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de Schipper, Matthieu A.; Ludka, Bonnie C.; Raubenheimer, Britt; Luijendijk, Arjen P.; Schlacher, Thomas A.

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Beach nourishment has complex implications for the future of sandy shores

Matthieu A. de Schipper*, Bonnie .C. Ludka, Britt Raubenheimer, Arjen P. Luijendijk, Thomas. A. Schlacher

*email: m.a.deschipper@tudelft.nl

Abstract

Beach nourishment—the addition of sand to increase the width or sand volume of the beach—is a widespread coastal management technique to counteract coastal erosion. Globally, rising sea levels, storms, and diminishing sand supplies threaten beaches, and the recreational, ecosystem, groundwater, and flood protection services they provide. Consequently, beach nourishment practices have evolved from focusing on maximizing the time sand stays on the beach, to also encompassing human safety and water recreation, groundwater dynamics, and ecosystem impacts. In this Perspective, we present a multi-disciplinary overview of beach nourishment, discussing physical aspects of beach nourishment alongside ecological and socioeconomic impacts. The future of beach nourishment practices will vary depending on local vulnerability, sand availability, financial resources, government regulations and efficiencies, and societal perceptions of environmental risk, recreational uses, ecological conservation and social justice. We recommend co-located multi-disciplinary research studies on the combined impacts of nourishments, and explorations of various designs to guide these globally diverse nourishment practices.

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Beach nourishment is a well-established engineering practice to slow erosion, maintain or expand sandy beaches, but sea level rise, diminishing sand resources, and recreational, groundwater and ecological concerns require new assessments and designs of this coastal management technique. This Perspective describes the multi-disciplinary aims and impacts of sandy beach nourishment.

[H1] Introduction

An estimated 15% of the world's sandy beaches have been retreating a meter or more per year on average in the last decades[1]. More than 10% of the global population lives within 10 m of present sea level[2] and is expected to grow to over a billion people by 2050[2], accelerating coastal development, and demands for stable shorelines and oceanfront recreational space. Moreover, sea level rise is predicted to further reduce beach width at many developed regions[3,4]. Together these trends create socio-economic demands for mitigation measures aimed at protecting existing coastal infrastructure, habitat and recreation[5].

A beach sand nourishment, also referred to as a sand replenishment or beach fill, is a coastal engineering and management project that mechanically increases the size of the above-water beach using off-site sand[6]. Sandy beach nourishment is widely used in coastal communities to promote tourism and protect infrastructure from flooding and erosion[6] (Fig. 1) . Additionally, these nourishments may be used to increase habitat for beach (foraging) species[7–9], repair storm damage[10], and dispose of dredged sediments, such as those from navigation channels. Projects can be implemented with the intent to grow or hold a shoreline in place, or as part of a managed retreat plan[11] that aims to slow erosion to allow for landward redevelopment[11]. Sand can be placed directly at the site of the identified local need (**Fig. 1a**), or updrift as part of a larger regional approach that utilizes natural transport pathways to address sand needs along the coast[12,13].

Nourishment can be preferred over hard structural engineering, such as jetties, seawalls, groynes and breakwaters, as it is less disruptive of natural sediment pathways[14]. Seawalls, for example, typically reduce sand supplies from cliff-bluff-failures and can drown the beach when constructed on shorelines experiencing decadal landward migration[15,16]. Jetties, groynes and breakwaters alter current–driven sand transport within the coastal cell, leaving adjacent beaches starved of sand[17]. Sometimes hard structures are combined with nourishments (**Fig. 1b,c**) with the intention to slow sand transport away from the original placement region and/or surrounding area[10,18–20].

Sandy beach nourishment became popular in the early 1900's[21] when opportunistic sources of sand (such as from harbor development dredging) were readily available. In places where development has slowed, smaller non-opportunistic placements (~100 m^3 per meter of alongshore beach[22,23]) are most commonly used as a temporary solution for localized erosion problems. More recently, owing to the recognition of the interconnectedness of regional littoral cells and their sediment budgets[24], repetitive nourishments along the coast are coordinated in regional sediment management plans[25] using either newly acquired sand or reusing dredged sediments (such from maintenance of nearby harbors). Some novel individual placements have been scaled to substantially modify the regional sediment budget over many years, such as in mega-nourishments (> 500 m^3/m alongshore[26–28]).

Recent advances in the fields of coastal engineering, ecology, and governance, in combination with changed societal demands, have called for more integrated nourishment approaches. Mono-disciplinary approaches focused on the above-water beach recreation or overtopping flood prevention alone have become hard to justify. Nourishment designs now often consider in-water recreation, groundwater dynamics (such as groundwater flood prevention and the protection or expansion of fresh groundwater supplies), and ecosystem services (such as fisheries and water filtration)[29]. As an example, several recent (pilot) nourishment designs explicitly include surfing along a sharp lateral edge, sheltered bathing in a lagoon (**Fig. 1d**) and the creation of multiple types of ecological habitats (**Fig. 1e**) while also providing the above-water recreation and flood prevention of more traditional designs. Furthermore, new approaches take advantage of natural dynamics and are designed to stimulate natural elements[30], harnessing the forces of nature to reach project goals rather than working against natural dynamics (synonymously referred to as *Building with Nature*[31], *Engineering with Nature*[32] and *Living Shorelines*[33] amongst others). For example, large artificial coastline perturbations can intensify alongshore transport gradients that redistribute sand across a wider region (Fig. 1e). Nourishment projects including artificial dunes with planted grasses and fencing are intended to stimulate wind-blown dune growth that can provide ecological habitat as well as flood and groundwater protection (**Fig. 1d**).

In this Perspective, we provide an overview of the interconnected multi-disciplinary aspects of beach nourishments in terms of sand redistribution; groundwater considerations; ecological, economic and recreational impacts; and sand mining. The future of beach nourishment practices will vary globally, depending on local vulnerability, sand availability, financial resources, government regulations and efficiencies, and societal perceptions of environmental risk, recreational uses, ecological conservation and social justice. We recommend research directions and design approaches that will guide these diverse nourishment practices.

