infauna are inhibited when grain size and composition of the fill sediment differ too much from the original beach sediment, resulting in increased compaction (Maurer *et al.*, 1978). Heavily compacted beaches consequently typically have a lower abundance of burrowing organisms (Lindquist and Manning, 2001). Burrowing of female sea turtles can also be hampered by compaction and the significance of sediment characteristics to the use of nourished beaches for turtle nesting, egg viability, and hatchling success has been documented (Nelson and Dickerson, 1988; Crain *et al.*, 1995; Steinitz *et al.*, 1998; Rumbold *et al.*, 2001).

Sediment grain size has a profound effect on microphytobenthos community structure (e.g. Sabbe and Vyverman, 1991; Paterson and Hagerthey, 2001); this, however, is mainly caused by the hydrodynamical forces regulating the distribution of sediment types and simultaneously also micro-algal functional groups. There is as yet no information of the effects of sediment grain size per se on the taxonomic and functional structure of microphytobenthic communities.

No results are available on how grain size distribution can be related directly or indirectly to populations of vascular plants and terrestrial arthropods, though for the latter the work of Den Hollander and Van Etten (1974) suggested grain-size preferences of the burrowing beetles of the genus *Bledius*.

Beach morphology. The morphology of beaches and their morphodynamic characteristics are known to largely determine benthic community structure (Degraer *et al.*, 2003; Rodil and Lastra, 2004).

Changes in the beach profile (linked to the grain-size distribution of the nourishment sands) can lead to changes in the hydrodynamics of the intertidal zone; an increase of the slope angle will increase wave energy on the beach (Kaufman and Pilkey, 1983), creating a hydrodynamically more stressful environment, leading to a reduction in diversity and abundance of the infauna (McLachlan, 1983). Significant changes of the profile can give rise to a change in the morphodynamic state, causing a slow recovery and maybe even a permanent shift in the ecological community structure.

Some researchers have suggested that changes in geomorphology and sediment characteristics even have a larger impact on the recovery rates of invertebrate populations than the direct effects of burial or mortality (Greene, 2002) and this in turn can indirectly affect the populations of foraging birds. For the other ecosystem components considered (vascular plants, microphytobenthos and terrestrial arthropods) no data are available. Altered beach morphology (but also compaction) may affect sea turtle nesting.

Presence of toxic substances and/or dead organisms. Sometimes the supplied sediment contains dead organisms, originating from the extraction site resulting in a temporal increase in organic matter and providing food for various birds including gulls and waders. This (temporary) organic enrichment could also have an effect on the entire beach ecosystem, but no data are available on the subject.

The absence of toxic substances (heavy metals, PACs, PCBs etc.) is of importance for all ecosystem components and thus it is often mentioned as an important quality criterion (Anonymous, 1989, 2002a; Adriaanse and Coosen, 1991).

Sediment colour. Colour, density and grain shape can change the heat retention capacity of the sand and thus alter the temperature of the beach sand (Anonymous, 1989). The ecological consequences of such alterations in the beach habitat are unknown. Changes in sediment temperature could influence respiration rates and reproductive success of benthic organisms.

Quantity characteristics of the nourishment sediment

Thickness of the applied sand determines the degree of burial of the organisms leading to high or even total mortality of buried benthic organisms and to potential loss of prey for predators feeding on these organisms (Dankers *et al.*, 1983; Adriaanse and Coosen, 1991; Anonymous, 1995; Löffler and Coosen, 1995; Charlier *et al.*, 1998; Peterson *et al.*, 2000b). The lethal thickness of a layer of deposited sand goes up to a maximum of 90 cm for some polychaetes (Löffler and Coosen, 1995; Essink, 1999). In most cases of traditional nourishment the deposited sand layer is about 1 to 2.5 m thick and remains for a long period of time (Coastal Waterways Division, pers. comm.), thus resulting in total mortality of resident benthic macrofauna; and typically the macrofauna originating from the borrow site also dies off completely (Menn *et al.*, 2003). No information on mortality of other ecosystem components is available, yet, with the exception of birds, it can be supposed that all other components will be affected similarly.

The consequences of deep burial have to be taken into account at the species level. Species-specific life-history traits will influence rate of recovery. While the originally resident organisms will die off, the newly nourished beach will be re-colonized, mainly through settlement of pelagic juvenile life stages of marine benthic organisms. Several species, however, do not have a pelagic stage and their populations recover at a much slower rate after nourishment (e.g. *Bathyporeia* and *Haustorius* (Saloman and Naughton, 1984); crustaceans in general (van Dalfsen and Essink, 2001)).

Very little information exists on the effects of burial on microphytobenthos. Wulff *et al.* (1997) documented the response of a sand-dwelling microbenthic community to burial by a 2.5 mm thick layer of mud. After one week, active upward migration of the microalgae (mainly diatoms) had resulted in the

restoration of photoautotrophic activity in the surface layers. Saburova and Polikarpov (2003) buried a natural sandy sediment microphytobenthos community under a 4-cm layer of sterile sand. After 24 hours the first cells reached the surface, but after five days about 20% was still present in the original layers. These experiments were conducted on intact cores placed in plastic tubes, so it is not possible to determine to what degree horizontal movement of the microphytobenthos might influence re-colonization of 'new' sediments. In both experiments, however, the thickness of the experimental covering layer was very much less than those applied in nourishment. Given that even a 4cm thick layer significantly hinders restoration of microphytobenthic activity, it is to be expected that beach nourishment will result in a very low survival and hence upward migration of the *in situ* microphytobenthos. Re-colonization will probably mainly be the result of new colonization via the water column or adjacent unburied sediments, or via deep reworking of the nourishment layers.

