Beach nourishment has complex implications for the future of sandy shores

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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 multidisciplinary overview of beach nourishment, discussing physical aspects of beach nourishment alongside ecological and socio-economic 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, multidisciplinary research studies on the combined impacts of nourishments, and explorations of various designs to guide these globally diverse nourishment practices.

An estimated 15% of the world's sandy beaches have been retreating a metre or more per year on average in the last several decades[1]. More than 10% of the global population lives within 10 m of the present sea level[2], and this is expected to grow to over a billion people by 2050 (REF.[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, potentially 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 1900s[21], when opportunistic sources of sand (such as from harbour development dredging) were readily available. In places where development has slowed, smaller, non-opportunistic placements (~100 m^3 per metre 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 as from maintenance of nearby harbours). 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 per metre 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. Monodisciplinary 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

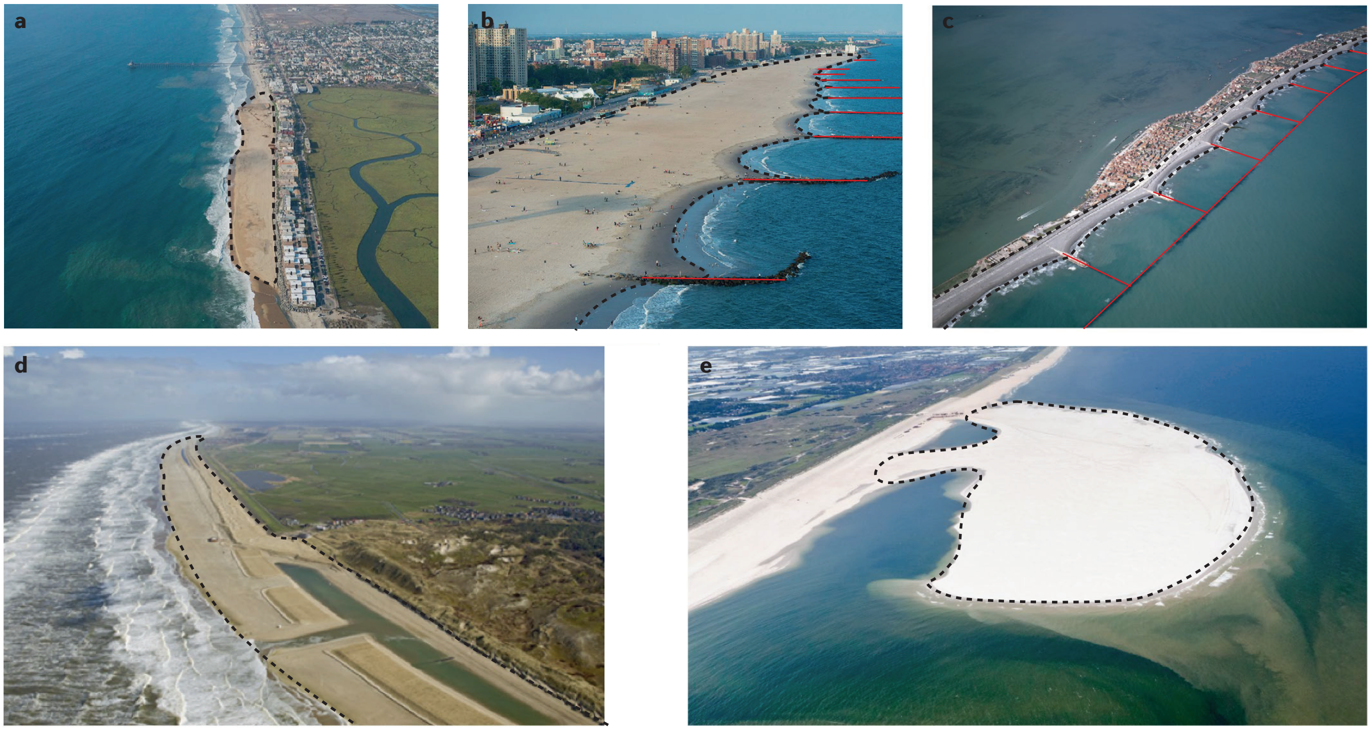


Fig. 1 | **Beach nourishment projects.** Nourishment sand bodies and additional hard structures indicated in black dashed and red lines respectively. **a** | Beach nourishment placement in progress, San Diego (USA). **b** | Beach nourishment with groyne field, Coney Island, New York (USA). **c** | Perched beach nourishment with groyne field and submerged sill, Pellestrina (Italy). **d** | Beach and dune nourishment with lagoon, Hondsbossche Dunes (the 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 (the Netherlands). Part **a** adapted with permission from REF.[54], Elsevier. Part **b** credit: Getty images/Bloomberg. Part **c** credit: Mauritius images GmbH/Alamy Stock Photo. Part **d** image courtesy of Royal Boskalis Westminster N.V. Part **e** image courtesy of Beeldbank Rijkswaterstaat/Joop van Houdt.

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 multidisciplinary 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.

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, harbour 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,c) or are erected nearby in the littoral cell to partially trap nourishment sand in adjacent regions. Sandy beach nourishments are widely practised 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 modelling of sand dynamics.

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[50] 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[51] but can also be a nuisance if it blankets properties and infrastructure near the beach[52]. Likewise, nourishment sand that moves alongshore to adjacent beaches can be beneficial (by widening the recreational and protective beach[12,53], for example) or harmful (by infilling of nearby harbour entrance channels or estuaries[54]).

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[50]. 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–f). 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 ~2 m, 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[54]. 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 upcoast and downcoast edges[43]. Tapered edges are often designed

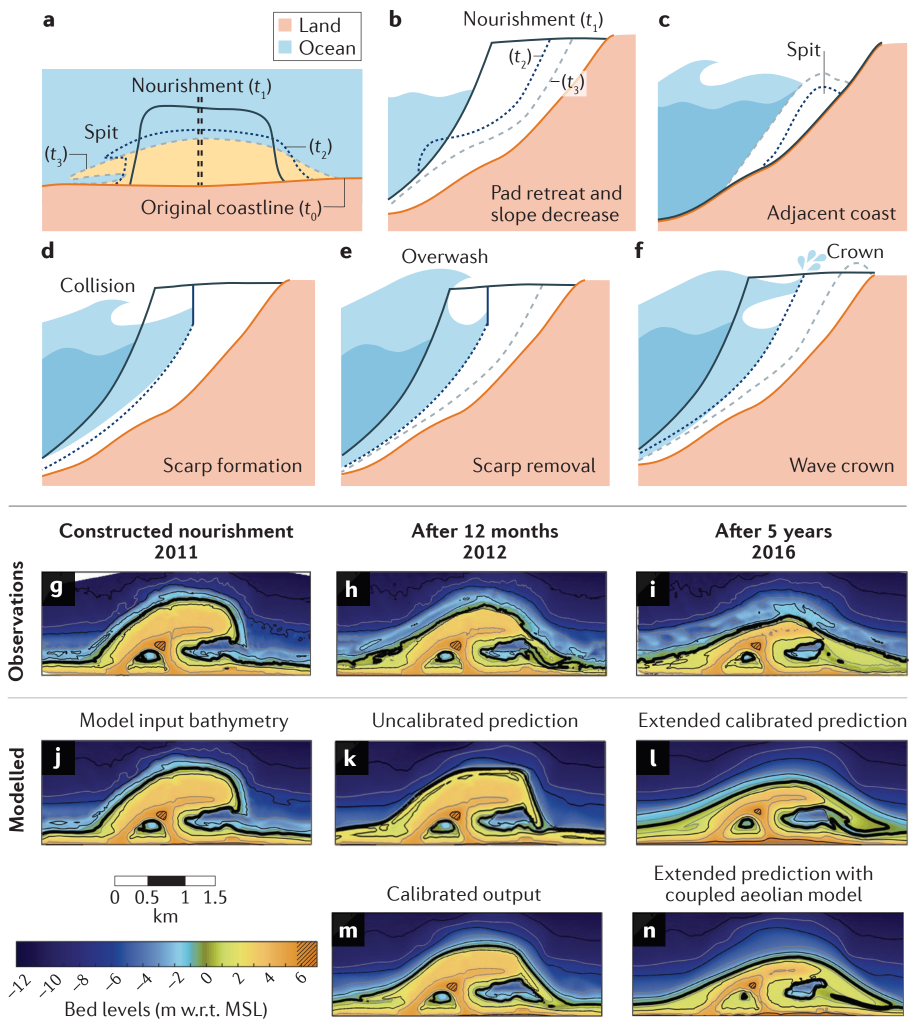


Fig. 2 | **Evolution of sandy beach nourishments.** Morphological evolution of a sandy beach nourishment in planform (bird's-eye view) and profile (side view). **a** | As the nourishment pad retreats, sand is redistributed laterally, with possible spit development along the edges. **b** | In the original 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), 12-month (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 and currents) model prediction. **l** | Eighteen-month calibrated, ocean-forced, extended 5-year prediction[91]. **m** | One-year calibrated, ocean-forced model output[47]. **n** | Eighteen-month calibrated, extended 5-year prediction including ocean-forced and wind-blown sand transport on the above-water beach[90]. Thick black lines in **g**–**n** denote the mean sea level (MSL).

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[54]. 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 and 2014 were combined with groynes (shore-perpendicular structures that extend from the beach into a portion of the surf zone) 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 with a design without a sill[46,62]. The perched beach concept has been practised worldwide[63], but results on the longevity of the nourishments are mixed and there is limited understanding as to 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[49,64] or provide a temporary buffer to storm impacts on landward infrastructure[65]. 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].

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 programmes tailored to beach nourishment behaviour measure both the underwater and the above-water beach, preferably obtained simultaneously to close the sediment balance[66]. 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 (grain size 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[54,59,67].

Techniques to monitor nourishment sand redistribution are evolving[68] — 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[69]. These technologies drastically increased spatial resolution and span, while maintaining <10-cm horizontal and vertical accuracy[53,54]. Above-water mapping technologies are often 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[53,54,67,70].

In the past decade, remote sensing imaging systems have further expanded data collection capabilities. These can be mounted on fixed (towers, rooftops)[71] or mobile (drones, airplanes, satellites) platforms[68]. Monocular (single viewing angle) imagery using optical cameras[1,71–73] or cloud penetrating radar[74] 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[75]), this method works best when shoreline migration is large (many tens of metres for satellite systems[73]). Newer remote imaging technologies that measure the 3D 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 3D surface from multiple photographs with different viewing angles[76–78]. Laser scanning[66] (lidar) is generally the most expensive and most accurate remote sensing technique[79,80], and can provide full waveform information useful for resolving different surface layers (such as vegetation on a dune[81]). These 3D datasets, including true colour information of the surface, open new opportunities to identify beach characteristics (such as distinguishing between native and nourishment sand[82] and cobble coverage[83]).

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[84], 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[79,85]. 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[86,87].