[H1] Beach sand nourishment

Nourishments can be constructed using various sediment types originating from inland or marine sources (such as sand[14], shingle[34], cobbles[35], and/or cohesive clays[18,36]), and can be placed on the above-water beach (beach nourishment) or submerged nearshore beach profile (shoreface nourishment)[6,14]. The sediment (fill material) is extracted from a borrow site, either, for the sole purpose of nourishment or as a result of nearby projects, such as excavation for development, harbor channel deepening or removal of excess sand near a coastal structure[13]. The extracted sediment is transported to the coast (typically by barge, pipeline or trucks) and then pumped, sprayed or dumped onto the placement site. Afterwards, bulldozers or other machinery sculpt the sand into the shape planned by the engineers.

Here, we focus on nourishments that add sand (non-cohesive sediments in the size range 0.062 – 2 mm) to open, ocean-exposed beaches where the majority of the sand volume is placed above the mean water line. The sand can be positioned on the upper beach including dunes and/or near the waterline, and can (partly) extend onto the underwater beach (**Fig. 1**). After placement, the sand is sometimes tilled to attain desired beach surface properties. Over time, waves, currents and wind move the added sand away from the original placement site, so repetitive nourishments, typically placed every few years, are often planned to maintain sand volumes on the beach over longer periods of time. Occasionally, hard engineering structures are constructed to enclose nourishment sand on the lateral or offshore side[10,19,20] (**Fig. 1b**), or are erected nearby in the littoral cell to partially trap nourishment sand in adjacent regions (**Fig. 1c**). Sandy beach nourishments are widely practiced globally[13,14,18,21,37–42] and observed lifetimes range from individual storms (days) to decades[14,43–45]. In this section, we discuss the redistribution of sand, followed by the monitoring and modeling of sand dynamics.

[H2] Sand redistribution

The added sand steepens and widens the beach, thereby altering currents, waves, wind and sediment transport in and around the placement area[6]. During the following months to years, nourishment sand moves from the placement area in both cross-shore (onshore or offshore) and longshore directions (upcoast and downcoast) such that the beach narrows and becomes less steep, while the shape of the local coastline smooths[6,46] (**Fig. 2a,b**). Erosion of sand from the initial placement area is fastest in the months after construction, especially during the first few storms[43,45,47]. Notably, when large volumes of sand are placed on the above-water beach only, the unnaturally steep profile results in large offshore transports and a rapid decrease of the beach width[46,48].

As nourishment sand is redistributed it becomes part of the larger sediment sharing system, and generally, the nourished site experiences erosion after placement, with sediment being transported to adjacent beaches[49]. Wave-driven offshore transport of nourishment sand can form abnormally large sandbars relative to natural sandbars at the site[44], potentially smothering offshore reef ecosystems[54] or acting as a soft breakwater. This sand can later return onshore during calmer wave conditions, increasing beach width again[44]. Wind-driven onshore transport of nourishment sand can accrete dunes[50] but can also be a nuisance if it blankets properties and infrastructure near the beach[51]. Likewise, nourishment sand that moves alongshore to adjacent beaches can be beneficial (by widening the recreational and protective beach[12,52], for example) or harmful (by infilling of nearby harbour entrance channels or estuaries[53]).

Similarly designed nourishments placed in the same geographic region and exposed to similar forcing, but composed of different grain sizes, have been observed to have drastically different retention times of the sand on the above-water beach[54]. Nourishment using coarser-grained sand is expected to create and maintain a steeper and wider beach, and may be selected to increase the longevity of the nourishment pad[6]. Conversely, sand that is much finer than the native sand can be used in a design to stimulate dune growth through wind-blown transport[55] but will also in-part be quickly and often permanently washed offshore by waves[46]. Even when using sands similar to native sand, the modified hydrodynamics resulting from placement[56] can exacerbate preferential transport of the finer fraction of nourishment sand during calm wave periods, altering grain size distribution patterns in a region much larger than the placement area[57].

As the placement region erodes, additional morphological features such as spits, scarps, and crowns can form (**Fig. 2c-e**). Scarps, near-vertical abrupt height variations on the beach profile, can be created by storm waves that erode, but do not overtop, the nourishment crest[58] (**Fig. 2d,e**). Similar to dunes, beach scarps are removed during storms when water levels overtop the crest[59]. Scarp heights can reach ~2m creating a hazard for beachgoers and impeding turtle nesting[60]. At flat-topped nourishments constructed with sand that is coarser than the native sand, scarps can evolve into crowns as waves deposit sand on the seaward side of the platform (**Fig. 2f**). The local elevation maximum of the crowns can cause water to pool in the backbeach[53]. In the longshore direction, spit-like features can form along the seaward ends of a nourishment pad (**Fig. 2a,c**) due to large sand transport gradients induced by coastline angles at the up and down-coast edges[43]. Tapered edges are often designed to minimize spit development when sand retention in the original placement area is desired, although spit development has been observed on nourishments with tapered edges[53]. In contrast, spit development was intentionally stimulated as part of the ‘Sand Engine’ mega-nourishment design to create a sheltered lagoon and habitat for juvenile flatfish and invertebrates[26] (**Fig. 1e**).

Hard structures are sometimes used in conjunction with nourishment works to reduce beach volume losses from the placement area[10,18–20]. For instance, approximately half of the sandy beach nourishments on the Chinese coast that were placed between 1994-2014 were combined with groynes (shore-perpendicular structures that extend from the beach into a portion of the surfzone) and/or breakwaters[18]. The construction of permeable or notched groynes and groyne fields (**Fig. 1b,c**) are methods that attempt to attenuate downdrift erosion problems while increasing sand retention updrift. Shore-parallel structures placed offshore (breakwaters), are used to reduce the amount of wave energy in their lee, and to modify nearshore currents such that sand accumulates at the shoreline onshore of the structure. However, contrary to their design intent, many submerged breakwater projects have caused shoreline erosion[61]. Similarly, natural or man-made submerged detached sills in deeper water can be used to create a perched beach (**Fig. 1c**) so that less sand volume is required to achieve a desired constructed beach width compared to a design without a sill [46,62]. The perched beach concept has been practiced worldwide[63], but results on the longevity of the nourishments are mixed and there is limited understanding why these projects are not always successful[62]. Additional research on the effectiveness of managing coastal sand resources using nourishment combined with hard structures is needed, and should also be assessed in terms of the groundwater, ecological, and recreational impacts.