The impact of beach nourishment on the foraging behaviour of wading birds is also poorly investigated, but there are indications that such impacts do occur. The die-off of the polychaete *Scolelepis squamata* after nourishment on the Dutch island of Texel resulted in a measurable drop in the number of foraging sanderling *Calidris alba* and catching success also decreased on the nourished beach (Dankers *et al.*, 1983). *Scolelepis squamata* is known as a primary food item of sanderling along the North Sea coast (Glutz von Blotzheim *et al.*, 1984).

Factors determining scale of impact

Timing, place and size of beach nourishment

Disturbance during the construction phase can cause nesting birds to leave their nests permanently or can cause them to stop foraging on nearby beaches, thus winter is proposed as the best season for undertaking nourishment (Melvin *et al.*, 1991; Peterson and Manning, 2001). High numbers of birds are often present in winter on many beaches and they will surely be affected by nourishment events, yet the nesting period remains the most vulnerable phase in the birds' annual cycle. Timing of nourishment should be considered in relation to the importance of the specific beach for nesting birds, on one hand, and resting and foraging birds on the other. Winter is, however, also the best season for a low impact on epibenthic organisms, as they are found in the shallow infralittoral zone and not on the beach itself during winter (Grober, 1992). Also for the larger benthic infauna this timing is preferable. If nourishment activities continue until May, the reproduction of macrobenthos is affected and recovery can be postponed until the next recruitment, macrobenthic animals can become smaller-sized and average biomass may drop gradually (Peterson *et al.*, 2000a).

The preferred time of nourishment entirely depends on the nature and location of the beach and the species inhabiting or exploiting it, but if it is chosen carefully, rapid recovery is possible (e.g. Saloman and Naughton, 1984).

Nourishment strategies and techniques

Nourishment strategies. Three common nourishment strategies exist: classic or profile nourishment, foreshore nourishment and backshore nourishment. Classic, profile nourishment involves the deposition of the sediment across the entire intertidal zone. With foreshore nourishment and backshore nourishment the sand is deposited on a narrower zone of the beach and gradually it is redistributed 'naturally' by wave action and winds respectively, on the foreshore and on the dry part of the beach. Whereas profile nourishment is expected to impact mainly the benthic fauna and flora of the littoral zone and through those also foraging birds, the foreshore and backshore nourishment would be expected to affect mainly the biota residing in the zones where the sediment is deposited (infralittoral benthos and foraging birds for foreshore

nourishment and terrestrial arthropods, vascular plants and nesting birds for backshore nourishment). In reality the difference between the effects of different strategies is somewhat more complex.

Classic nourishment ensures that the maximum width of the beach is maintained and the material is sorted by wave action, thus lowering compaction (Anonymous, 1989). With this strategy the installed profile should be rather stable. Little should change, given the reigning hydrodynamics and aeolian forces, and only a minority of the sediment will be redistributed in an offshore direction (Anonymous, 2002c).

Foreshore nourishment is being used in many countries and it minimizes the size of the directly impacted surface area (Charlier *et al.*, 1998). The foreshore is nourished by dumping the fill sediment directly from the ship. While the intertidal organisms are only gradually covered with sand and should be able to survive, the overall damaging impact of this strategy may be higher (Thompson, 1973; Oliver and Slattery, 1976): in wintertime some seasonally migrating benthic beach animals such as bivalves (e.g. *Donax*) and crabs often live on the foreshore and thus they will be covered with sand by foreshore nourishment if it is executed in winter (Grober, 1992). Furthermore, resident foreshore species may be adversely affected.

With backshore nourishment the sediment becomes gradually distributed towards the sea over the entire profile until a dynamic equilibrium is reached. Although this is said to result in minimal physical and ecological damage, in contrast to foreshore nourishment it gives rise to a narrower dry section of the beach (Anonymous, 2002c) which may be unfavourable for nesting birds. Van Dolah *et al.* (1992) advise depositing the sand high on the beach, far above the average sea level. This should result in a gradual sand distribution (Niemeyer *et al.*, 1996) and lower mortality of the burrowed animals. Effects of backshore nourishment on organisms of the dry beach including vascular plants, terrestrial arthropods and nesting birds have, however, been neglected in nearly all studies.

Dankers *et al.* (1983) investigated two nourishment projects in the Netherlands: on the isle of Texel, sand was spread across the entire beach (i.e. classic, profile nourishment), while on the isle of Ameland the sand was deposited at the base of the coastal dunes as a bank of sand (backshore nourishment). Recovery of the macrobenthos on Ameland occurred faster (hardly any impact) than on Texel (not until after 20 months).

Piling sand on the dry beach ('bulldozing') may lead to an elevated slope of the beach, causing higher wave energy on the beach (Kaufman and Pilkey, 1983) and thus creating a more stressful environment, decreasing diversity and abundance of infaunal assemblages (McLachlan, 1983). It is, however, likely that this is only a temporary effect, as wave action will rapidly restore the beach profile. Mechanically distributing sand across the beach is said to pose a superfluous — but also unknown — pressure on the ecosystem because the sand can be distributed naturally across the beach by waves and winds (Basco, 1999).