We envision that as the space-borne 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 centimetres[76,78,79], which will help map sand redistribution, expand our understanding of geomorphological processes and enhance our ability to develop or calibrate numerical models.

Modelling 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[88]. Furthermore, these models must encompass broad temporal (from seconds, such as during an 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[89]. Sometimes, models that use different resolutions can be coupled to resolve multiple scales[90], for example, by running high-detail models for small spatial scales and/or short timescales, in conjunction with aggregated low-resolution models for large spatial scales and/or long timescales. Other approaches attempt to accelerate model simulations by 'compressing' the number of time steps[91], by using only the moments with the most impactful forcing conditions[47] or implementing simplified but efficient lookup tables that categorize the beach response to generalized forcing conditions[92].

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[93]. When calibrated, these computationally fast models can provide information on beach change on the largest of scales (years, kilometres)[94]. 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 and spit formation), more complex models are needed based on the upscaling of processes (process-based modelling, for example, REFS[95,96]). 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[97]. Current state-of-the-art cross-shore process-based models perform best for predominantly offshore-directed morphological development on timescales of days, such as the large erosion of nourished profiles during a storm[98]. When applied to natural profiles and moderate waves, model skill is significantly reduced up to the point that a simulated development, when compared with observed changes, can be worse than a no-change prediction[99].

Planform process-based models have a domain that extends both alongshore and cross-shore, but have limited resolution in the water column[91,100]. Recent planform model computations are apt at reproducing the multi-year evolution (both erosion and accretive sand volumes) of a mega beach nourishment[47,91] (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 to the surrounding (native) sand and may be able to reproduce the coarsening of the sand as fines are transported out of the area[101]. Sufficient high-quality sediment composition data are needed to further develop and test these grain size-specific transports.

Uncertainties in model forecasts arise from both the forcing (such as wave, wind, water-level conditions) and the 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[102]. For 50-year 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 modelling 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[103] in determining the output. Computational power has increased such that, if model physics 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[103]. 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 are 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[103] and vegetation[104] 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[90] (FIG. 2n). However, given the difficulty in modelling 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[105], and observations will continue to be essential for model testing.

Groundwater impacts

Changes to aquifers below beaches and dunes are increasingly considered as part of coastal zone management practices, as these impact flooding and freshwater quantities. For example, storms can cause groundwater salinization[106–110] — especially concerning for low-lying islands with limited freshwater supplies, such as the barrier islands along subsiding coasts[111] and Pacific atolls[112,113] — and contribute to coastal flooding[114]. 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 with when considering marine inundation alone[115,116].

The behaviour 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[117,118] (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[118]. Moreover, the elevated nourishment pads can retain ocean water in the added sediment, especially during storms with large surge and wave-driven set-up, even in the absence of inundation[119], and the increased groundwater levels and inland-propagating groundwater bulge[120,121], can potentially contribute to inland flooding[54,122] (FIG. 3b,c). Moreover, seaward seepage (FIG. 3c) of the groundwater onto the beach can reduce the wind-driven onshore transport that is needed to build dunes[123], while also reducing the effective weight of sediments submerged by waves, enabling sands to be swept offshore more easily[124].

Groundwater flow in beaches is sensitive to both cross-shore profile shape as well as porosity and grain size[125], and these three aspects can be (temporarily) altered after nourishment[54,63,126]. 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.

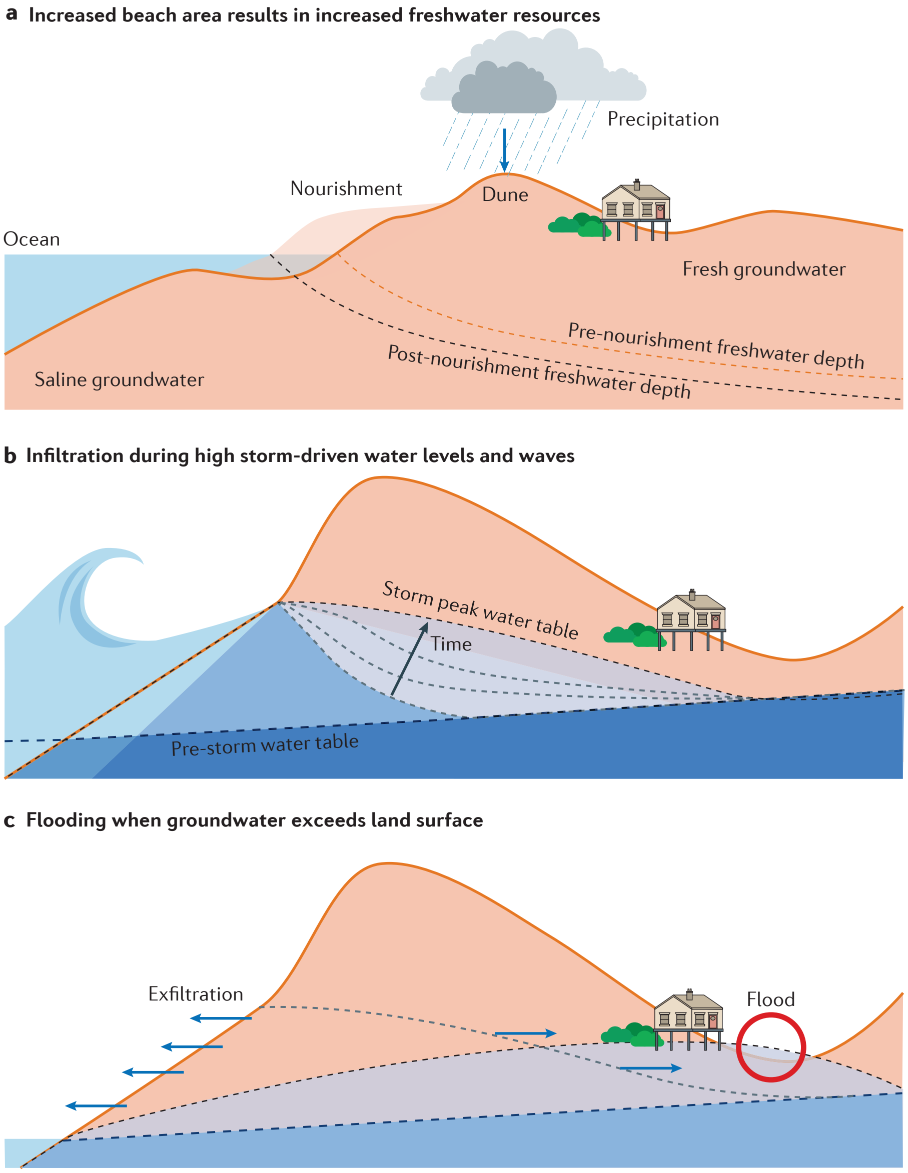


Fig. 3 | **Groundwater processes related to nourishments.** Fresh rainwater is trapped in the ground (surface aquifer) above saline water that infiltrates from the ocean. **a** | Beach nourishments expand the region that traps water, including precipitation, potentially expanding freshwater resources.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

Ecological impacts

Habitat attributes are the main determinant of biodiversity and ecological structure in beach ecosystems[127–132]. 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 ecosystems 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)[133–138] (FIG. 4a). Beach species are adapted to high-energy environments with rapidly changing conditions[139], yet, this does not imply that they are resilient to habitat changes and physical forces caused by nourishments[140–144]. Indeed, many coastal ecosystems are deteriorating[145–147], owing to human activities in the coastal zone (FIG. 4b), such as infrastructure, beach armouring, off-road vehicle traffic and beach grooming, and nourishment can compound ecological stressors.

Detrimental impacts of nourishment[148–150] 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 upward[151,152] and mechanical crushing by heavy machinery, functionally similar to the crushing effects by off-road vehicles driven over beach invertebrates buried in the sand[153–156].

Increased water turbidity from nourishment operations that bring fine

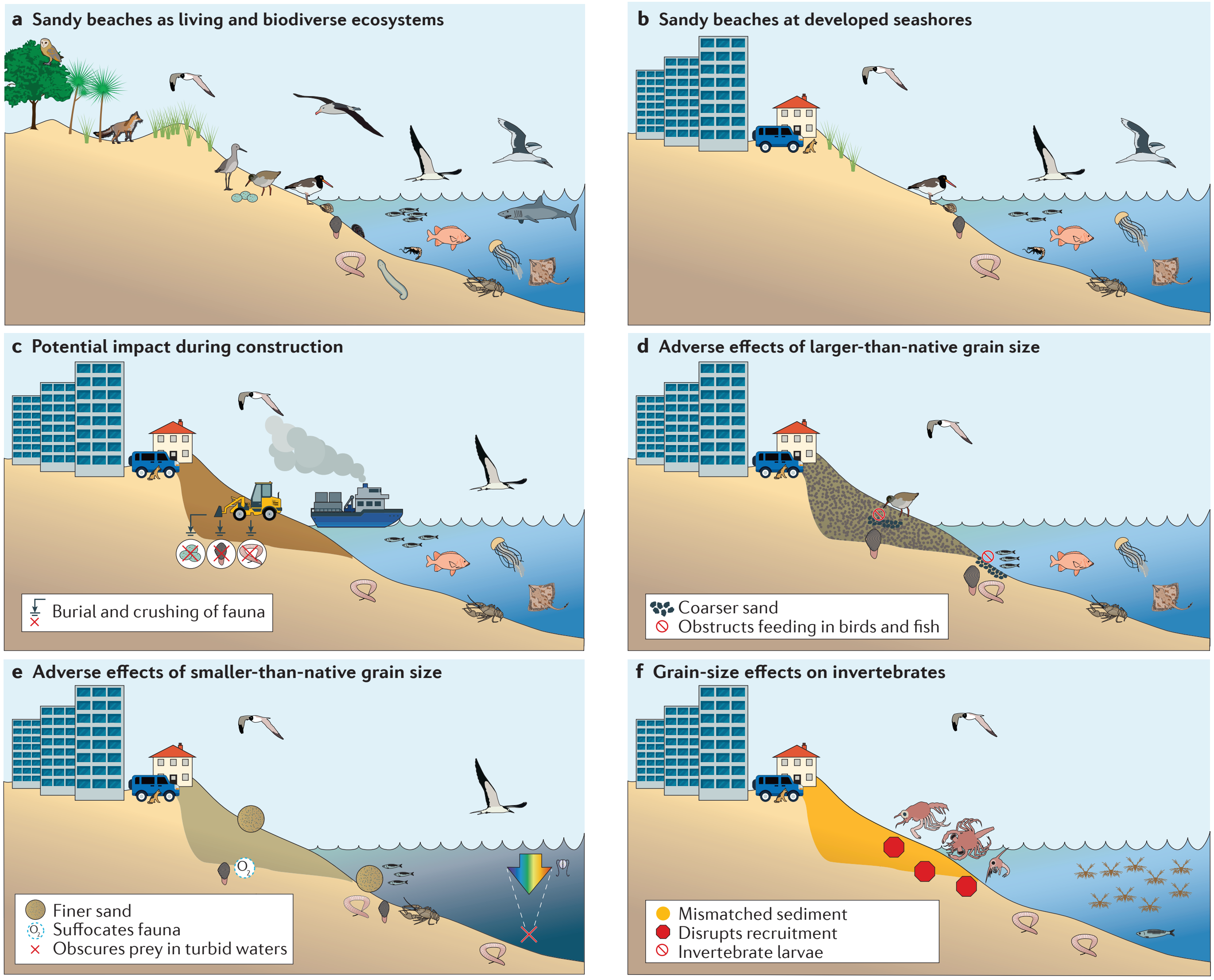


Fig. 4 | **Potential ecological changes during and following beach nourishment. a** | Ocean beaches without significant human stressors are ecosystems rich in species and individuals. **b** | Human activities at developed (eroding) seashores often result in a reduction in beach fauna. **c** | Beach nourishment 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** | As 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.

material into suspension and the suspended silt can clog the delicate feeding structures of filter feeding invertebrates (such as clams)[142]; more turbid surf zone waters can also limit prey detection, thereby impairing feeding by fish[141] (FIG. 4e). These impacts can extend beyond the immediate spatial footprint to affect adjacent systems (including reefs and seagrass meadows) several kilometres away through turbidity plumes[157].