The 'success' of beach nourishment projects, viewed in terms of how the sand is redistributed by waves and wind, can be difficult to assess accurately as there is no single set of widely agreed criteria and the success depends on the objective[28]. Consequently, using retention time of sand in the original placement region as the prime criterion to assess 'success', can lead to the conclusion that the nourishment has failed, especially if the objective was to locally increase beach width for recreation[49,65] or provide a temporary buffer to storm impacts on landward infrastructure[66]. However, movement of sand by waves, currents, and wind is an expected process, so many coastal experts advocate for success criteria based on a wider regional sediment budget when the objective is to mitigate long-term coastal erosion in a coastal cell[26].

[H2] Monitoring sand redistribution at beach nourishments

Monitoring the sand redistribution of beach nourishments is conducted to evaluate project performance and impacts, and to increase general understanding of coastal dynamics. Optimal monitoring programs tailored to beach nourishment behavior measure both the underwater and the above-water beach, preferably obtained simultaneously to close the sediment balance[67]. On open coast beaches, adjacent coastal sections should also be included to trace dispersed sediments and must be large enough to encompass a reference area that remains unaffected by the nourishment, such that the sand level response can be assessed in the context of natural variability in the forcing. We recommend that monitoring should extend for at least 500 m on either side of the nourishment, with longer stretches recommended for large nourishments and beaches with highly energetic, oblique incident waves, and include sediment properties (grainsize and distribution) and local hydrodynamic data (waves, currents and water levels). Furthermore, it is important to survey the area immediately after the works, which provides a clear estimate of the deposited sand volume in-situ rather than estimates from recorded discharges in the dredging process[30]. After this first survey, short time intervals between consecutive surveys (for instance, weeks apart and after each storm) can be necessary to capture the rapid initial response. High cross-shore (1 m or smaller) and alongshore (100 m or smaller) resolution is needed to capture the presence of scarps and spits[53,59,68].

Techniques to monitor nourishment sand redistribution are evolving[69]—all-terrain-vehicles equipped with survey-grade Global Navigation Satellite Systems, real-time kinematic corrections, and inertial measurement units largely replaced traditional rod and level surveys at the turn of the last century[70]. These technologies drastically increased spatial resolution and span while maintaining <10 cm horizontal and vertical accuracy[52,53]. Above-water mapping technologies often are combined with sonar on boats and personal watercraft for measurements of the underwater beach. As bubbles and suspended sediment can sometimes obscure the sonar signal in the shallow water surf-zone, dollies pushed to wading depths or large amphibious vehicles are used to help ensure continuous measurements across the profile[52,53,68,71].

In the past decade, remote sensing imaging systems have further expanded data collection capabilities. These can be mounted on fixed (towers, rooftops)[72] or mobile platforms (drones, airplanes, satellites)[69]. Monocular (single viewing angle) imagery using optical cameras[1,72–74] or cloud penetrating radar[75] are used to detect the horizontal location of the land-water intersection of the nourishment and adjacent beaches. These systems can provide long time series at remote locations with small operational costs, although, owing to uncertainties (especially such as those in estimating water levels[76]), this method works best when shoreline migration is large (many 10's of meters for satellite systems[74]). Newer remote imaging technologies that measure the 3-D beach surface provide more accuracy than monocular imagery, which relies on the detection of the land-water intersection. For example, photogrammetric methods (such as structure from motion) reconstruct a 3-D surface from multiple photographs with different viewing angles[77–79]. Laser scanning[67] (lidar) is generally the most expensive and accurate remote sensing technique[80,81], and can provide full wave-form information useful for resolving different surface layers (such as vegetation on a dune[82]). These 3-D datasets, including true color information of the surface, open new opportunities to identify beach characteristics (such as distinguishing between native and nourishment sand[83] and cobble coverage[84]).

Observing bathymetry (underwater topography) through remote sensing remains challenging, but there has been some success in clear waters where the seafloor is visible in optical camera imagery[85], or using laser altimetry with sufficient power to record reflections of the seafloor despite the water-air interface and the scattering of the (green) laser pulse in the waterbody[80,86]. These approaches enable high resolution mapping over large spatial ranges. Alternative technology, deriving bathymetry from remotely sensed surf-zone wave speed and shape, is also being developed[87,88].

We envision that as the spaceborne photogrammetry and laser altimetry records grow, they will be especially transformative for our field. Satellites are providing time-continuous global coverage of sand levels with accuracy on the order of cm's[77,79,80], which will help map sand redistribution, expand our understanding of geomorphological processes and enhance our ability to develop or calibrate numerical models.

[H1] Modeling beach nourishments

Models of sand redistribution help coastal managers evaluate the impacts of different nourishment design strategies. However, understanding and forecasting nourishment evolution is challenging — models must account for changes in sand levels over several years, which are often a delicate balance between storm and recovery processes[89]. Furthermore, these models must encompass broad temporal (from seconds, such as during overtopping event during a storm, to decades, as with dune development or sea level rise) and spatial scales (from individual grains to littoral cells). Computational constraints require these processes to be aggregated through extensive parameterization[90]. Sometimes models that use different resolutions can be coupled to resolve multiple scales[91], for example by running high detail models for small spatial and/or short timescales, in conjunction with aggregated low resolution models for large spatial and/or long timescales. Other approaches attempt to accelerate model simulations by "compressing" the number of timesteps[92], by using only the moments with the most impactful forcing conditions[47], or implementing simplified but efficient look-up tables that categorize the beach response to generalized forcing conditions[93].

Sand redistribution models range from simple to complex. In their simplest form, coastline models estimate the shoreline position by schematizing the along-coast sand redistribution as a diffusion (shoreline smoothing) process where the shoreline orientation relative to the incident wave conditions governs the alongshore transports over time[94]. When calibrated, these computationally fast models can provide information on beach change of the largest of scales (years, kms)[95]. Hybrid models can improve upon coastline model physics by accounting for the effect of realistic complex bathymetry (such as nearshore canyons or rocky platforms) on wave propagation. To represent multiple specific details of the nourishment beyond the shape of the coastline (like variations in planform shape), and to provide information needed for ecological and recreational assessments (including sediment sorting, shells, and spit formation) more complex models are needed based on the upscaling of processes (process-based modelling)[e.g. 96,97].

Process-based models can be subdivided into profile models and planform models. Profile process-based models solve the cross-shore sediment balance at multiple vertical levels, but at only one alongshore location[98]. Current state-of-the-art cross-shore process-based models perform best for predominantly offshore directed morphological development on time scales of days, such as the large erosion of nourished profiles during a storm[99]. When applied to natural profiles and moderate waves, model skill is significantly reduced up to the point that a simulated development, when compared to observed changes, can be worse than a no-change prediction[100].