Nourishment techniques. Rainbow spraying increases the chance for an elevated flux of salt towards the coastal dunes, significantly exceeding natural spray and causing the dunes to become salty and damaging the vegetation (Adriaanse and Coosen, 1991; van der Wal *et al.*, 1995; see also below).

Density and compaction greatly increase if the sand is pumped as a mixture of sediment and water ('slurry') (Anonymous, 1989). Compaction may be three or four times higher than on the original beach and might even increase after the construction phase (Ryder, 1991). Elevated compaction might hamper burrowing of benthic organisms.

Supplying the nourishment sand by means of pipelines is the most commonly used method. If the supply is deposited from the backshore side of the beach towards the foreshore, the coarse material will settle near the backshore deposit bank and the fine material will be deposited downhill together with the slurry (Kana and Mohan, 1998). This kind of nourishment concentrates the coarsest fraction where it is needed most and improves the lifespan of the (backshore) sand bank, but the downhill movement of the fines into the swash zone can cause elevated turbidity of the coastal waters, resulting in ecological effects associated with elevated levels of fines. With foreshore nourishment, turbidity might also increase, and suspension of the sediment may also cause washout of the biota.

Indirect and cumulative effects

Indirect and cumulative ecological effects of beach nourishment are hardly known (Nordstrom, 2000; Greene, 2002). These effects were not incorporated in Figure 1, but will be mentioned briefly here.

Nearby beaches (including their coastal dunes, foreshore and groynes), but also adjacent wetlands, might be influenced by nourishment through *longshore transport* (by water) (e.g. Thomalla and Vincent, 2003) and aeolian transport of sand. As species associations of deeper, subtidal underwater zones are less capable of surviving nourishment and as they recover more slowly, seaward transport of sand should be avoided (Rakocinski *et al.*, 1996). It can, however, be expected that foreshore areas and their inhabiting organisms, are used to routine inundation with sand such as occurs during storms. Furthermore, avoiding offshore movement of sand is difficult in practice, as storms naturally move sand seaward.

An input of sediment into the system will diminish deficits in the sediment budget, at and upstream of the nourishment site. Beach nourishment affects the sediment budget (Eitner and Ragutzki, 1994), but has no effect on tides, waves, currents or changes in storm frequency if the applied volume of sand is kept at a minimum and no hard structures are built in combination with nourishment (Anonymous, 2002b). Background erosion remains constant and the sand volume lost in storms will not alter; beach nourishment does, however, slow down background erosion and offers storm protection to the hinterland. Finally, it should be noted that the shape of the sand grains affects compaction (Anonymous, 1989) but not sediment transport (van der Wal, 1998). Indirect effects such as elevated pressure on the ecosystem caused by augmented tourist activities after enlarging the dry beach should not be ignored.

Greene (2002) stressed the possibility of cumulative effects, both (1) temporal as a consequence of the replenishment frequency and (2) spatial as a consequence of the overall impact of several nourishment projects in the same region, and also (3) synergisms between temporal and spatial aspects. Currently, little is known of the physical and ecological effects of long lasting and repeated nourishment. An example is the grain size becoming coarser over the years because of repeated nourishment with coarse sands. Repeated nourishment can furthermore initiate (1) higher compaction of the beach sediment, (2) long-term elevated turbidity and (3) permanently altered sediment composition and beach morphology (Anonymous, 1989).

The combined effects of simultaneous nourishment projects along an entire coastline should be considered (Anonymous, 1999). Several short projects are preferred over long-lasting ones, especially in areas where short-term morphological changes are unpredictable (Hillen and Roelse, 1995).

CONCLUSIONS

Focusing on the ecological damage beach nourishment may cause, we have reviewed the impact nourishment can have on a natural beach and concluded that nourishment is not an entirely ecologically sound coastal defence alternative. We should, however, stress that in practice, coastal defence alternatives to nourishment will generally be far more damaging to shoreline ecology (e.g. Dankers *et al.*, 1983; Adriaanse and Coosen, 1991; Brown and McLachlan, 2002; Greene, 2002) and it seems likely that nourishment is the most ecologically sound coastal defence alternative available. In addition, a beach requiring nourishment is often in an already unnatural condition, making it somewhat dangerous to assess the differential impact of nourishment. Local natural values may have already been lowered prior to nourishment for a number of reasons including recreation, pollution and earlier coastal defence history (including previous nourishment) at a certain beach. In some cases, nourishment may even create suitable habitats for rare or threatened organisms such as piping plovers (*Charadrius melodus*) (Nordstrom *et al.*, 2000) and sea turtles (Witham, 1990; Lebuff and Haverfield, 1992; Crain *et al.*, 1995).

Yet, even while nourishment may be more benign than other types of coastal protection, an impact of such magnitude brings about sizeable changes in the beach ecosystem. From this review, some guidelines for future nourishment are gathered and/or deduced and some considerations for future research on the ecological impact of beach nourishment are proposed.