After the nourishment has been implemented, the altered cross shore profile shape can create unfavourable conditions for foraging, spawning or nesting[158,159]. Moreover, a mismatch of sediment properties between the added material and the original sands[160–162] can impact habitat conditions. For example, excess shell hash can impede probing for clams by shorebirds (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[163]. Wave sheltering provided by breakwaters can shift communities from consumer-dominated to producer-dominated systems[164]. Furthermore, hard structures can create barriers to the transport of mobile animals living on the ocean floor and to the dispersal of propagules[163].

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[165]. 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[151] to several years[143,166]. 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[167].

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[165]. However, larger nourishment volumes typically bury organisms under a larger depth of sand, which potentially makes 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[146,152,159,168]. 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 with 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[169]; however, nourishment projects lower on the beach that prioritize ecological functioning over other objectives are generally rarer 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 seaward nor unnaturally elevated, and with biologically suitable slope, relief and sediment composition) should examine the full capability of using nourishment for ecological restoration.

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.

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[46,54], the survival of beach fauna[141–143], groundwater flows[125] and the satisfaction of tourists[170], sand needs to be carefully chosen, and mined sand that resembles the native is typically preferred[171]. However, there is a predicted global shortage of sand due to high demand for concrete, land reclamation and coastal nourishments[172,173], and, owing to a shortage of inland sand sources, marine and coastal sands are increasingly mined for concrete[173]. 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[174]. 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[175–177]. In some projects where borrow areas are close, such as the shallow nearshore seabed and/or nearby inlets or harbours that are dredged frequently, the cost of sand can be lower than US\$5 per m^3 (BOX 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 US\$200 per m^3, making sand trading a part of international disputes[173]. Global nourishment costs might reach hundreds of billions of US\$ per year before the end of the century[178]. Government regulations and contract type (such as Construct Only or Design & Construct) can also drastically influence sand pricing[179]. 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%[180].

New areas for sand mining could become economically viable over the next decades as sand prices continue to escalate and melting ice caps open up new potential mining sites, but the ecological harms associated with mining distant sands need careful evaluation and mitigation before extraction takes place[181]. For example, mining of marine sands affects marine mammals via noise and light pollution[171], and invertebrate assemblages of the seafloor could take years to recover[182]. '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[183], 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 2–5 kg of CO_2 (REFS[175,184]). The CO_2 footprint increases with transport distance from the mining site to the beach[176], 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[176,184]. 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 suboptimal from an ecological or recreational standpoint[185]. 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 standpoint. New developments in efficient nourishment placement strategies and vessel (fuel) technology[186] must also be explored further to reduce the overall environmental footprint of beach nourishment.

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[187]. However, visitor appreciation studies in the USA and Australia show that beaches perceived to be excessively wide are unattractive to visitors[188], as they make the ocean less accessible for water-based activities, such as surfing, swimming and scuba diving[187]. Altered beach slopes and the development of scarps on the nourishment can create hazards[189] and impede lifeguards' views and vehicle access[190]. Nourishments also affect in-water recreation. Sharp bends in the planform shape can generate strong flows that impact bather safety[190] and affects sandbar patterns[191], sometimes resulting in stronger rip current flows[192]. In the USA, 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[192], additional research is needed to provide generic evidence on the link between nourishment, rip currents and altered swimmer safety[192]. The changes in sandbar morphology and wave breaking patterns can also alter the quality of surf breaks[12,193,194]. Although implementing nourishments with irregular outlines and steep end sections can mitigate some of these negative effects on surfing[195,196], these surfing-specific design features with strong coastline curvatures are typically short-lived (weeks to months) and can negatively impact swimmer safety[190].

Box 1 | **Regional nourishment strategies**

United States, San Diego County, Southern California

The Southern California coastal zone contains large cliffed sections, intersected with river and estuarine valleys (panel a). 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)[45,54] are typically placed to protect coastal infrastructure and bolster tourism, impacting beach spawning fish[159], shorebirds[146] and invertebrates[149]. Sands are obtained from a mix of harbour dredge material[159] and offshore pits[149], with costs of US$12–25 per m^3 (REF.[224]). These projects are financed by state and federal funds, with smaller contributions from the local cities.

Australia, South East Queensland

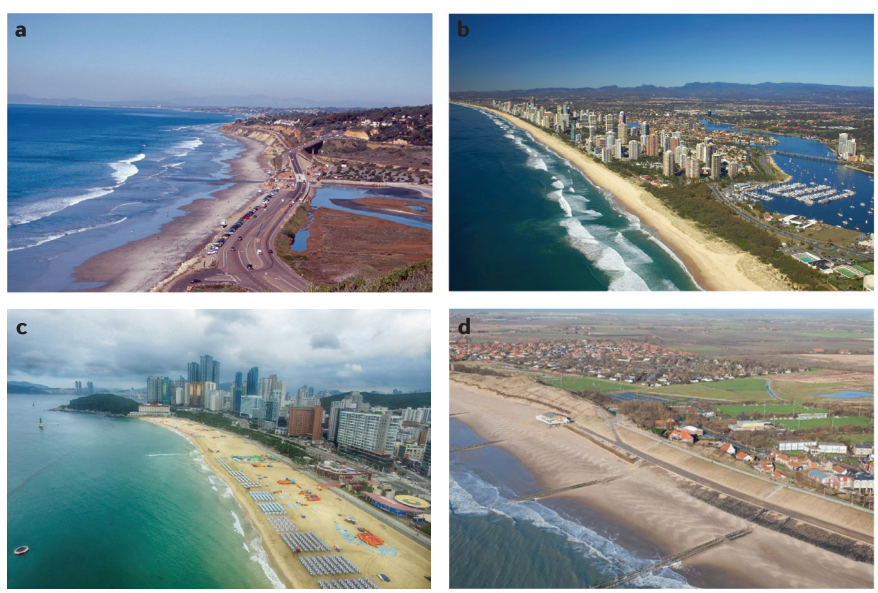
The southernmost part of the Queensland coastline contains large, low-lying sandy islands, backed by lagoons and inlet systems (panel b) [225]. These beach systems host, amongst others invertebrates, fish and larger scavengers[152,226]. Tourist beaches on this coastline have been nourished since the 1970s[227]. Surfing conditions are engineered by an artificial reef in the nearshore zone[228]. Local and state government have invested in a continual programme 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%) is obtained from offshore sources[227]. Costs are ~US$5 per m^3 (REF.[213]). 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 downcurrent of the estuarine inlet[12].

South Korea, east coast

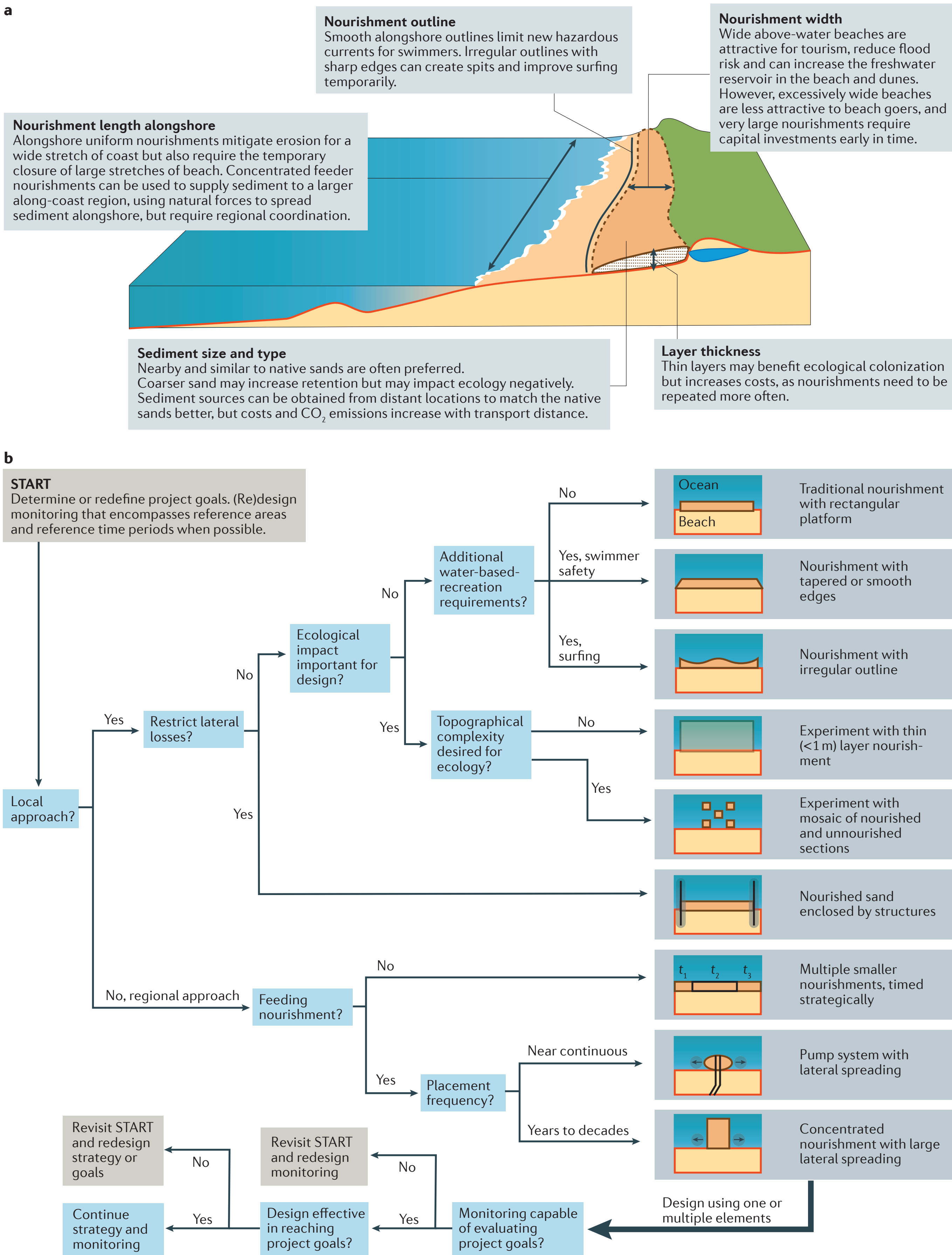
The South Korean east coast is a rocky coastline with embayed sandy beaches[229] subjected to multiple severe storm and typhoon events each year[230], and some parts suffer from structural erosion. Urban areas along the east coast of South Korea typically consist of coastal infrastructure fronted by a narrow beach (panel c), 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 distant from the beach[42]. Costs are US$35–45 per m^3.