Planform process-based models have a domain that extends both alongshore and cross-shore, but have limited resolution in the water column[92,101]. Recent planform model computations are apt at reproducing the multi-year evolution (both erosion and accretive sand volumes) of a mega beach nourishment[47,92] (**Fig. 2g-n**). However, these models have yet to be rigorously tested in the peer-reviewed literature on beach nourishments of a more typical size. The latest process-based numerical models have the ability to differentiate between sediment of different grain sizes at a project site. For example, these models can be used to examine nourishments with different grain sizes than the surrounding (native) sand and may be able to reproduce the coarsening of the sand as fines are transported out of the area[102]. Sufficient high-quality sediment composition data is needed to further develop and test these grain size specific transports.

Uncertainties in model forecasts arise both from the forcing (such as wave, wind, water level conditions) and model limitations. For instance, at the well monitored Sand Engine mega-nourishment, model parameter uncertainty was found to be comparable to the uncertainty in future wave forcing conditions (wind, waves, currents) for a 2.5 year calibrated coastline position model that forecasted an additional 2.5 years[103]. For 50- to 100-year predictions of shoreline location on erodible coastlines, the model framework for how the beach responds to sea level rise dictates the uncertainty in the modeling outcome more than any other factor. In other words, model choice outweighs the climate change scenario, sea level rise, sand supply, vertical ground motions and wave-driven shoreline response[98] in determining the output. Computational power has increased such that if model skill was improved, probabilistic approaches with a large number of (ensemble) forcing conditions could help coastal planners navigate nourishment decisions in the face of uncertain sea level rise, and changing wave and weather conditions[104]. In the meantime, models are only reliable when they have been site-specifically calibrated and validated, and when the forecasted conditions are similar to those that were used in calibration and validation[47]. As sufficient calibration data is often lacking, nourishment designs are still done in a pragmatic manner, relying on both numerical model output and expert judgment.

A promising development in morphodynamic modelling of nourishments is the inclusion of additional spatial domains and disciplines, such as groundwater[104] and vegetation[105] models. For example, connecting wave transport models with wind transport models has been important in long term predictions, as it accounts for transport of sediment towards the dunes and aeolian infilling of nourishment waterbodies[91] (**Fig. 2n**). However, given the difficulty in modeling sediment transport, numerical models of nourishment response will likely continue to be highly parameterized with incomplete physics for some time. Therefore, research comparing the performance of more complex models to simple models is needed to assess when the added complexity and computational demands are warranted[106], and observations will continue to be essential for model testing.

[H1] Groundwater impacts

Changes to aquifers below beaches and dunes are increasingly considered as part of coastal zone management practices as these impact flooding and fresh water quantities. For example, storms can cause groundwater salinization[107–111]—especially concerning for low-lying islands with limited freshwater supplies such as the barrier islands along subsiding coasts[112] and Pacific atolls[113-114]—and contribute to coastal flooding[115]. For example, a sea level rise model assessment for urban Honolulu, Hawaii (USA) at the end of the century, found that including groundwater processes doubles the size of the flood-prone area compared to when considering marine inundation alone[116,117].

The behavior and dynamics of groundwater near the land-ocean interface are highly complex and variable, and thus responses to nourishment are challenging to predict. Beach nourishments increase coastal elevation of the beach and are therefore likely to reduce the probability of land surface inundation, infiltration of seawater, and salinization. In addition, beach nourishments increase the terrestrial extent of the coast, leading to increased trapping of precipitation and enhanced groundwater recharge, resulting in increased freshwater resources[118,119] (**Fig. 3a**). However, expansion of the freshwater resources owing to beach nourishments can be limited or modulated by erosion of the added sands during storms[119]. Moreover, the elevated nourishment pads can retain ocean water in the added sediment, especially during storms with large surge and wave-driven setup, even in the absence of inundation[120], and the increased groundwater levels and inland-propagating groundwater bulge[121,122], potentially contributing to inland flooding[53,123] (**Fig. 3b**). Moreover, seaward seepage (**Fig. 3c**) of the groundwater onto the beach can reduce the wind-driven onshore transport that is needed to build dunes[124], while also reducing the effective weight of sediments submerged by waves, enabling sands to be swept offshore more easily[125].

Groundwater flow in beaches is sensitive to both cross-shore profile shape as well as porosity and grainsize[126], and these three aspects can be (temporarily) altered after nourishment[53,63,127]. It is presently unknown if these aspects significantly impact freshwater resources and groundwater-induced flooding on recently nourished beaches, and additional study is needed to understand groundwater flow in nourished beaches and its coupling with flooding, sediment transport, and vegetation.

[H1] Ecological Impacts

Habitat attributes are the main determinant of biodiversity and ecological structure in beach ecosystems[128–133]. Sediment properties (including texture, size, moisture, and organic matter), topography (slope elevation, width, and relief), hydrodynamic forces (wave exposure, currents, and tides) and biological interactions (productivity, carbon subsidies, and predation) shape the structure of beach ecosystems. These ecosystem harbour diverse assemblages of burrowing invertebrates and larger animals that nest and feed in the surf zone, the intertidal shore, and the coastal dunes (such as birds, sea turtles, rays, and sharks)[134–139] (**Fig. 4a**). Beach species are adapted to high-energy environments with rapidly changing conditions[140], yet this does not imply they are resilient to habitat changes and physical forces caused by nourishments[141–145]. Indeed, many coastal ecosystems are deteriorating[146–148] owing to human activities in the coastal zone, such as infrastructure, beach armouring, off road vehicle traffic, and beach grooming, and nourishment can compound ecological stressors (**Fig. 4b**).

Detrimental impacts of nourishment[149–151] largely concern the loss of ecological features during nourishment construction. Most of these reductions are in the number of species and individuals, often for invertebrates buried in the sand, but also for birds and fishes. The mechanisms are varied (**Fig. 4c-f**), but processes commonly identified during construction include burial and suffocation under a sand layer that exceeds the capacity to burrow upwards[152,153] and mechanical crushing by heavy machinery, functionally similar to the crushing effects by off-road vehicles driven over beach invertebrates buried in the sand[154–157]. Increased water turbidity from nourishment operations that bring fine material into suspension and the suspended silt can clog the delicate feeding structures of filter-feeding invertebrates (such as clams)[143]; more turbid surf-zone waters can also limit prey detection and thereby impair feeding by fish[142] (**Fig. 4e**). These impacts can extend beyond the immediate spatial footprint to affect adjacent systems (including reefs and seagrass meadows) several kilometers away through turbidity plumes[158].