Guidelines for an ecologically good practice of beach nourishment

Based on the review of known impacts of beach nourishment on elements of the beach ecosystem, some guidelines for executing nourishment with minimal detrimental effects on the sandy beach ecosystem, are summarized below.

Sediment

Sediment characteristics play a very important role in the impact of beach nourishment on the ecosystem sediment composition and beach morphology.

The importance of grain-size distribution of the nourishment sand for ecological recovery could be questioned, as it can be expected that the grain-size distribution will be restored very rapidly by natural conditions such as currents and storms. A gradual shift towards a morphological equilibrium (depending on the current hydrodynamic conditions) can be expected, but it is crucial to understand that ecological recovery can only be expected after this equilibrium is established. Thus, to limit the ecological impact, nourishment sands with a comparable sediment composition to that of the natural sediment should be used, to allow swift recovery of the benthic fauna (Parr *et al.*, 1978; Nelson, 1993; Löffler and Coosen, 1995; Peterson *et al.*, 2000a). The ecological arguments for retaining the original grain size are further supported by geomorphologists to avoid a sharp transition from dissipative to reflective beaches (Anfuso *et al.*, 2001).

Compaction may be three or four times higher than on the original beach (Ryder, 1991). This can be solved by ploughing or 'tilling' the beach (Dean, 2002), but it is mainly a short-term problem, as wave action will soften the beach, especially during storms.

While the impact of sediment colour is largely unknown it seems precautionary to use sands with the same colour as the original sediment. Finally, toxic substances should be absent (Anonymous, 1989, 2002a; Adriaanse and Coosen, 1991).

Timing

When aiming at a minimal ecological impact, nourishment should be completed within a single winter, starting after October and ending around March (Anonymous, 1989). This timing is optimal for nesting birds in the northern hemisphere (Anonymous, 1999).

As a number of organisms spend the winter months in the shallow infralittoral zone, it is possible that the reduced impact due to this timing becomes undone with foreshore nourishment. It should be noted that this guideline relates only to mesothermic zones of the northern hemisphere. As a rule, nourishment should be executed during periods of low beach use by birds and other migrating or mobile organisms and the preferred season is entirely site-specific, depending on an area's location and natural heritage interests.

Size

Generally, a number of smaller projects (<800 m length of shore) is preferred over a single large nourishment project (Adriaanse and Coosen, 1991; Löffler and Coosen, 1995; Peterson *et al.*, 2000b). The short distance between nourished and unnourished beach strips allows swift re-colonization, depending on species-specific dispersal capacities. This may very well be the case for infauna but seems to be doubtful for birds.

Nourishment strategy

No clear choice can be made among the three mentioned nourishment strategies (classic or profile nourishment, foreshore nourishment and backshore nourishment). It seems advisable to decide on this point in respect to the local natural values of the beach ecosystem at the nourishment site. Each strategy has its major impact on a different part of the beach. Choices will have to be made in view of the vulnerability of the organisms residing in each zone of the beach.

Shortcomings of former research and options for future research

Notwithstanding the amount of literature on the ecological effects of beach nourishment, it still remains impossible to objectively assess the ecological effects of future nourishment projects and thus to formulate a scientifically sound, ecological adjustment of these projects.

Most studies only take into account one ecosystem component, failing to address the overall ecological effects and thus making it very difficult to form a general picture of the effects on the whole ecosystem necessary in order to effectively adjust future nourishment projects. Since in many cases the available information on the ecosystem of a certain beach is incomplete, it is advisable to enlarge and integrate this body of information prior to the impact assessment. Knowledge on local conditions of the beach ecosystem (e.g. breeding bird colonies or fish nursery grounds) might help to prioritize among the information needed.

Secondly, because of pragmatic restrictions inherent to field experiments, such as the investigation of the ecological effects of beach nourishment, imperfections in the design of the research strategy often diminish the scientific value and thus convictive power of the investigations (e.g. Stauble and Nelson, 1985; Adriaanse and Coosen, 1991; Nelson, 1993; Elzinga *et al.*, 2001; Peterson and Manning, 2001; Finkl, 2002). Imperfections often encountered include the lack of (1) sampling prior to nourishment (e.g. Parr *et al.*, 1978; McLachlan, 1996; Rakocinski *et al.*, 1996), (2) control sites or badly chosen control sites (e.g. Reilly and Bellis, 1983; McLachlan, 1996), (3) replication of impact and/or control site (e.g. Rakocinski *et al.*, 1996), (4) detailed sampling through time (e.g. Rakocinski *et al.*, 1996), (5) interspersation (i.e. spatial alternation) of impact and control sites (e.g. Dankers *et al.*, 1983), (6) long-term monitoring, failing to monitor full ecological recovery (e.g. Rakocinski *et al.*, 1996) and (7) monitoring the physicochemical environment along with the biological characteristics (e.g. Reilly and Bellis, 1983). Only by avoiding the abovementioned strategic imperfections will a solid basis for future adjustments of nourishment projects be set.