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 defence against flooding (panel d)[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 ~US$5 per m^3 (REF.[236]). Federal planning allows for experimenting with new nourishment designs, such as concentrated mega nourishments.



Part **a** credit: Alamy Stock Photo/yury miller. Part **b** credit: Alamy Stock Photo/David Wall. Part **c** credit: Alamy Stock Photo/Busan Drone. Part **d** image courtesy of Beeldbank Rijkswaterstaat/Joop van Houdt.


a
Nourishment outline
Smooth alongshore outlines limit new hazardous currents for swimmers. Irregular outlines with sharp edges can create spits and improve surfing temporarily.
Nourishment width
Wide above-water beaches are attractive for tourism, reduce flood risk and can increase the freshwater reservoir in the beach and dunes. However, excessively wide beaches are less attractive to beach goers, and very large nourishments require capital investments early in time.
Nourishment length alongshore
Alongshore uniform nourishments mitigate erosion for a wide stretch of coast but also require the temporary closure of large stretches of beach. Concentrated feeder nourishments can be used to supply sediment to a larger along-coast region, using natural forces to spread sediment alongshore, but require regional coordination.
Sediment size and type
Nearby and similar to native sands are often preferred.
Coarser sand may increase retention but may impact ecology negatively.
Sediment sources can be obtained from distant locations to match the native sands better, but costs and CO_2 emissions increase with transport distance.
Layer thickness
Thin layers may benefit ecological colonization but increases costs, as nourishments need to be repeated more often.
b
START
Determine or redefine project goals. (Re)design monitoring that encompasses reference areas and reference time periods when possible.
Local approach?
Yes
Restrict lateral losses?
No
Ecological impact important for design?
No
Additional water-based-recreation requirements?
No
Yes, swimmer safety
Yes, surfing
Yes
Topographical complexity desired for ecology?
No
Yes
Yes
No, regional approach
Feeding nourishment?
No
Yes
Placement frequency?
Near continuous
Years to decades
Ocean
Beach
Traditional nourishment with rectangular platform
Nourishment with tapered or smooth edges
Nourishment with irregular outline
Experiment with thin (<1 m) layer nourish-ment
Experiment with mosaic of nourished and unnourished sections
Nourished sand enclosed by structures
t_1 t_2 t_3
Multiple smaller nourishments, timed strategically
Pump system with lateral spreading
Concentrated nourishment with large lateral spreading
Design using one or multiple elements
Monitoring capable of evaluating project goals?
No
Revisit START and redesign monitoring
Yes
Design effective in reaching project goals?
No
Revisit START and redesign strategy or goals
Yes
Continue strategy and monitoring

◀ Fig. 5 | **Integration of impacts into nourishment design. a** | Main design parameters impacting coastal zone functions. **b** | Flow chart 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.

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[197]. Economic evaluations typically contain three main site-specific elements: changes in coastal property value, changes in tourism revenue, and the cost of the coastal management works. The optimal beach width can be translated to an estimated optimal nourishment frequency and size to maximize revenues[198]. In these analyses, larger values of beach width revenues, property value or background erosion rate result in increasing nourishment frequency[199]. 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[198,200] and local versus regional approaches to decision making can affect the economic balance. Coupled coastline economic models for nourishments currently under development[200] 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 US$700 return[201], 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[187,188,202], 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[203]. Moreover, nourishing with sand dissimilar from the native mineralogical composition can result in changes in beach sand colour, which impacts visitor appreciation, with light-coloured nourished sediment being preferred by visitors in some cases, such as seen in Cuba and Italy[170,204]. Comparisons of natural and nourished beaches in Spain showed that nourished beaches have distinct different colours (quantified using the CIE L*a*b* methodology), which can persist for years after sand is added[205].

Given limited sand resources, difficult decisions will arise about which beach will be saved by frequent nourishments[185]. With property values being higher behind wider beaches (all else being equal)[197], investments to restore and widen beaches can presumably be higher in more affluent beach communities[178]. Therefore, upholding principles of social justice in democratic systems calls for equitable regulated approaches to decision making in beach restoration[206,207]. 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. Inclusion can be implemented in the design, for example, by requiring public access every half mile after the construction of a beach nourishment[208].

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[209], 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.

Integrating perspectives

The previous sections outline the progress that has been made in nourishment impact science and highlights the connectivity between the various impacts such as linkages between beach width variations and economics; altered grain size and fauna recovery; sand mining location and visitor appreciation through sand type and colour (FIG. 5a). Some of the requirements are in direct contradiction and demand a trade-off; 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). Modelling 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 (for example, REFS[28,63,210–212]), typically focuses on geometrical aspects alone (like beach width or beach volume). Visitor appreciation surveys and economic evaluations (in cost–benefit analysis[213], Travel Cost Method or Contingent Valuation Method[214], for example) are also used widely, despite the 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[29,145]. An ecosystem-services framework[29,145,215] 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 with the pre-nourished or adjacent coasts[165], which can be viewed as a positive or negative impact, depending on (cultural) views on ecology and restoration[216]. In some communities, ecosystem functions may be a priority that dictates nourishment design[33,217]. 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.

Future directions

Many of the world's sandy beaches are subjected to 'coastal squeeze', trapped between rising seas and increasing development on land[4,147]. 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[218–221]. 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[222], 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, at Dongsha beach, China[65]), whereas large-scale nourishments are designed to last decades at other locations (as with the Sand Engine, the Netherlands[53]).

Impacts arising from beach nourishment thematically reflect and intersect multiple fields of science, emphasizing the need for collaborative, multidisciplinary 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[123]). Moreover, natural, engineered and sea level-rise scenarios must be intercompared to inform management decisions, where observations are critical to assess models. Palaeoclimate 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.

Continued research will be crucial to inform the decisions ahead and to enable us to use our sand resources effectively and sensibly. Whilst the various impacts of addressing beach retreat and erosion with nourishment are outlined, we caution against unmonitored adoption of nourishment strategies, mainly because future forcing conditions (such as storm variability, fossil fuel emissions and sea level rise scenario) are uncertain, and a solid foundation in properly managing impacts with design is lacking. In the face of uncertainty, we recommend trigger based adaptation planning. Using this method, when predetermined metrics (triggers such as a narrow beach width or low species abundance) are observed, changes in planning pathways (such as nourishment or retreat) will be initiated to prevent harmful thresholds (such as flooding or species loss) from being crossed[223]. Trigger metrics should be central components of ongoing monitoring campaigns, and adaptation pathways can be iteratively improved as lessons are learned from monitoring and modeling coastal management practices. 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'.

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1. Luijendijk, A. et al. The state of the world's beaches. *Sci. Rep.* **8**, 6641 (2018).
2. Merkens, J. L., Reimann, L., Hinkel, J. & Vafeidis, A. T. Gridded population projections for the coastal zone under the Shared Socioeconomic Pathways. *Glob. Planet. Change* **145**, 57–66 (2016).
3. Ranasinghe, R., Callaghan, D. & Stive, M. J. F. Estimating coastal recession due to sea level rise: beyond the Bruun rule. *Clim. Change* **110**, 561–574 (2012).
4. Vousdoukas, M. I. et al. Sandy coastlines under threat of erosion. *Nat. Clim. Chang.* **10**, 260–263 (2020).
5. Nicholls, R. J. Planning for the impacts of sea level rise. *Oceanography* **24**, 144–157 (2011).
6. Dean, R. G. *Beach Nourishment: Theory and Practice* (World Scientific, 2003).
7. Montague, C. L. Ecological engineering of inlets in southeastern Florida: design criteria for sea turtle nesting beaches. *J. Coast. Res.* **18**, 267–276 (1993).
8. Li, S. et al. A comparison of coastal habitat restoration projects in China and the United States. *Sci. Rep.* **9**, 14388 (2019).
9. van der Meulen, F., van der Valk, B., Vertegaal, K. & van Eerden, M. 'Building with nature' at the Dutch dune coast: compensation target management in Spanjaards Duin at EU and regional policy levels. *J. Coast. Conserv.* **19**, 707–714 (2015).
10. Leonard, L., Clayton, T. D., Dixon, K. & Pilkey, O. H. US beach replenishment experience: a comparison of the Atlantic, Pacific and Gulf coasts. *J. Coast. Res.* **89**, 1994–2006 (1989).
11. Hino, M., Field, C. B. & Mach, K. J. Managed retreat as a response to natural hazard risk. *Nat. Clim. Chang.* **7**, 364–370 (2017).
12. Castelle, B., Turner, I. L., Bertin, X. & Tomlinson, R. Beach nourishments at Coolangatta Bay over the period 1987–2005: impacts and lessons. *Coast. Eng.* **56**, 940–950 (2009).
13. Cooke, B. C., Jones, A. R., Goodwin, I. D. & Bishop, M. J. Nourishment practices on Australian sandy beaches: A review. *J. Environ. Manage.* **113**, 319–327 (2012).
14. Hanson, H. et al. Beach nourishment projects, practices, and objectives — a European overview. *Coast. Eng.* **47**, 81–111 (2002).
15. Young, A. P. et al. Coarse sediment yields from seacliff erosion in the Oceanside littoral cell. *J. Coast. Res.* **263**, 580–585 (2010).
16. Fletcher, C. H., Richmond, B. M. & Mullane, R. A. Beach loss along armored shorelines on Oahu, Hawaiian Islands. *J. Coast. Res.* **13**, 209–215 (1997).
17. Bruun, P. The development of downdrift erosion. *J. Coast. Res.* **11**, 1242–1257 (1995).
18. Luo, S., Liu, Y., Jin, R., Zhang, J. & Wei, W. A guide to coastal management: Benefits and lessons learned of beach nourishment practices in China over the past two decades. *Ocean Coast. Manag.* **134**, 207–215 (2016).
19. Lanza, S. & Randazzo, G. Tourist-beach protection in north-eastern Sicily (Italy). *J. Coast. Conserv.* **17**, 49–57 (2013).
20. Gómez-Pina, G., Fages, L., Ramírez, J. L., Muñoz-Pérez, J. J. & Enríquez, J. in *Coastal Engineering 2006* (ed. McKee Smith, J.) 4167–4178 (World Scientific, 2006).
21. Valverde, H. R., Trembanis, A. C. & Pilkey, O. H. Summary of beach nourishment episodes on the U.S. East Coast barrier islands. *J. Coast. Res.* **15**, 1100–1118 (1999).
22. Flick, R. E. The myth and reality of southern California beaches. *Shore Beach* **61**, 3–13 (1993).
23. Liu, Z., Cui, B. & He, Q. Shifting paradigms in coastal restoration: Six decades' lessons from China. *Sci. Total Environ.* **566–567**, 205–214 (2016).
24. Hamm, L. et al. A summary of European experience with shore nourishment. *Coast. Eng.* **47**, 237–264 (2002).
25. Jiménez, J. A., Gracia, V., Valdemoro, H. I., Mendoza, E. T. & Sánchez-Arcilla, A. Managing erosion-induced problems in NW Mediterranean urban beaches. *Ocean Coast. Manag.* **54**, 907–918 (2011).
26. Stive, M. J. F. et al. A new alternative to saving our beaches from sea-level rise: the sand engine. *J. Coast. Res.* **29**, 999–1008 (2013).