After the nourishment has been implemented, the altered cross-shore profile shape can create unfavorable conditions for foraging, spawning or nesting[159,160]. Moreover, a mismatch of sediment properties between the added material and the original sands[161–163] can impact habitat conditions. For example, excess shell hash can impede probing for clams by shorebirds[143,162,164–166] (**Fig. 4d**), and a change in sediment texture can make the beach unsuitable for larval settlement and adult survival (**Fig. 4f**).

Hard structures used in combination with nourishments can additionally impact ecosystems. For example groynes can trap higher volumes of wrack (such as algae and seagrasses) on the updrift side, while reducing accumulations downdrift[167]. Wave-sheltering provided by breakwaters can shift communities from consumer- to producer-dominated systems[168]. Furthermore, hard structures can create barriers to the transport of mobile animals living on the ocean floor and to the dispersal of propagules[167].

From an ecological perspective, the best nourishment would be the nourishment that does minimal harm to the pre-nourishment habitat, restores ecological values lost due to previous human activities and, depending on the local views on ecology, creates new habitats[169]. Information gaps remain that limit our ability to design more environmentally benign strategies, or create habitat opportunities with engineering works. Primarily, the trajectories of recovery and the thresholds of habitat change that species and assemblages can biologically accommodate are unknown. Put another way, what is the biological 'dose-response curve' of beach engineering works? Ecological impacts are often measured by comparing (unimpacted) control regions with impact areas. Understanding the large scale, long-term (natural) variation in species (species richness, biomass, and abundance) and habitat (such as water quality and turbidity) is vital for contextualizing nourishment impacts. Reported recovery times vary widely, from weeks[152] to several years[144,165]. There is little consensus on impact and recovery, mainly because almost all ecological studies are much too short (generally months), limiting our ability to make robust inferences about impacts and recovery[164].

Changes to the design and timing of beach nourishment can create opportunities to develop practices with a smaller ecological impact. For example, concentrated nourishments with large volumes are intended to slowly feed the adjacent coasts with sand, as an alternative to multiple repeated nourishments along the coast[26]. This method may minimize ecological harm because of its localized placement footprint, which reduces the alongshore stretch that experiences the initial burial event. These large placements also extend the time period between successive nourishments, which allows time for populations to partly recover, as surviving or recolonizing organisms reproduce[169]. However, larger nourishment volumes typically bury organisms under a larger depth of sand, which potentially making initial ecological impacts in the placement area more severe. Alternatively, continuous and much smaller scale placements in thin layers or mosaics are proposed to potentially reduce mortality of fauna from deep burial and to enhance chances for recolonization[147,153,160,170]. A comparative study of the ecological impacts of these different strategies is needed to advance this debate and connect nourishment intervals, placement volumes and shapes, with recovery timescales. The study should not only be compared to the existing ecosystem at the coastal stretch (**Fig. 4b**) but equally to the original natural shoreline system (**Fig. 4a**) and alternative man-made interventions (such as armouring and seawalls).

Many dune restoration projects have prioritized ecological restoration[171], however nourishment projects lower on the beach that prioritize ecological functioning over other objectives are generally more rare than other types of nourishment, and there is a dearth of studies on the projects that do have this priority. In the future, attempts to create beach habitats that mimic previously existing (site-specific) wave-exposed shores (neither excessively extended seawards nor unnaturally elevated, and with biologically suitable slope, relief and sediment composition) should examine the full capability of using nourishment for ecological restoration.

[H1] Broader impacts

To fully assess the impact of nourishments, it is essential to also understand how nourishment sands are extracted, how the sand placed on the beach impacts recreation, and how the investment interacts with the larger socio-economic setting of the coastal zone.

[H2] Sand mining

The process of extracting and transporting sand for beach nourishment is an integral part of nourishment projects, and partially determines their broader environmental impact. Because sediment properties can have important consequences for, the longevity of the nourished beach[46,53], the survival of beach fauna[142–144], groundwater flows[126], and the satisfaction of tourists[172], sand needs to be carefully chosen, and mined sand that resembles the native is typically preferred[173]. However, there is a predicted global shortage of sand due to high demand for concrete, land reclamation, and coastal nourishments[174,175], and owing to a shortage of inland sand sources, marine and coastal sands are increasingly mined for concrete[156]. Extraction from riverbeds and the nearshore system for building aggregates removes sand that would naturally build beaches, increasing nourishment demands while also reducing the availability of sand for nourishment. Meanwhile, the need for nourishment sands might increase by an order of magnitude based on sea level rise projections—for example, by 2100, nourishment volumes to maintain the Dutch coast could be up to 20 times larger than current volumes[176]. Sand availability ultimately shapes the feasibility of a sandy strategy, where mega nourishment designs of over 20 million m^3 (**Fig 1d,e**) might only be feasible at locations with ample sand supplies, such as the North Sea's shallow sandy shelf offshore of the Dutch coast.

The pressure on sand as a resource is reflected in nourishment costs, which are primarily governed by the distance between the borrow (extraction) location and the nourishment (placement) location, as well as the nourishment execution method and sand volume[177–179]. In some projects where borrow areas are close, such as the shallow nearshore seabed and/or nearby inlets or harbors that are dredged frequently, the cost of sand can be lower than 5 US$ per m^3 (Textbox 1). At locations with limited sand resources of a suitable size (such as Florida, USA or Singapore), long travel distances may raise the price of sand to 200 US$ per m^3, making sand trading a part of international disputes[175,180]. Global nourishment costs might reach hundreds of billions in US$ per year before the end of the century[181]. Government regulations and contract type (such as Construct only or Design & Construct) can also drastically influence sand pricing[182]. For example, the reported Dutch nourishment sand prices are often based on construction costs only, without having to acquire permits or purchase the sand. In contrast, engineering and environmental assessments required to obtain a permit for sand extraction in California can cost hundreds of thousands to millions of US$, such that total nourishment costs can be raised by ~40%[183].