Finally, all studies describe the effects rather than investigating the biological processes responsible for these effects. Only by investigating underlying processes such as those related to impact size and rate of recovery, can the effects of future projects be predicted and thus objective ecological adjustments in nourishment practice suggested. The biological processes, relevant for nourishment effects, comprise (1) the process of disturbance and survival during nourishment (short-term) and (2) the process of re-colonization after nourishment (medium- to long-term) (van Dalfsen and Essink, 2001). Disturbance and survival are mainly determined by species-specific tolerances, while re-colonization is determined by (1) species-specific dispersal and migration capacities and (2) species-specific habitat demands and tolerances, including physical and biological elements. If scientific attention can be paid to these processes, this will finally allow scientists to objectively execute an ecosystem-directed evaluation and adjustment of future nourishments.

In conclusion to our review, we acknowledge the need for coastal protection. Yet, while coastal protection is necessary for a number of socioeconomic reasons related to, for example, tourism, housing and urban development, we feel that the ecological impact of any form of coastal protection needs careful consideration. Protection of often highly productive beach habitats is crucial to safeguard natural resources. Therefore, fine-tuning of nourishment practice for the sake of ecological damage control deserves attention. Even rethinking the design of nourishment projects in order to combine coastal protection with enhancing biota has been suggested (Nordstrom, 2005).

ACKNOWLEDGEMENTS

This research was funded by the Flemish Coastal Waterways Division (AWZ-WWK – contract number 202.165) and Ghent University (GOA2005). We are grateful to two anonymous referees and Dr John Baxter for their comments on an earlier draft of this paper.

REFERENCES

- Adriaanse LA, Coosen J. 1991. Beach and dune nourishment and environmental aspects. *Coastal Engineering* **16**: 129–146.
- Anfuso G, Benavente J, Gracia FJ. 2001. Morphodynamic responses of nourished beaches in SW Spain. *Journal of Coastal Conservation* **7**: 71–80.
- Anonymous. 1984. *Shore Protection Manual*, Vol. 1. US Army Corps of Engineers: Washington, DC.
- Anonymous. 1989. *Engineer Manual — Engineering and Design, Environmental Engineering for Coastal Shore Protection*. EM 1110-2-1204. US Army Corps of Engineers: Washington, DC.
- Anonymous. 1995. *Beach Nourishment and Protection*. National Research Council — Committee for Beach Nourishment and Protection, National Academy Press: Washington, DC.
- Anonymous. 1999. Environmental report: use of federal offshore sand resources for beach and coastal restoration in New Jersey, Maryland, Delaware, and Virginia. OCS Study: MMS 99-0036. US Department of the Interior/Minerals Management Service — Office of International Activities and Marine Minerals: Washington, DC.
- Anonymous. 2001. The New York districts' biological monitoring program for the Atlantic Coast of New Jersey, Asbury Park to Manasquan Section beach erosion control project. Final report. US Army Corps of Engineers — Waterways Experiment Station: Vicksburg, MS.
- Anonymous. 2002a. *Coastal Engineering Manual*. EM 1110-2-1100. US Army Corps of Engineers: Washington, DC.
- Anonymous. 2002b. *Phipps Ocean Park Beach Restoration Project, Town of Palm Beach, Palm Beach County, Florida. Draft Supplemental Environmental Impact Statement*. US Army Corps of Engineers: Washington, DC.
- Anonymous. 2002c. California beach restoration study. California Department of Boating and Waterways and State Coastal Conservancy (CDBWSSC): Sacramento, CA.
- Basco DR. 1999. Overview of beach engineering in the United States of America. Report for Research Center for Disaster Environment — Disaster Prevention Research Institute — Kyoto University, Kyoto, Japan.
- Beyst B, Hostens K, Mees J. 2002. Factors influencing the spatial variation in fish and macrocrustacean communities in the surf zone of sandy beaches in Belgium. *Journal of the Marine Biological Association of the United Kingdom* **82**: 181–187.
- Brown AC, McLachlan A. 2002. Sandy shore ecosystems and the threats facing them: some predictions for the year 2025. *Environmental Conservation* **29**(1): 62–77.
- Charlier RH, De Meyer CP. 1995. New developments on coastal protection along the Belgian coast. *Journal of Coastal Research* **11**(4): 1287–1293.
- Charlier RH, De Meyer CP. 2000. Ask nature to protect and build-up beaches. *Journal of Coastal Research* **16**(2): 385–390.
- Charlier RH, Decroo D, De Meyer CP, Lahousse B. 1998. To feed or not to feed, that is often the question. *International Journal of Environmental Studies* **55**: 1–23.
- Clayton TD. 1991. Beach replenishment activities on U.S. continental Pacific coast. *Journal of Coastal Research* **7**(2): 1195–1210.
- Crain AD, Bolten AB, Bjorndal KA. 1995. Effects of beach nourishment on sea turtles: review and research initiatives. *Restoration Ecology* **3**: 95–104.
- Dankers N, Binsbergen M, Zegers K. 1983. De effecten van zandsuppletie op de fauna van het strand van Texel en Ameland. Report 83/6, Rijksinstituut voor Natuurbeheer, Texel, The Netherlands.
- Dean RG. 1987. Coastal sediment processes: toward engineering solutions. In *Proceedings of Coastal Sediments '87*. American Society of Civil Engineers: New York, 1–24.
- Dean RG. 2002. *Beach Nourishment: Theory and Practice*. Advanced Series on Ocean Engineering, no. 18. World Scientific: River Edge, NJ.
- Degraer S, Volckaert A, Vincx M. 2003. Macrobenthic zonation patterns along a morphodynamical continuum of macrotidal, low tide bar/rip and ultra-dissipative sandy beaches. *Estuarine, Coastal and Shelf Science* **56**(3–4): 459–468.