27. Banno, M., Takewaka, S. & Kuriyama, Y. in *Proceedings of Coastal Dynamics 2017* (eds Aagaard, T., Deigaard, R. & Fuhrman, D.) 820–829 (Univ. Copenhagen, 2017).
28. Liu, G. et al. A method to nourished beach stability assessment: The case of China. *Ocean Coast. Manag.* **177**, 166–178 (2019).
29. van Oudenhoven, A. P. E. et al. 'Mind the Gap' between ecosystem services classification and strategic decision making. *Ecosyst. Serv.* **33**, 77–88 (2018).
30. Morris, R. L. et al. in *Oceanography and Marine Biology: An Annual Review* (eds Hawkins, S. J. et al.) 169–228 (CRC Press, 2019).
31. de Vriend, H. J., van Koningsveld, M., Aarninkhof, S. G. J., de Vries, M. B. & Baptist, M. J. Sustainable hydraulic engineering through building with nature. *J. Hydro-Environ. Res.* **9**, 159–171 (2015).
32. Bridges, T. et al. *Engineering With Nature* (Environmental Laboratory (U.S.), Engineering With Nature Program (U.S.), U.S. Army Engineer Research and Development Center (U.S.), 2018).
33. Powell, E. J., Tyrrell, M. C., Milliken, A., Tirpak, J. M. & Staudinger, M. D. A review of coastal management approaches to support the integration of ecological and human community planning for climate change. *J. Coast. Conserv.* **23**, 1–18 (2019).
34. McFarland, S., Whitcombe, L. & Collins, M. Recent shingle beach renourishment schemes in the UK: some preliminary observations. *Ocean Coast. Manag.* **25**, 143–149 (1994).
35. Shu, F. et al. Morphodynamics of an artificial cobble beach in Tianquan Bay, Xiamen, China. *J. Ocean Univ. China* **18**, 868–882 (2019).
36. Baptist, M. J. et al. Beneficial use of dredged sediment to enhance salt marsh development by applying a 'Mud Motor'. *Ecol. Eng.* **127**, 312–323 (2019).
37. Clayton, T. D. Beach replenishment activities on U.S. continental Pacific coast. *J. Coast. Res.* **7**, 1195–1210 (1991).
38. Haddad, T. C. & Pilkey, O. H. Summary of the New England beach nourishment experience (1935-1996). *J. Coast. Res.* **14**, 1395–1404 (1998).
39. Trembanis, A. C. & Pilkey, O. H. Summary of beach nourishment along the U.S. Gulf of Mexico shoreline. *J. Coast. Res.* **14**, 407–417 (1998).
40. Palalane, J., Larson, M., Hanson, H. & Juízo, D. Coastal erosion in Mozambique: Governing processes and remedial measures. *J. Coast. Res.* **32**, 700–718 (2016).
41. Cai, F., Dean, R. G. & Liu, J. Beach nourishment in China: status and prospects. *Coast. Eng. Proc.* https://doi.org/10.9753/icce.v32.management.31 (2010).
42. Lee, W. D., Kim, I. H., Yoon, J. S., Cho, W. C. & Hur, D. S. Analysis of beach deformation according to nourishing sand in Haeundae Beach, Korea. *J. Coast. Res.* **75**, 1372–1376 (2016).
43. Elko, N. A. & Wang, P. Immediate profile and planform evolution of a beach nourishment project with hurricane influences. *Coast. Eng.* **54**, 49–66 (2007).
44. Yates, M. L., Guza, R. T., O'Reilly, W. C. & Seymour, R. J. Seasonal persistence of a small southern California beach fill. *Coast. Eng.* **56**, 559–564 (2009).
45. Seymour, R., Guza, R. T., O'Reilly, W. & Elgar, S. Rapid erosion of a small southern California beach fill. *Coast. Eng.* **52**, 151–158 (2005).
46. Dean, R. G. Equilibrium beach profiles: characteristics and applications. *J. Coast. Res.* **7**, 53–84 (1991).
47. Luijendijk, A. P. et al. The initial morphological response of the Sand Engine: A process-based modelling study. *Coast. Eng.* **119**, 1–14 (2017).
48. Smith, A. W. S. Discussion of: Pilkey, O. H., 1990. A time to look back at beach replenishment (editorial), Journal of Coastal Research, 6(1), iii-vii. And, Leonard, L.; Clayton, T., and Pilkey, O.H., 1990. An analysis of replenished beach design parameters on U.S. east coast barrier islands, Journal of Coastal Research, 6(1) 15-36. *J. Coast. Res.* **6**, 1041–1045 (1990).
49. Dean, R. G. & Campbell, T. J. in *Springer Handbook of Ocean Engineering* (eds Dhanak, M. R. & Xiros, N. I.) 635–652 (Springer, 2016).
50. Ludka, B. C., Gallien, T. W., Crosby, S. C. & Guza, R. T. Mid-El Niño erosion at nourished and unnourished Southern California beaches. *Geophys. Res. Lett.* **43**, 4510–4516 (2016).
51. Hoonhout, B. & de Vries, S. Aeolian sediment supply at a mega nourishment. *Coast. Eng.* **123**, 11–20 (2017).
52. Jackson, N. L. & Nordstrom, K. F. Aeolian sediment transport and landforms in managed coastal systems: a review. *Aeolian Res.* **3**, 181–196 (2011).
53. de Schipper, M. A. et al. Initial spreading of a mega feeder nourishment: Observations of the Sand Engine pilot project. *Coast. Eng.* **111**, 23–38 (2016).
54. Ludka, B. C., Guza, R. T. & O'Reilly, W. C. Nourishment evolution and impacts at four southern California beaches: A sand volume analysis. *Coast. Eng.* **136**, 96–105 (2018).
55. de Schipper, M. A. Alongshore variability of nourished and natural beaches. PhD thesis, Delft University of Technology, Faculty of Civil Engineering and Geosciences (2014).
56. Radermacher, M., de Schipper, M. A., Swinkels, C., MacMahan, J. H. & Reniers, A. J. H. M. Tidal flow separation at protruding beach nourishments. *J. Geophys. Res. Oceans* **122**, 63–79 (2017).
57. Huisman, B. J. A., de Schipper, M. A. & Ruessink, B. G. Sediment sorting at the Sand Motor at storm and annual time scales. *Mar. Geol.* **381**, 209–2296 (2016).
58. van Bemmelen, C. W. T., de Schipper, M. A., Darnall, J. & Aarninkhof, S. G. J. Beach scarp dynamics at nourished beaches. *Coast. Eng.* **160**, 103725 (2020).
59. de Alegria-Arzaburu, A. R., Mariño-Tapia, I., Silva, R. & Pedrozo-Acuña, A. Post-nourishment beach scarp morphodynamics. *J. Coast. Res.* **65**, 576–581 (2013).
60. Crain, D. A., Bolten, A. B. & Bjorndal, K. A. Effects of beach nourishment on sea turtles: review and research initiatives. *Restor. Ecol.* **3**, 95–104 (1995).
61. Ranasinghe, R. & Turner, I. L. Shoreline response to submerged structures: a review. *Coast. Eng.* **53**, 65–79 (2006).
62. Moreno, L. et al. An engineering method for the preliminary functional design of perched beaches. theoretical approach. *J. Coast. Res.* **85**, 1261–1265 (2018).
63. Muñoz-Perez, J. J., Gallop, S. L. & Moreno, L. J. A comparison of beach nourishment methodology and performance at two fringing reef beaches in Waikiki (Hawaii, USA) and Cadiz (SW Spain). *J. Mar. Sci. Eng.* **8**, 266 (2020).
64. Pilkey, O. H. The fox guarding the hen house. *J. Coast. Res.* **11**, iii–v (1995).
65. Guo, J. et al. Monitoring and evaluation of sand nourishments on an embayed beach exposed to frequent storms in eastern China. *Ocean Coast. Manag.* **195**, 105284 (2020).
66. Cooper, N. J., Leggett, D. J. & Lowe, J. P. Beach-profile measurement, theory and analysis: Practical guidance and applied case studies. *Water Environ. J.* **14**, 79–88 (2000).
67. Ludka, B. C. et al. Sixteen years of bathymetry and waves at San Diego beaches. *Sci. Data* **6**, 161 (2019).
68. Splinter, K. D., Harley, M. D. & Turner, I. L. Remote sensing is changing our view of the coast: Insights from 40 years of monitoring at Narrabeen-Collaroy, Australia. *Remote Sens.* **10**, 1744 (2018).
69. Browder, A. E. & Dean, R. G. Monitoring and comparison to predictive models of the Perdido Key beach nourishment project, Florida, USA. *Coast. Eng.* **39**, 173–191 (2000).
70. Lee, G. H., Nicholls, R. J. & Birkemeier, W. A. Storm-driven variability of the beach-nearshore profile at Duck, North Carolina, USA, 1981–1991. *Mar. Geol.* **148**, 163–177 (1998).
71. Holman, R. A. & Stanley, J. The history and technical capabilities of Argus. *Coast. Eng.* **54**, 477–491 (2007).
72. Elko, N. A., Holman, R. A. & Gelfenbaum, G. Quantifying the rapid evolution of a nourishment project with video imagery. *J. Coast. Res.* **214**, 633–645 (2005).
73. Vos, K., Harley, M. D., Splinter, K. D., Simmons, J. A. & Turner, I. L. Sub-annual to multi-decadal shoreline variability from publicly available satellite imagery. *Coast. Eng.* **150**, 160–174 (2019).
74. Vandebroek, E. et al. Semi-automated monitoring of a mega-scale beach nourishment using high-resolution TerraSAR-X satellite data. *Remote Sens.* **9**, 653 (2017).
75. Silva, P. G., da, Coco, G., Garnier, R. & Klein, A. H. F. On the prediction of runup, setup and swash on beaches. *Earth-Sci. Rev.* **204**, 103148 (2020).
76. Almeida, L. P. et al. Deriving high spatial-resolution coastal topography from sub-meter satellite stereo imagery. *Remote Sens.* **11**, 590 (2019).
77. Wiggins, M., Scott, T., Masselink, G., Russell, P. & McCarroll, R. J. Coastal embayment rotation: Response to extreme events and climate control, using full embayment surveys. *Geomorphology* **327**, 385–403 (2019).
78. Shean, D. E. et al. An automated, open-source pipeline for mass production of digital elevation models (DEMs) from very-high-resolution commercial stereo satellite imagery. *ISPRS J. Photogramm. Remote Sens.* **116**, 101–117 (2016).
79. Magruder, L. et al. New Earth orbiter provides a sharper look at a changing planet. *Eos* https://doi.org/10.1029/2019EO133233 (2019).
80. Phillips, M. S., Blenkinsopp, C. E., Splinter, K. D., Harley, M. D. & Turner, I. L. Modes of berm and beachface recovery following storm reset: observations using a continuously scanning lidar. *J. Geophys. Res. Earth Surf.* **124**, 720–736 (2019).
81. Launeau, P. et al. Full-waveform LiDAR pixel analysis for low-growing vegetation mapping of coastal foredunes in Western France. *Remote Sens.* **10**, 669 (2018).
82. Deronde, B., Houthuys, R., Henriet, J. P. & Van Lancker, V. Monitoring of the sediment dynamics along a sandy shoreline by means of airborne hyperspectral remote sensing and LIDAR: a case study in Belgium. *Earth Surf. Process. Landf.* **33**, 280–294 (2008).
83. Matsumoto, H. & Young, A. P. Automated cobble mapping of a mixed sand-cobble beach using a mobile LiDAR system. *Remote Sens.* **10**, 1253 (2018).
84. Casella, E. et al. Mapping coral reefs using consumer-grade drones and structure from motion photogrammetry techniques. *Coral Reefs* **36**, 269–275 (2017).
85. Peeri, S., Gardner, J. V., Ward, L. G. & Morrison, J. R. The seafloor: A key factor in LiDAR bottom detection. *IEEE Trans. Geosci. Remote Sens.* **49**, 1150–1157 (2011).
86. Brodie, K. L. et al. Evaluation of video-based linear depth inversion performance and applications using altimeters and hydrographic surveys in a wide range of environmental conditions. *Coast. Eng.* **136**, 147–160 (2018).
87. Gawehn, M. et al. The application of a radar-based depth inversion method to monitor near-shore nourishments on an open sandy coast and an ebb-tidal delta. *Coast. Eng.* **159**, 103716 (2020).
88. Hoefel, F. & Elgar, S. Wave-induced sediment transport and onshore sandbar migration. *Science* **299**, 1885–1887 (2003).
89. Elko, N. et al. The future of nearshore processes research. *Shore Beach* **83**, 13–38 (2015).
90. Luijendijk, A. P., de Vries, S., van het Hooft, T. & de Schipper, M. A. in *Coastal Sediments 2019* (eds Wang, P., Rosati, J. D. & Vallee, M.) 1319–1326 (World Scientific, 2019).
91. Luijendijk, A. P., de Schipper, M. A. & Ranasinghe, R. Morphodynamic acceleration techniques for multi-timescale predictions of complex sandy interventions. *J. Mar. Sci. Eng.* **7**, 78 (2019).
92. Huisman, B. J. A., Walstra, D. J. R., Radermacher, M., de Schipper, M. A. & Ruessink, B. G. Observations and modelling of shoreface nourishment behaviour. *J. Mar. Sci. Eng.* **7**, 59 (2019).
93. Weathers, H. D. & Voulgaris, G. Evaluation of beach nourishment evolution models using data from two South Carolina, USA beaches: Folly Beach and Hunting Island. *J. Coast. Res.* **69**, 84–98 (2013).
94. Tonnon, P. K., Huisman, B. J. A., Stam, G. N. & van Rijn, L. C. Numerical modelling of erosion rates, life span and maintenance volumes of mega nourishments. *Coast. Eng.* **131**, 51–69 (2018).
95. Lesser, G. R., Roelvink, J. A., van Kester, J. A. T. M. & Stelling, G. S. Development and validation of a three-dimensional morphological model. *Coast. Eng.* **51**, 883–915 (2004).
96. Zyserman, J. A. & Johnson, H. K. Modelling morphological processes in the vicinity of shore-parallel breakwaters. *Coast. Eng.* **45**, 261–284 (2002).
97. Walstra, D. J. R., Reniers, A. J. H. M., Ranasinghe, R., Roelvink, J. A. & Ruessink, B. G. On bar growth and decay during interannual net offshore migration. *Coast. Eng.* **60**, 190–200 (2012).
98. Barnard, P. L. et al. Development of the Coastal Storm Modeling System (CoSMoS) for predicting the impact of storms on high-energy, active-margin coasts. *Nat. Hazards* **74**, 1095–1125 (2014).
99. Kalligeris, N., Smit, P. B., Ludka, B. C., Guza, R. T. & Gallien, T. W. Calibration and assessment of process-based numerical models for beach profile evolution in southern California. *Coast. Eng.* **158**, 103650 (2020).
100. Roelvink, D. et al. Modelling storm impacts on beaches, dunes and barrier islands. *Coast. Eng.* **56**, 1133–1152 (2009).