New areas for sand mining could become economically viable over the next decades as sand prices continue to escalate and melting icecaps open up new potential mining sites, but the ecological harms associated with mining distant sands need careful evaluation and mitigation before extraction takes place[184]. For example, mining of marine sands affects marine mammals via noise and light pollution[173] and invertebrate assemblages of the seafloor could take years to recover[185]. 'Landscaping' the mining pits to create irregularities in the mined seabed have been proposed to facilitate fauna recolonization, and a pilot study revealed a positive impact of pit landscaping on demersal fish[186], but the idea requires further testing in the field to lower the combined ecological harm caused by seabed mining.

In addition to being directly ecologically damaging through sand extraction, constructing a sand nourishment has a substantial CO_2 footprint related to sand mining and transportation. For a project using nearby marine sources, the emissions per m^3 of disposed sediments are 2 to 5 kg of CO_2 [177,187]. The CO_2 footprint increases with transport distance from the mining site to the beach[178], emphasizing the need to identify nearby sand sources that can be safely extracted. Moreover, the type of dredging vessel and the disposal method (such as pipeline transport through pumping, spraying or dumping through bottom doors without pumping) affect fuel consumption and are important controls on total emission quantity[178,187]. Calculations and comparisons of carbon footprint are therefore site specific and difficult to compare to other coastal protection alternatives.

Given the costs and the emissions associated with sand mining at remote locations, more local sources may need to be considered in the future, even if these are sub-optimal from an ecological or recreational standpoint[180]. Using sediments from nearby (shipping) channels or estuaries, reduces the disturbance of untouched seafloors, restores natural sediment pathways and might, where possible, prove to be the most viable option to sand mining from a sustainability point. New developments in efficient nourishment placement strategies and vessel (fuel) technology[188] must also be explored further to reduce the overall environmental footprint of beach nourishment.

[H2] Recreational impacts

Nourished beaches are often designed to enhance human recreational space, both above and below the water, especially in tourist areas. Broader beaches can accommodate more visitors and land-based activities and are therefore often preferred to narrow beaches[189]. However, visitor appreciation studies in the US and Australia show that beaches perceived to be excessively wide are unattractive to visitors[190] as they make the ocean less accessible for water-based activities, such as surfing, swimming, and scuba[189]. Altered beach slopes and the development of scarps on the nourishment can create hazards[191], and impede lifeguard's views and vehicle access[192]. Nourishments also affect in-water recreation. Sharp bends in the planform shape can generate strong flows that impact bather safety[192] and affects sand bar patterns[193], sometimes resulting in stronger rip current flows[194]. In the US, increased numbers of drownings and accidents (up to 300%) have been reported after several beach nourishments. Yet without statistics on concurrent variations or altered beach usage[194], additional research is needed to provide generic evidence on the link between nourishment, rip currents and altered swimmer safety[194]. The changes in sandbar morphology and wave breaking patterns can also alter the quality of surf breaks[12,195,196]. Although implementing nourishments with irregular outlines and steep end-sections can mitigate some of these negative effects on surfing[197,198], these surfing-specific design features with strong coastline curvatures are typically short lived (weeks-months) and can negatively impact swimmer safety[192].

[H2] Social and Economic impacts

Increasing beach width via nourishment is often considered to be beneficial for above-water recreation, tourism, and coastal property values from an economic standpoint[199]. Economic evaluations typically contain three main elements: changes in coastal property value, changes in tourism revenue and the cost of coastal management works, and quantitative input of these elements is very site specific. The optimal beach width can be translated to an estimated optimal nourishment frequency and size to maximize revenues[200]. In these analyses, larger values of beach width revenues, property value or background erosion rate result in increasing nourishment frequency[201]. When lateral spreading of the nourished sand is taken into account, though, achieving an optimal strategy becomes more complex as nourishment losses from one town might benefit another[200,202] and local versus regional approaches to decision making can affect the economic balance. Coupled coastline-economic models for nourishments currently under development[202] should be expanded to account for groundwater and ecological impacts, and the scarcity of sand resources.

Although some coasts have high estimated returns, such as for the Florida coast (USA), where each US$ invested in nourishments is estimated to have a 700 US$ return[203], nourishing an existing touristic beach is not without risks for amenity values. There are many factors that determine beach visitor appreciation, such as vehicle parking, facilities, and water clarity[189,190,204], and restricted beach access and machinery can impact the visual aesthetics of the beach during the months of construction, causing temporary reduction in tourist revenues[205]. Moreover, nourishing with sand dissimilar from the native mineralogical composition can result in changes in beach sand color, which impacts visitor appreciation, with light colored nourished sediment being preferred by visitors in some cases, such as seen in Cuba and Italy[172,206]. Comparisons of natural and nourished beaches in Spain showed that nourished beaches have distinct different colors (quantified using the CIEL*a*b* methodology) which can persist for years after sand is added[207].

Given limited sand resources, difficult decisions will arise about which beach will be saved by frequent nourishments[180]. With property values being higher behind wider beaches (or else being equal)[199], investments to restore and widen beaches can presumably be higher in more affluent beach communities[181]. Therefore, upholding principles of social justice in democratic systems calls for equitable regulated approaches to decision-making in beach restoration[208,209]. These approaches should use valuation methods that are inclusive of non-local beach users, who in many cases cannot afford to live near the coast. If beach nourishments are installed using (in part) public funds, inclusion can be implemented in the design, for example by requiring public access every half mile after the construction of a beach nourishment[210]. Furthermore, it is possible that some beaches might be able to migrate landward with sea level rise, but would drown when backed by hard structures. Interesting questions are thus posed about whether to prioritize making way for the migrating beach (often a public asset), or protecting existing (often private) coastal infrastructure in place. Nourishment could be useful for either purpose[211], although more research is needed to assess effectiveness and feasibility. Communities might choose to restore different local beaches for different purposes, and designs could be optimized accordingly, for instance a nourishment for surfing at one location, with another for sunbathing elsewhere.

[H1] Integrating perspectives

The previous sections outline the progress that has been made in nourishment impact science and highlights the connectivity between the various impacts—linkages between beach width variations and economics; altered grain size and fauna recovery; sand mining location and visitor appreciation through sand type and color (**Fig. 5a**). Some of the requirements are in direct contradiction and demand a tradeoff, for instance: the desire for thin layer nourishments for rapid ecological recolonization is difficult to combine with economical sand mining and placement which favours large quantities; coarser sand to increase sand retention times on the beach versus sand similar to native for healthy ecological habitat; or smooth outline designs for better swimmer safety versus an irregular outline to enhance surfing (**Fig. 5**). Integrated designs and approaches will therefore need to look beyond sediment spreading and dredging costs alone. Quantitative impact analyses and thresholds for some of the aspects are currently still lacking, requiring an iterative procedure in the design process (**Fig. 5b**). Modeling studies, combined with site specific calibration and validation, can offer useful guidance throughout the decision making process.