- Den Hollander J, Van Etten JCA. 1974. De oekologie van *Bledius arenarius* en *B. subniger* op het Oostvoornse strand (Coleoptera, Staphylinidae). *Entomologische Berichten* **34**: 155–160.
- Eitner V, Ragutzki G. 1994. Effects of artificial beach nourishment on nearshore sediment distribution (Island of Norderney, southern North Sea). *Journal of Coastal Research* **10**(3): 637–650.
- Elzinga CL, Salzer DW, Willoughby JW, Gibbs JP. 2001. *Monitoring Plant and Animal Populations*. Blackwell Science: Malden, MA.
- Essink K. 1999. Ecological effects of dumping of dredged sediments; options for management. *Journal of Coastal Conservation* **5**: 69–80.
- Esteves LS, Finkl CW. 1998. The problem of Critically Eroded Areas (CEA): an evaluation of Florida beaches. *Journal of Coastal Research* **SI**(26): 11–18.
- Finkl CW. 2002. Long-term analysis of trends in shore protection based on papers appearing in the Journal of Coastal Research, 1984–2000. *Journal of Coastal Research* **18**(2): 211–224.
- Glutz von Blotzheim UN, Bauer KM, Bezzel E (eds). 1984. *Handbuch der Vögel Mitteleuropas. Vol. 6: Charadriiformes (Part 1)*. Aula: Wiesbaden.
- Goldberg WM. 1989. Environmental monitoring of beach restoration: benthic flora and fauna in the vicinity of Boca Raton North project, 1988. Unpublished paper, 7 pp.
- Gorzelany JF, Nelson WG. 1987. The effects of beach replenishment on the benthos of a sub-tropical Florida beach. *Marine Environmental Research* **21**: 75–94.
- Greene K. 2002. *Beach nourishment: a review of the biological and physical impacts*. ASMFC Habitat Management Series no. 7. Atlantic States Marine Fisheries Commission, Washington, DC.
- Grober LE. 1992. The ecological effects of beach replenishment. Master's project, School of the Environment, Duke University, Durham, NC.
- Haddad TC, Pilkey OH. 1998. Summary of the New England beach nourishment experience (1935–1996). *Journal of Coastal Research* **14**(4): 1395–1404.
- Hall SJ. 1994. Physical disturbance and marine benthic communities: life in unconsolidated sediments. *Oceanography and Marine Biology: An Annual Review* **32**: 179–239.
- Hamm L, Capobianco M, Dette HH, Lechuga A, Spanhoff R, Stive MJF. 2002. A summary of European experience with shore nourishment. *Coastal Engineering* **47**: 237–264.
- Hanson H, Brampton A, Capobianco M, Dette HH, Hamm L, Laustrop C, Lechuga A, Spanhoff AR. 2002. Beach nourishment projects, practices, and objectives — a European overview. *Coastal Engineering* **47**: 81–111.
- Hillen R, Roelse P. 1995. Dynamic preservation of the coastline in the Netherlands. *Journal of Coastal Conservation* **1**(1): 17–28.
- Hume AK, Pullen EJ. 1988. Biological effects of marine sand mining and fill placement for beach replenishment: lessons for other uses. *Marine Mining* **7**: 123–136.
- Jaramillo E, Contreras H, Quijón P. 1996. Macroinfauna and human disturbance in a sandy beach of south-central Chile. *Revista Chilena de Historia Natural* **69**: 655–663.
- Kana TW, Mohan RK. 1998. Analysis of nourished profile stability following the fifth Hunting Island (SC) beach nourishment project. *Coastal Engineering* **33**: 117–136.
- Kaufman W, Pilkey O. 1983. *The Beaches are Moving, the Drowning of America's Shoreline*. Duke University Press: Durham, NC.
- Khayrallah NH, Jones AM. 1980. The ecology of *Bathyporeia pilosa* (Amphipoda: Haustoriidae) in the Tay estuary. I. Factors influencing the distribution on Tayport and Tentsmuir beaches. *Proceedings of the Royal Society of Edinburgh* **78B**: 109–119.
- Lebuff CR, Haverfield EM. 1992. Nesting success of the loggerhead turtle (*Caretta caretta*) on Captiva Island, Florida — a nourished beach. In *Proceedings of the Eleventh Annual Workshop on Sea Turtle Biology and Conservation. 26 February–2 March 1991, Jekyll Island, Georgia*, Salmon M, Wyneken J (eds). Technical Memorandum NMFS-SEFC-302, National Oceanographic and Atmospheric Administration, Washington, DC; 69–71.
- Lindquist N, Manning L. 2001. Impacts of beach nourishment and beach scraping on critical habitat and productivity of surf fishes. Final Report to the NC Fisheries Resource Grant Program, Morehead City.
- Löffler M, Coosen J. 1995. Ecological impact of sand replenishment. In *Directions in European Coastal Management*, Healy MG, Doody JP (eds). Samara Publishing: Cardigan; 291–299.
- Maurer DL, Keck RT, Tinsman JC, Leathern WA, Wethe CA, Huntzinger M, Lord C, Church TM. 1978. Vertical migration of benthos in simulated dredged material overburdens. Vol. I: Marine benthos. Technical Report D-78-35. US Army Corps of Engineers: Washington, DC.
- McLachlan A. 1983. Sandy beach ecology — a review. In *Sandy Beaches as Ecosystems*, McLachlan A, Erasmus T (eds). Dr W. Junk: The Hague; 321–380.
- McLachlan A. 1991. Ecology of coastal dune fauna. *Journal of Arid Environments* **21**: 229–243.