101. Huisman, B. J. A., Ruessink, B. G., de Schipper, M. A., Luijendijk, A. P. & Stive, M. J. F. Modelling of bed sediment composition changes at the lower shoreface of the Sand Motor. *Coast. Eng.* **132**, 33–49 (2018).
102. Kroon, A., de Schipper, M. A., van Gelder, P. & Aarninkhof, S. G. J. Ranking uncertainty: Wave climate variability versus model uncertainty in probabilistic assessment of coastline change. *J. Coast. Eng.* **158**, 103673 (2020).
103. Le Cozannet, G. et al. Quantifying uncertainties of sandy shoreline change projections as sea level rises. *Sci. Rep.* **9**, 42 (2019).
104. Baas, A. C. W. Simulating dune landscapes in vegetated environments. *Scenario* **6**, 1–22 (1997).
105. Ranasinghe, R. On the need for a new generation of coastal change models for the 21st century. *Sci. Rep.* **10**, 2010 (2020).
106. Anderson, W. P. & Lauer, R. M. The role of overwash in the evolution of mixing zone morphology within barrier islands. *Hydrogeol. J.* **16**, 1483–1495 (2008).
107. Terry, J. P. & Falkland, A. C. Responses of atoll freshwater lenses to storm-surge overwash in the Northern Cook Islands. *Hydrogeol. J.* **18**, 749–759 (2010).
108. Ataie-Ashtiani, B., Werner, A. D., Simmons, C. T., Morgan, L. K. & Lu, C. How important is the impact of land-surface inundation on seawater intrusion caused by sea-level rise? *Hydrogeol. J.* **21**, 1673–1677 (2013).
109. Morgan, L. K. & Werner, A. D. Seawater intrusion vulnerability indicators for freshwater lenses in strip islands. *J. Hydrol.* **508**, 322–327 (2014).
110. Ketabchi, H., Mahmoodzadeh, D., Ataie-Ashtiani, B. & Simmons, C. T. Sea-level rise impacts on seawater intrusion in coastal aquifers: Review and integration. *J. Hydrol.* **535**, 235–255 (2016).
111. Chang, S. W., Nemec, K., Kalin, L. & Clement, T. P. Impacts of climate change and urbanization on groundwater resources in a barrier island. *J. Environ. Eng.* **142**, D4016001 (2016).
112. White, I. & Falkland, T. Management of freshwater lenses on small Pacific islands. *Hydrogeol. J.* **18**, 227–246 (2010).
113. Oberle, F. K. J., Swarzenski, P. W. & Storlazzi, C. D. Atoll groundwater movement and its response to climatic and sea-level fluctuations. *Water* **9**, 650 (2017).
114. Befus, K. M., Barnard, P. L., Hoover, D. J., Finzi-Hart, J. A. & Voss, C. I. Increasing threat of coastal groundwater hazards from sea-level rise in California. *Nat. Clim. Change* **10**, 946–952 (2020).
115. Rotzoll, K. & Fletcher, C. H. Assessment of groundwater inundation as a consequence of sea-level rise. *Nat. Clim. Change* **3**, 477–481 (2013).
116. Habel, S., Fletcher, C. H., Anderson, T. R. & Thompson, P. R. Sea-level rise induced multi-mechanism flooding and contribution to urban infrastructure failure. *Sci. Rep.* **10**, 3796 (2020).
117. Huizer, S., Oude Essink, G. H. P. & Bierkens, M. F. P. Fresh groundwater resources in a large sand replenishment. *Hydrol. Earth Syst. Sci.* **20**, 3149–3166 (2016).
118. Huizer, S., Radermacher, M., de Vries, S., Oude Essink, G. H. P. & Bierkens, M. F. P. Impact of coastal forcing and groundwater recharge on the growth of a fresh groundwater lens in a mega-scale beach nourishment. *Hydrol. Earth Syst. Sci.* **22**, 1065–1080 (2018).
119. Robinson, C., Xin, P., Li, L. & Barry, D. A. Groundwater flow and salt transport in a subterranean estuary driven by intensified wave conditions. *Water Resour. Res.* **50**, 165–181 (2014).
120. Li, L., Cartwright, N., Nielsen, P. & Lockington, D. Response of coastal groundwater table to offshore storms. *China Ocean Eng.* **18**, 423–431 (2004).
121. Trglavcnik, V., Morrow, D., Weber, K. P., Li, L. & Robinson, C. E. Analysis of tide and offshore storm-induced water table fluctuations for structural characterization of a coastal island aquifer. *Water Resour. Res.* **54**, 2749–2767 (2018).
122. Housego, R. et al. *Barrier Island Groundwater* (ICCE, 2018).
123. Silva, F. G., Wijnberg, K. M., de Groot, A. V. & Hulscher, S. J. M. H. The influence of groundwater depth on coastal dune development at sand flats close to inlets. *Ocean Dyn.* **68**, 885–897 (2018).
124. Horn, D. P. Beach groundwater dynamics. *Geomorphology* **48**, 121–146 (2002).
125. Evans, T. B. & Wilson, A. M. Groundwater transport and the freshwater–saltwater interface below sandy beaches. *J. Hydrol.* **538**, 563–573 (2016).
126. Román-Sierra, J., Muñoz-Perez, J. J. & Navarro-Pons, M. Beach nourishment effects on sand porosity variability. *Coast. Eng.* **83**, 221–232 (2014).
127. Soares, A. G., McLachlan, A. & Schlacher, T. A. Disturbance effects of stranded kelp on populations of the sandy beach bivalve *Donax serra* (Röding). *J. Exp. Mar. Biol. Ecol.* **205**, 165–186 (1996).
128. Schlacher, T. A. et al. Sandy beach ecosystems: key features, sampling issues, management challenges and climate change impacts. *Mar. Ecol.* **29**, 70–90 (2008).
129. Schlacher, T. A. & Thompson, L. Environmental control of community organisation on ocean-exposed sandy beaches. *Mar. Freshw. Res.* **64**, 119–129 (2013).
130. Schlacher, T. A. & Thompson, L. Spatial structure on ocean-exposed sandy beaches: faunal zonation metrics and their variability. *Mar. Ecol. Prog. Ser.* **478**, 43–55 (2013).
131. Schoeman, D. S., Schlacher, T. A. & Defeo, O. Climate-change impacts on sandy-beach biota: crossing a line in the sand. *Glob. Change Biol.* **20**, 2383–2392 (2014).
132. Rafael Barboza, F. & Defeo, O. Global diversity patterns in sandy beach macrofauna: A biogeographic analysis. *Sci. Rep.* **5**, 14515 (2015).
133. Maslo, B. et al. Selecting umbrella species for conservation: A test of habitat models and niche overlap for beach-nesting birds. *Biol. Conserv.* **203**, 233–242 (2016).
134. Maslo, B. et al. Regional drivers of clutch loss reveal important trade-offs for beach-nesting birds. *PeerJ* **4**, e2460 (2016).
135. Schlacher, T. et al. The early shorebird will catch fewer invertebrates on trampled sandy beaches. *PLoS ONE* **11**, e0161905 (2016).
136. Olds, A. D. et al. The ecology of fish in the surf zones of ocean beaches: A global review. *Fish Fish.* **19**, 78–89 (2018).
137. Rae, C., Hyndes, G. A. & Schlacher, T. A. Trophic ecology of ghost crabs with diverse tastes: Unwilling vegetarians. *Estuar. Coast. Shelf Sci.* **224**, 272–280 (2019).
138. Schlacher, T. A. et al. Key ecological function peaks at the land–ocean transition zone when vertebrate scavengers concentrate on ocean beaches. *Ecosystems* **23**, 906–916 (2020).