Assessments of beach nourishment performance need to be as diverse and nuanced as nourishment goals and impacts; which is no small challenge. The traditional monodisciplinary assessment of beach nourishment performance, used across the globe [e.g. 28,63,64,212,213], typically focuses on geometrical aspects alone (like beach width or beach volume). Visitor appreciation surveys and economic evaluations (in Cost-Benefit analysis [214], Travel Cost Method or Contingent Valuation Method[215], for example) are also used widely despite often oversimplification of nourishment impacts, especially ecological impacts. Multidisciplinary evaluations require extensive monitoring plans that measure not only sand levels, currents and granulometry, but that also include ecological surveys, such as species abundance and water turbidity values, groundwater, social and recreational aspects (including surveys of beach appreciation and lifeguard statistics) and economic data (such as property values and visitor spending)[30].

Instituting procedures to ensure avoidance or mitigation of ecological harm require social norms that embrace the ecosystem nature of sandy beaches and explicitly value the environmental services they deliver, thereby balancing conservation needs with other societal demands from a beach system[29,146,159]. An ecosystem services framework[29,146,216] promises to capture many of the impacts mentioned, yet an objective approach is still difficult, as ecological perceptions are varied. For example, creating nourishments with a more complex shape can lead to a wider variety of species and new ecological communities compared to the pre-nourished or adjacent coasts[169], which can be viewed as a positive or negative impact depending on (cultural) views on ecology and restoration[217]. In some communities, ecosystem functions may be a priority that dictates nourishment design[33,218]. New designs (thin layers, mosaics, concentrated or continuous drip-feeding nourishments, to name a few) could foster healthier ecological habitats than traditional rectangular beach fills but are yet to be rigorously tested and compared.

[H1] Future directions

Many of the world's sandy beaches are subjected to 'coastal squeeze', trapped between rising seas and increasing development on land[4,148]. As sand supplies dwindle, sea levels rise, and storm characteristics transform, the effectiveness of current engineered coastal adaptation strategies, including beach nourishment, in protecting vulnerable coastal communities is uncertain[219–222]. Regardless, beach nourishment is likely to remain a popular engineering solution in the foreseeable future to support coastal tourism economies, lower risks of coastal hazards[223], create habitat zones[9] and reuse sediment dredged from inland waterbodies[13]. Local erosion trends and risks to infrastructure, projections of local sea-level rise, availability of sand, and societal values vary across the globe (**Box 1**), and future nourishment strategies must reflect these differences. For some locations small scale nourishments with lifespans of a month might be preferred (for example, as at Dongsha beach, China[66]), whereas large scale nourishments are designed to last decades at other locations (as with the Sand Engine, Netherlands[52]).

Impacts arising from beach nourishment thematically reflect and intersect multiple fields of science, emphasizing the need for collaborative, multi-disciplinary research. A clear example is the effect of nourishment on surface and subsurface processes due to altered beach sediment size and composition. Granulometry and mineralogy determine multiple aspects of beach ecosystems (morphology, seawater filtration, sediment retention, groundwater flows, organic matter content, habitat suitability for invertebrates, feeding opportunities for fish and birds, recreational value and perception, amongst others), but the interactions and feedback links that create additive and synergistic drivers of broader environmental and socio-economic impacts are rarely identified or measured.

We identify three broad needs in coastal nourishment science: a better quantitative understanding of sediment transport processes, particularly the fluxes of sediment in the cross-shore direction between dunes and deep water; threshold levels for ecological impacts, in other words, the magnitude of habitat change above which we regularly observe significant ecological harm attributable to engineering works; and the groundwater response to changing beach profiles, including expansion of freshwater resources and impacts on inland flooding, sediment transport (by exfiltration, for example), and growth of vegetation (which can stabilize dunes and other features[124]). Moreover, natural, engineered and sea level rise scenarios must be intercompared to inform management decisions, where observations are critical to assess models. Paleoclimate records and observations of beaches experiencing unusually large relative sea level rise could provide insight as to how projected sea level rise is to affect different beaches in the future, and should be further integrated with modelled projections of coastal response

Whilst the various impacts of addressing beach retreat and erosion with nourishment are outlined, we caution against unmonitored adoption of nourishment strategies, mainly because a solid foundation in properly managing impacts with design is lacking. Continued research will be crucial to inform the decisions ahead and to use our sand resources effectively and sensibly. New observation techniques will need to be developed to map impacts over a larger area. These studies must result in numerical prediction tools that can interpolate scarce observation points and forecast nourishment impacts under different circumstances. New pilot projects to experiment and quantitatively assess alternative nourishment approaches are furthermore recommended to test and develop operational capabilities in a fresh framework that reflects the environmental diversity and social aspirations of our coastal ‘beachscapes’.

Affiliations

M.A. de Schipper (Delft University of Technology, Delft, The Netherlands)
B.C. Ludka (Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, United States)
B. Raubenheimer (Woods Hole Oceanographic Institution, Woods Hole, MA, United States)
A.P. Luijendijk (Deltares, Delft University of Technology, Delft, the Netherlands)
T. A. Schlacher (USC – University of the Sunshine Coast, Australia)

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Author contributions

MA de Schipper and BC Ludka conceived the project. All co-authors contributed to the writing and editing of the manuscript. MA de Schipper and BC Ludka gave special attention to the Introduction, Sand redistribution, Broader Impacts, Integrating Perspectives and Future Directions. B Raubenheimer gave special attention to Groundwater Impacts and Integrating Perspectives. AP Luijendijk gave special attention to the Sand Redistribution, TA Schlacher gave special attention to Ecological Impacts, Integrating Perspectives and Future Directions. MA de Schipper compiled edits of the text and finalized them in collaboration with the editor.

Competing interests

The authors declare no competing interests.