- McLachlan A. 1996. Physical factors in benthic ecology: effects of changing sand particle size on beach fauna. *Marine Ecology Progress Series* **131**: 205–217.
- Melvin SM, Griffin CR, MacIvor LH. 1991. Recovery strategies for Piping Plovers in managed coastal landscapes. *Coastal Management* **19**: 21–34.
- Menn I, Junghans C, Reisen K. 2003. Buried alive: effects of beach nourishment on the infauna of an erosive shore in the North Sea. *Senckenbergiana maritima* **32**: 125–145.
- Miller DC, Muir CL, Hauser OA. 2002. Detrimental effects of sedimentation on marine benthos: what can be learned from natural processes and rates? *Ecological Engineering* **19**: 211–232.
- Moffett MD, McLachlan A, Winter PED, De Ruyck AMC. 1998. Impact of trampling on sandy beach macrofauna. *Journal of Coastal Conservation* **4**: 87–90.
- Naqvi SM, Pullen EJ. 1982. *Effects of Beach Nourishment and Borrowing on Marine Organisms*. US Army Corps of Engineers: Fort Belvoir, VA.
- Nelson DA, Dickerson DD. 1988. Effects of beach nourishment on sea turtles. Tait LS (ed.). In *Proceedings of the beach preservation technology conference '88*. Florida shore & Beach Preservation Association, Incorporated: Tallahassee, GA.
- Nelson WG. 1993. Beach restoration in the Southeastern US: environmental effects and biological monitoring. *Ocean and Coastal Management* **19**: 157–182.
- Newell RC, Seiderer LJ, Hitchcock DR. 1998. The impact of dredging works in coastal waters: a review of the sensitivity to disturbance and subsequent recovery of biological resources on the sea bed. *Oceanography and Marine Biology: An Annual Review* **36**: 127–178.
- Niemeyer HD, Kaiser R, Knaack H. 1996. Effectiveness of a combined beach and shoreface nourishment on the island of Norderney, East Frisia, Germany. In *Proceedings of the 25th International Conference on Coastal Engineering, Orlando, FL*. ASCE: New York; 1–14.
- Nordstrom KF. 2000. *Beaches and Dunes of Developed Coasts*. Cambridge University Press: Cambridge.
- Nordstrom KF. 2005. Beach nourishment and coastal habitats: research needs to improve compatibility. *Restoration Ecology* **13**(1): 215–222.
- Nordstrom KF, Lampe R, Vandemark LM. 2000. Re-establishing naturally-functioning dunes on developed coasts. *Environmental Management* **25**: 37–51.
- Oliver JS, Slattery PN. 1976. Effects of dredging and disposal on the benthos in Monterey Bay, California. Technical Paper 76-15, US Army Corps of Engineers: Fort Belvoir, VA.
- Parr T, Diener D, Lacy S. 1978. Effects of beach replenishment on the nearshore sand fauna at Imperial beach, California. Miscellaneous Report 78-4, US Army Corps of Engineers: Fort Belvoir, VA.
- Paterson DM, Hagerthey SE. 2001. Microphytobenthos in contrasting coastal ecosystems: biology and dynamics. In *Ecological Comparisons of Sedimentary Shores*, K. Reise (ed.). Ecological studies no. 151, Springer-Verlag: Berlin.
- Peterson CH, Manning L. 2001. How beach nourishment affects the habitat value of intertidal beach prey for surf fish and shorebirds and why uncertainty still exists. In *Proceedings of the Coastal Ecosystems and Federal Activities Technical Training Symposium*. U.S. Fish and Wildlife Service: Atlanta, GA, 1–2.
- Peterson CH, Hickerson DHM, Johnson GG. 2000a. Short-term consequences of nourishment and bulldozing on the dominant large invertebrates of a sandy beach. *Journal of Coastal Research* **16**(2): 368–378.
- Peterson CH, Summerson HC, Thomson E, Lenihan HS, Grabowski J, Manning L, Micheli F, Johnson G. 2000b. Synthesis of linkages between benthic and fish communities as a key to protecting essential fish habitat. *Bulletin of Marine Science* **66**(3): 759–774.
- Rakocinski CF, Heard RW, LeCroy SE, McLelland JA, Simons T. 1996. Responses by macrobenthic assemblages to extensive beach restoration at Perdido Key, Florida, U.S.A. *Journal of Coastal Research* **12**(1): 326–353.
- Raudkivi AJ, Dette H-H. 2002. Reduction of sand demand for shore protection. *Coastal Engineering* **45**: 239–259.
- Reilly FJ, Bellis VJ. 1983. The ecological impact of beach nourishment with dredged materials on the intertidal zone at Bogue Banks, North Carolina. Miscellaneous Report 83-3. US Army Corps of Engineers: Fort Belvoir, VA.
- Rivas Higuera H. 2003. Habitat selection of sympatric and allopatric *Bathyporeia pilosa* and *Bathyporeia sarsi* populations. MSc thesis, University of Gent.
- Rodil IF, Lastra M. 2004. Environmental factors affecting benthic macrofauna along a gradient of intermediate sandy beaches in northern Spain. *Estuarine, Coastal and Shelf Science* **61**: 37–44.
- Rumbold DG, Davis PW, Perretta C. 2001. Estimating the effect of beach nourishment on *Caretta caretta* (loggerhead sea turtle) nesting. *Restoration Ecology* **9**: 304–310.
- Ryder C. 1991. The effects of beach nourishment on sea turtle nesting and hatch success. Unpublished report to Sebastian Inlet Tax District Commission, December 1991.
- Sabbe K, Vyverman W. 1991. Distribution of benthic diatom assemblages in the Westerschelde (Zeeland, The Netherlands). *Belgian Journal of Botany* **124**: 91–101.