139. Brown, A. Behavioural plasticity as a key factor in the survival and evolution of the macrofauna on exposed sandy beaches. *Rev. Chil. Hist. Nat.* **69**, 469–474 (1996).
140. Dugan, J. E. et al. Give beach ecosystems their day in the sun. *Science* **329**, 1146 (2010).
141. Manning, L. M., Peterson, C. H. & Fegley, S. R. Degradation of surf-fish foraging habitat driven by persistent sedimentological modifications caused by beach nourishment. *Bull. Mar. Sci.* **89**, 83–106 (2013).
142. Manning, L. M., Peterson, C. H. & Bishop, M. J. Dominant macrobenthic populations experience sustained impacts from annual disposal of fine sediments on sandy beaches. *Mar. Ecol. Prog. Ser.* **508**, 1–15 (2014).
143. Peterson, C. H., Bishop, M. J., D'Anna, L. M. & Johnson, G. A. Multi-year persistence of beach habitat degradation from nourishment using coarse shelly sediments. *Sci. Total Environ.* **487**, 481–492 (2014).
144. Schlacher, T. A. et al. Golden opportunities: a horizon scan to expand sandy beach ecology. *Estuar. Coast. Shelf Sci.* **157**, 1–6 (2015).
145. Barbier, E. B. et al. The value of estuarine and coastal ecosystem services. *Ecol. Monogr.* **81**, 169–193 (2011).
146. Defeo, O. et al. Threats to sandy beach ecosystems: a review. *Estuar. Coast. Shelf Sci.* **81**, 1–12 (2009).
147. Schlacher, T. A. et al. Sandy beaches at the brink. *Divers. Distrib.* **13**, 556–560 (2007).
148. Speybroeck, J. et al. Beach nourishment: an ecologically sound coastal defence alternative? A review. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **16**, 419–435 (2006).
149. Wooldridge, T., Henter, H. J. & Kohn, J. R. Effects of beach replenishment on intertidal invertebrates: A 15-month, eight beach study. *Estuar. Coast. Shelf Sci.* **175**, 24–33 (2016).
150. Schooler, N. K., Dugan, J. E. & Hubbard, D. M. No lines in the sand: Impacts of intense mechanized maintenance regimes on sandy beach ecosystems span the intertidal zone on urban coasts. *Ecol. Indic.* **106**, 105457 (2019).
151. Jones, A. R., Murray, A., Lasiak, T. A. & Marsh, R. E. The effects of beach nourishment on the sandy-beach amphipod *Exoediceros fossor*: impact and recovery in Botany Bay, New South Wales, Australia. *Mar. Ecol.* **29**, 28–36 (2008).
152. Schlacher, T. A., Noriega, R., Jones, A. & Dye, T. The effects of beach nourishment on benthic invertebrates in eastern Australia: impacts and variable recovery. *Sci. Total Environ.* **435–436**, 411–417 (2012).
153. Schlacher, T. A. & Thompson, L. M. C. Exposure of fauna to off-road vehicle (ORV) traffic on sandy beaches. *Coast. Manag.* **35**, 567–583 (2007).
154. Schlacher, T. A., Thompson, L. M. C. & Walker, S. J. Mortalities caused by off-road vehicles (ORVs) to a key member of sandy beach assemblages, the surf clam *Donax deltoides*. *Hydrobiologia* **610**, 345–350 (2008).
155. Sheppard, N., Pitt, K. A. & Schlacher, T. A. Sub-lethal effects of off-road vehicles (ORVs) on surf clams on sandy beaches. *J. Exp. Mar. Biol. Ecol.* **380**, 113–118 (2009).
156. Thompson, L. & Schlacher, T. Beach recreation impacts benthic invertebrates on ocean-exposed sandy shores. *Biol. Conserv.* **147**, 123–132 (2011).
157. Manzanera, M., Alcoverro, T., Jiménez, J. A. & Romero, J. The large penumbra: Long-distance effects of artificial beach nourishment on *Posidonia oceanica* meadows. *Mar. Pollut. Bull.* **86**, 129–137 (2014).
158. Convertino, M. et al. Anthropogenic renourishment feedback on shorebirds: a multispecies Bayesian perspective. *Ecol. Eng.* **37**, 1184–1194 (2011).
159. Martin, K. L. M. & Adams, L. C. Effects of repeated sand replenishment projects on runs of a beach-spawning fish, the California grunion. *J. Mar. Sci. Eng.* **8**, 178 (2020).
160. Van Tomme, J., Vanden Eede, S., Speybroeck, J., Degraer, S. & Vincx, M. Macrofaunal sediment selectivity considerations for beach nourishment programmes. *Mar. Environ. Res.* **84**, 10–16 (2013).
161. Peterson, C. H., Hickerson, D. H. M. & Johnson, G. G. Short-term consequences of nourishment and bulldozing on the dominant large invertebrates of a sandy beach. *J. Coast. Res.* **16**, 368–378 (2000).
162. Viola, S. M., Hubbard, D. M., Dugan, J. E. & Schooler, N. K. Burrowing inhibition by fine textured beach fill: implications for recovery of beach ecosystems. *Estuar. Coast. Shelf Sci.* **150**, 142–148 (2014).
163. Dugan, J. E., Airoldi, L., Chapman, M. G., Walker, S. J. & Schlacher, T. Estuarine and coastal structures: environmental effects, a focus on shore and nearshore structures. *Treatise Estuar. Coast. Sci.* **8**, 17–41 (2012).
164. Martins, G. M., Amaral, A. F., Wallenstein, F. M. & Neto, A. I. Influence of a breakwater on nearby rocky intertidal community structure. *Mar. Environ. Res.* **67**, 237–245 (2009).
165. van Egmond, E. M. et al. A mega-nourishment creates novel habitat for intertidal macroinvertebrates by enhancing habitat relief of the sandy beach. *Estuar. Coast. Shelf Sci.* **207**, 232–241 (2018).
166. Peterson, C. H., Bishop, M. J., Johnson, G. A., D'Anna, L. M. & Manning, L. M. Exploiting beach filling as an unaffordable experiment: benthic intertidal impacts propagating upwards to shorebirds. *J. Exp. Mar. Biol. Ecol.* **338**, 205–221 (2006).
167. Peterson, C. H. & Bishop, M. J. Assessing the environmental impacts of beach nourishment. *Bioscience* **55**, 887–896 (2005).
168. Brock, K. A., Reece, J. S. & Ehrhart, L. M. The effects of artificial beach nourishment on marine turtles: differences between loggerhead and green turtles. *Restor. Ecol.* **17**, 297–307 (2009).
169. Lithgow, D. et al. Linking restoration ecology with coastal dune restoration. *Geomorphology* **199**, 214–224 (2013).
170. Pranzini, E. et al. Sand colour at Cuba and its influence on beach nourishment and management. *Ocean Coast. Manag.* **126**, 51–60 (2016).
171. Greene, K. in *ASMFC Habitat Management Series # 7* 1–174 (Atlantic States Marine Fisheries Commission, 2002).
172. Bendixen, M., Best, J., Hackney, C. & Iversen, L. L. Time is running out for sand. *Nature* **571**, 29–31 (2019).
173. Peduzzi, P. Sand, rarer than one thinks. *Environ. Dev.* **11**, 208–218 (2014).
174. Haasnoot, M. et al. Adaptation to uncertain sea-level rise; how uncertainty in Antarctic mass-loss impacts the coastal adaptation strategy of the Netherlands. *Environ. Res. Lett.* **15**, 034007 (2020).
175. Vidal, R. & van Oord, G. Environmental impacts in beach nourishment: a comparison of options. *Terra Aqua* **19**, 14–20 (2010).