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Publisher's note

Figure legends

Fig 1. **Beach nourishment projects**. Nourishment sand bodies and additional hard structures indicated in black dashed and red lines respectively. a| Beach nourishment placement in progress, San Diego (USA). b| Beach nourishment with groyne field, Coney Island (New York, USA). c| Perched beach nourishment with groyne field and submerged sill, Pellestrina (Italy). d| Beach and dune nourishment with lagoon, Hondsbossche (Netherlands). e| 'Sand Engine Mega Nourishment' intended to feed adjacent beaches with constructed lake and lagoon for additional types of recreational and ecological habitats, Kijkduin (Netherlands). **[PR: CHECK AND ADD IMAGE PERMISSIONS]**

Fig 2. **Evolution of sandy beach nourishments.** Morphological evolution of a sandy beach nourishment in planform (bird's eye view) and profile (side-view). a| As the nourishment pad retreats, sand is redistributed laterally, with possible spit development along the edges. b| In the original placement region, erosion of the pad coincides with a general decrease of the profile slope. c| At adjacent coastal sections, nourishment sand delivered by spit features creates an elevated bump on the profile. d| Erosion of the nourishment near the water line can result in the creation of scarps. e| Scarps can be removed when high waves overwash the scarp crest. f| Crowns can form when overtopping waves bring sediment on top of the nourishment pad. Advances in morphodynamic model predictions illustrated for the 'Sand Engine' nourishment, with the columns representing the initial (2011), one year (2012) and 5-year bed levels (2016). g| Observed bed levels in 2011. h| Observed bed levels in 2012. i| Observed bed levels in 2016. j| Model input. k| The uncalibrated 1 year ocean-forced (waves & currents) model prediction. l| 18 month calibrated, ocean-forced, extended 5 year prediction[92]. m| 1 year calibrated, ocean-forced model output[47]. n| 18 month calibrated extended 5 year prediction including ocean-forcing and wind-blown sand transport on the above-water beach[91]. Thick black lines in g-n note the mean sea level.

Figure 3. Groundwater processes related to nourishments. Fresh rainwater is trapped in the ground (surface aquifer) above saline water that infiltrates from the ocean. a| Beach nourishments expand the region that traps water, including

precipitation, potentially expanding freshwater resources. b| During large ocean surge and wave events, the beach and dune absorbs seawater, creating a groundwater bulge that increases in magnitude with storm period. c| Following a storm, the groundwater under the dune exfiltrates onto the beach, potentially enhancing erosion or reducing onshore blowing sand that could rebuild the dune. In addition, the groundwater bulge moves inland, potentially causing flooding in low-lying areas.

Figure 4. Potential ecological changes during and following beach nourishment. a| Ocean beaches without significant human stressors are ecosystems rich in species and individuals. b| Human activities at developed (eroding) seashores often result in a reduction in beach fauna. c| Beach nourishment can cause a range of changes to beach habitats and their fauna. These impacts can arise through direct mechanical impact. d| Excess coarse material, such as shell hash, can make it difficult for predators to detect prey and to extract prey from the seafloor. e| High concentrations of silts and clays in suspension can suffocate infauna, by clogging their gills. f| Because invertebrates living in the sand have very specific requirements, changes to granulometry are often inimical to beach fauna, including lower recruitment by larvae from the ocean. Note, the panels are conceptual sketches only, with organisms and human activities not to scale.

Figure 5. Integration of impacts into nourishment design. a| Main design parameters impacting coastal zone functions. b| Flowchart for designing and evaluating beach nourishments. Nourishment strategy examples (not comprehensive) show the diversity in designs and their relation to design choices. Actual designs could combine several elements to reflect the nourishment project goals.

[b1] Regional nourishment strategies

[bH1] United States, San Diego County, Southern California

The Southern California coastal zone contains large cliffed sections, intersected with river and estuarine valleys. Wide beaches in this region are primarily the result of large opportunistic nourishments between the 1940s and 1980s[22]. More recently smaller nourishments (order of magnitude 200,000 m^3)[45,53] are typically placed to protect coastal infrastructure and bolster tourism, impacting beach-spawning fish[160], shore birds[147] and invertebrates[150]. Sands are obtained from a mix of harbor dredge material[160] and offshore pits[150] with costs of 12-25 US$ per m^3 (Ref[224]). These projects are financed by state and federal funds, with smaller contributions from the local cities.

[bH1] Australia, SE-Queensland

The southernmost part of the Queensland coastline contains large, low-lying sandy islands backed by lagoons and inlet systems[225]. These beach systems host amongst others invertebrates, fish and larger scavengers[153,226]. Tourist beaches on this coastline have been nourished since the 1970s[227]. Surfing conditions are engineered by an artificial reef in the nearshore zone[228]. Local and state government have invested in a continual program that adds sand from a nearby estuarine inlet to popular tourist beaches. The majority of the sand is dredged from nearby estuaries and inlets and a small percentage of the sands (15%) are obtained from offshore sources[227]. Costs are ~ 5 US$ per m^3 (Ref[214]). Sand supply is also enhanced by an estuarine bypass system, a continuous beach nourishment system that redistributes sand from the updrift beach through a pipeline to several outlets on beaches down-current of the estuarine inlet[12].

[bH1] South Korea, East Coast

The South Korean east coast is a rocky coastline with embayed sandy beaches[229] subjected to multiple severe storm and typhoon events per year[230], and some parts suffer from structural erosion. Urban areas along the east coast of South Korea typically consist of coastal infrastructure fronted by a narrow beach, increasing the demand for coastal protection and space for recreation using frequent beach nourishments[42,230,231]. Even in these developed regions, the beach ecosystem hosts a range of species, including various burrowing and tube-dwelling amphipods[232]. Sand is mined from nearby rivers and estuaries or from offshore areas at distance of the beach[42]. Costs are 35-45 US$ per m^3.

[bH1] The Netherlands.

The majority of the Netherlands is situated below mean sea level and is densely populated. A narrow beach and dune ridge are the primary defense against flooding[233]. High potential for inundation damages have led to frequent nourishment interventions that are backed by federal funding and with long-term nationwide planning. Annually, 10-15 million m^3 of sand is used in nourishment projects along the sandy shoreline[26]. Nourished sand is placed on the beach but also in shallow waters (4-6 m water depth) with the intent that it will either act as a breakwater sandbar or feed sand onshore. These nourishments are found to affect macroinvertebrates, bivalves and migrating birds (amongst others)[234,235]. These sands are mined 5 km offshore in shallow waters (~20 m water depth) from a wide continental shelf. Costs are ~ 5 US$ per m^3 (Ref[236]). Federal planning allows for experimenting with new nourishment designs, such as concentrated mega nourishments.

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