- Saburova MA, Polikarpov IG. 2003. Diatom activity within soft sediments: behavioural and physiological processes. *Marine Ecology Progress Series* **251**: 115–126.
- Saloman CH, Naughton SP. 1984. Beach restoration with offshore dredged sand: effects on nearshore macroinfauna. Technical Memorandum NMFS-SEFC-133. National Oceanic and Atmospheric Administration (NOAA): Panama City, FL.
- Stauble DK, Nelson WG. 1985. Guidelines for beach nourishment: a necessity for project management. In *Proceedings of the Fourth Symposium on Coastal and Ocean Management 'Coastal Zone '85, Baltimore, MD, July 30–August 1, 1985*. American Society of Civil Engineers: New York, 1002–1021.
- Steinitz MJ, Salmon M, Wyneken J. 1998. Beach renourishment and loggerhead turtle reproduction: a seven year study at Jupiter Island, Florida. *Journal of Coastal Research* **14**: 1000–1013.
- Stienen EWM, Schekkerman H. 2000. Statistische analyse van de verspreiding en de broedresultaten van kustbroedvogels in het Deltagebied: relaties met habitatkenmerken, predatiedruk en toerisme. Internal report, Alterra, Wageningen.
- Thomalla F, Vincent CE. 2003. Beach response to shore-parallel breakwaters at Sea Palling, Norfolk, UK. *Estuarine, Coastal and Shelf Science* **56**(2): 203–212.
- Thompson JR. 1973. Ecological effects of offshore dredging and beach nourishment: a review. Miscellaneous Paper 73-1, US Army Corps of Engineers: Fort Belvoir, VA.
- Trembanis AC, Pilkey OH, Valverde HR. 1999. Comparison of beach nourishment along the U.S. Atlantic, Great Lakes, Gulf of Mexico, and New England Shorelines. *Coastal Management* **27**: 329–340.
- Valverde HR, Trembanis AC, Pilkey OH. 1999. Summary of beach nourishment episodes on the US East Coast barrier islands. *Journal of Coastal Research* **15**(4): 1100–1118.
- van Dalfsen JA, Essink K. 2001. Benthic community response to sand dredging and shoreface nourishment in Dutch coastal waters. *Senckenbergiana maritima* **31**(2): 329–332.
- van de Koppel J, Herman PMJ, Thoolen P, Heip CHR. 2001. Do alternate stable states occur in natural ecosystems? Evidence from a tidal flat. *Ecology* **82**(12): 3449–3461.
- van der Putten WH, Peters BAM. 1997. How soil-borne pathogens may affect plant competition. *Ecology* **78**(6): 1785–1795.
- van der Wal D. 1998. The impact of the grain-size distribution of nourishment sand on aeolian sand transport. *Journal of Coastal Research* **14**(2): 620–631.
- van der Wal D, Peters BAM, van der Putten WH, van Tongeren OFR. 1995. Inventariserend onderzoek naar de ecologische effecten van zandsuppletie. Rijkswaterstaat — Dienst Weg-en Waterbouwkunde voor Technische Adviescommissie voor de Waterkeringen — Werkgroep Zandige Kust en Rijksinstituut voor Kust en Zee.
- Van Dolah RF, Wendt PH, Martore RM, Levisen MV, Roumillat WA. 1992. Final report for a physical and biological monitoring study of the Hilton Head beach nourishment project. Marine Resource Research Institute, Hilton Head Island, SC.
- Van Dolah RF, Martore RM, Lynch AE, Levisen MV, Wendt PH, Whitaker DJ, Anderson WD. 1994. Environmental evaluation of the Folly Beach nourishment project. US Army Corps of Engineers: Charleston, SC.
- Witham R. 1990. A case report on beach erosion, beach nourishment and sea turtle nesting. In *Proceedings of the Tenth Annual Workshop on Sea Turtle Biology and Conservation. 20–24 February 1990, Hilton Head Island, South Carolina*, Richardson TH, Richardson JI, Donnelly M. (eds). Technical Memorandum NMFS-SEFC-278, National Oceanographic and Atmospheric Administration, Washington, DC; 157–160.
- Wulff A, Sundbäck K, Nilsson C, Carlson L, Jönsson B. 1997. Effect of sediment load on the microbenthic community of a shallow-water sandy sediment. *Estuaries* **20**: 547–558.