176. van der Bilt, V. Assessing emission performance of dredging projects. Master's thesis, Delft University of Technology, Faculty of Civil Engineering and Geosciences (2019).
177. Hoagland, P., Jin, D. & Kite-Powell, H. L. The costs of beach replenishment along the U.S. Atlantic Coast. *J. Coast. Res.* **278**, 199–204 (2012).
178. Hinkel, J. et al. A global analysis of erosion of sandy beaches and sea-level rise: An application of DIVA. *Glob. Planet. Change* **111**, 150–158 (2013).
179. CEDA. Effective contract-type selection in the dredging industry. A guidance paper. *Central Dredging Association (CEDA)* https://dredging.org/media/ceda/org/documents/resources/cedaonline/2019-12-ecs.pdf (2019).
180. SANDAG & Moffatt & Nichol. Feasibility study. San Diego regional beach sand replenishment project, San Diego, California. *SANDAG* http://www.sandag.org/uploads/publicationid/publicationid_1327_7318.pdf (2007).
181. Bendixen, M., Iversen, L. L. & Overeem, I. Greenland: Build an economy on sand. *Science* **358**, 879 (2017).
182. Boyd, S. E., Limpenny, D. S., Rees, H. L. & Cooper, K. M. The effects of marine sand and gravel extraction on the macrobenthos at a commercial dredging site (results 6 years post-dredging). *ICES J. Mar. Sci.* **62**, 145–162 (2005).
183. de Jong, M. F. et al. Impact on demersal fish of a large-scale and deep sand extraction site with ecosystem-based landscaped sandbars. *Estuar. Coast. Shelf Sci.* **146**, 83–94 (2014).
184. Jiao, S., Chen, X. & Du, Q. in *Proceedings of the 2011 International Conference on Electronics, Communications and Control (ICECC 2011)* 3604–3607 (ICECC, 2011).
185. Parkinson, R. W. & Ogurcak, D. E. Beach nourishment is not a sustainable strategy to mitigate climate change. *Estuar. Coast. Shelf Sci.* **212**, 203–209 (2018).
186. Goncalves Castro, M. B., Mestemaker, B. T. W. & Van Den Heuvel, H. in *International Conference on Modelling and Optimisation of Ship Energy Systems* (2019).
187. Pendleton, L., Mohn, C., Vaughn, R. K., King, P. & Zoulas, J. G. Size matters: The economic value of beach erosion and nourishment in Southern California. *Contemp. Econ. Policy* **30**, 223–237 (2012).
188. Todd, D. J. & Bowa, K. Development of beach health index for the Gold Coast, Australia. *J. Coast. Res.* **75**, 710–714 (2016).
189. Muller, M. W. Beach replenishment and surf-zone injuries along the coast of Delmarva, USA. *Ocean Coast. Manag.* **151**, 127–133 (2018).
190. de Zeeuw, R. C., de Schipper, M. A., Roelvink, D., de Vries, S. & Stive, M. J. F. in *Proceedings of the Coastal Engineering Conference* (2012).
191. de Schipper, M. A. et al. in *Coastal Dynamics 2013: 7th International Conference on Coastal Dynamics, Arcachon, France* (Bordeaux University, 2013).
192. Fletemeyer, J., Hearin, J., Haus, B. & Sullivan, A. The impact of sand nourishment on beach safety. *J. Coast. Res.* **341**, 1–5 (2018).
193. Dally, W. R. & Osiecki, D. A. Evaluating the impact of beach nourishment on surfing: Surf City, Long Beach Island, New Jersey, U.S.A. *J. Coast. Res.* **344**, 793–805 (2018).
194. Corne, N. P. The implications of coastal protection and development on surfing. *J. Coast. Res.* **25**, 427–434 (2009).
195. Albada, E., Goshow, C. & Dompe, P. Effect of beach nourishment on surfing – observations from the St. Johns county shore protection project. *Florida Shore and Beach Preservation Association (FSBPA)* https://fsbpa.com/07Proceedings/05Albada2007.pdf (2007).
196. Miller, J. K., Mahon, A. M. & Herrington, T. O. in *Proceedings of the Coastal Engineering Conference* 1–15 (2010).
197. Gopalakrishnan, S., Smith, M. D., Slott, J. M. & Murray, A. B. The value of disappearing beaches: A hedonic pricing model with endogenous beach width. *J. Environ. Econ. Manage.* **61**, 297–310 (2011).
198. Lazarus, E. D., McNamara, D. E., Smith, M. D., Gopalakrishnan, S. & Murray, A. B. Emergent behavior in a coupled economic and coastline model for beach nourishment. *Nonlinear Process. Geophys.* **18**, 989–999 (2011).
199. Murray, A. B., Gopalakrishnan, S., McNamara, D. E. & Smith, M. D. Progress in coupling models of human and coastal landscape change. *Comput. Geosci.* **53**, 30–38 (2013).
200. Lazarus, E. D., Ellis, M. A., Murray, A. B. & Hall, D. M. An evolving research agenda for human-coastal systems. *Geomorphology* **256**, 81–90 (2016).
201. USACE. *New Directions in Water Resources Planning for the U.S. Army Corps of Engineers* (National Academies Press, 1999).
202. Parsons, G. R., Massey, D. M. & Tomasi, T. Familiar and favorite sites in a random utility model of beach recreation. *Mar. Resour. Econ.* **14**, 299–315 (1999).
203. Costa, M. F. & Kahn, J. R. Boa Viagem erosion prevention and beach nourishment project. *IX Congr. da Assoc. Bras. Estud. do Quaternário* (2003).
204. Nordstrom, K. F., Pranzini, E., Jackson, N. L. & Coli, M. The marble beaches of Tuscany. *Geogr. Rev.* **98**, 280–300 (2008).
205. Asensio-Montesinos, F. et al. The origin of sand and its colour on the south-eastern coast of Spain: Implications for erosion management. *Water* **12**, 377 (2020).
206. Gopalakrishnan, S., McNamara, D., Smith, M. D. & Murray, A. B. Decentralized management hinders coastal climate adaptation: the spatial-dynamics of beach nourishment. *Environ. Resour. Econ.* **67**, 761–787 (2017).
207. Martinich, J., Neumann, J., Ludwig, L. & Jantarasami, L. Risks of sea level rise to disadvantaged communities in the United States. *Mitig. Adapt. Strateg. Glob. Chang.* **18**, 169–185 (2013).
208. Whitehead, J. C., Dumas, C. F., Herstine, J., Hill, J. & Buerger, B. Valuing beach access and width with revealed and stated preference data. *Mar. Resour. Econ.* **23**, 119–135 (2008).
209. Masselink, G., Russell, P., Rennie, A., Brooks, S. & Spencer, T. Impacts of climate change on coastal geomorphology and coastal erosion relevant to the coastal and marine environment around the UK. *MCCIP Sci. Rev.* https://doi.org/10.14465/2020.arc08.cgm (2020).
210. Verhagen, H. J. Analysis of beach nourishment schemes. *J. Coast. Res.* **12**, 179–185 (1996).
211. Dean, R. G. & Yoo, C. H. Beach-nourishment performance predictions. *J. Waterw. Port Coast. Ocean Eng.* **118**, 567–586 (1992).
212. Pan, Y. et al. Performance evaluation of a beach nourishment project at West Beach in Beidaihe, China. *J. Coast. Res.* **27**, 769–783 (2011).
213. Raybould, M. & Mules, T. A cost–benefit study of protection of the northern beaches of Australia's Gold Coast. *Tour. Econ.* **5**, 121–139 (1999).
214. Shin, B. S. & Kim, K. H. in *Proceedings of the 7th International Conference on Asian and Pacific Coasts (APAC 2013)* 69–74 (APAC, 2013).
215. Martino, S. & Amos, C. L. Valuation of the ecosystem services of beach nourishment in decision-making: The case study of Tarquinia Lido, Italy. *Ocean Coast. Manag.* **111**, 82–91 (2015).
216. Murcia, C. et al. A critique of the 'novel ecosystem' concept. *Trends Ecol. Evol.* **29**, 548–553 (2014).
217. Temmerman, S. et al. Ecosystem-based coastal defence in the face of global change. *Nature* **504**, 79–83 (2013).
218. Hinkel, J. et al. The ability of societies to adapt to twenty-first-century sea-level rise. *Nat. Clim. Chang.* **8**, 570–578 (2018).
219. Hauer, M. E. Migration induced by sea-level rise could reshape the US population landscape. *Nat. Clim. Chang.* **7**, 321–325 (2017).
220. Hauer, M. E. et al. Sea-level rise and human migration. *Nat. Rev. Earth Environ.* **1**, 28–39 (2020).
221. Oppenheimer, M. et al. Chapter 4: Sea Level Rise and Implications for Low Lying Islands, Coasts and Communities. *IPCC* **355**, 126–129 (2019).
222. Griffith, A. D., Coburn, A. S., Peek, K. M. & Young, R. S. in *Learning from the Impacts of Superstorm Sandy* (eds Bret Bennington, J. & Farmer, E. C.) 57–68 (Academic Press, 2014).
223. Stephens, S. A., Bell, R. G. & Lawrence, J. Developing signals to trigger adaptation to sea-level rise. *Environ. Res. Lett.* **13**, 10 (2018)
224. Griggs, G. & Kinsman, N. Beach widths, cliff slopes, and artificial nourishment along the California coast. *Shore* **84**, 1–12 (2016).
225. Gontz, A. M., Moss, P. T. & Wagenknecht, E. K. Stratigraphic architecture of a regressive strand plain, flinders beach, north Stradbroke Island, Queensland, Australia. *J. Coast. Res.* **30**, 575–585 (2014).
226. Bingham, E. L. et al. Functional plasticity in vertebrate scavenger assemblages in the presence of introduced competitors. *Oecologia* **188**, 583–593 (2018).
227. Jackson, A., Hill, P. & McGrath, J. A history of the implementation and evolution of sand nourishment methods on the Gold Coast, Australia. *Coasts Ports* **2013**, 418–423 (2013).
228. Turner, I. L. et al. Predicted and observed coastline changes at the Gold Coast artificial reef. *Coast. Eng.* **2000**, 1836–1847 (2001).
229. de Boer, W. et al. Understanding coastal erosion processes at the Korean east coast. *Proc. Coast. Dyn.* **2017**, 1336–1347 (2017).
230. Chang, J. I. & Yoon, S. The economic benefit of coastal erosion control in Korea. *J. Coast. Res.* **1**, 1317–1321 (2016).
231. Kim, K.-H., Yoo, H.-S. & Kobayashi, N. Mitigation of beach erosion after coastal road construction. *J. Coast. Res.* **27**, 645–651 (2011).
232. Ok, H. Y., Ho, Y. S. & Suh, H. L. Seasonal zonation patterns of benthic amphipods in a sandy shore surf zone of Korea. *J. Crustac. Biol.* **22**, 459–466 (2002).
233. Kabat, P. et al. Dutch coasts in transition. *Nat. Geosci.* **2**, 450–452 (2009).
234. Janssen, G. M., Leewis, L. & Marx, S. in *Sandy Beaches and Coastal Zone Management – Proceedings of the Fifth International Symposium on Sandy Beaches* 121–123 (2011).
235. Leewis, L., van Bodegom, P. M., Rozema, J. & Janssen, G. M. Does beach nourishment have long-term effects on intertidal macroinvertebrate species abundance? *Estuar. Coast. Shelf Sci.* **113**, 172–181 (2012).
236. Stronkhorst, J., Huisman, B., Giardino, A., Santinelli, G. & Santos, F. D. Sand nourishment strategies to mitigate coastal erosion and sea level rise at the coasts of Holland (The Netherlands) and Aveiro (Portugal) in the 21st century. *Ocean Coast. Manag.* **156**, 226–276 (2018).

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