

## Beach nourishment has complex implications for the future of sandy shores

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

**DOI**

[10.1038/s43017-020-00109-9](https://doi.org/10.1038/s43017-020-00109-9)

**Publication date**

2021

**Document Version**

Accepted author manuscript

**Published in**

Nature Reviews Earth and Environment

**Citation (APA)**

de Schipper, M. A., Ludka, B. C., Raubenheimer, B., Luijendijk, A. P., & Schlacher, T. A. (2021). Beach nourishment has complex implications for the future of sandy shores. *Nature Reviews Earth and Environment*, 2(1), 70-84. <https://doi.org/10.1038/s43017-020-00109-9>

**Important note**

To cite this publication, please use the final published version (if applicable).  
Please check the document version above.

**Copyright**

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

**Takedown policy**

Please contact us and provide details if you believe this document breaches copyrights.  
We will remove access to the work immediately and investigate your claim.

1 **Beach nourishment has complex implications for the future of sandy shores**

2

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

4 Schlacher

5 \*email: [m.a.deschipper@tudelft.nl](mailto:m.a.deschipper@tudelft.nl)

6 **Abstract**

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

21

22 **Table of contents summary**

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

## 28 [H1] Introduction

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

36  
37 A beach sand nourishment, also referred to as a sand replenishment or beach fill, is a coastal  
38 engineering and management project that mechanically increases the size of the above-water  
39 beach using off-site sand<sup>6</sup>. Sandy beach nourishment is widely used in coastal communities to  
40 promote tourism and protect infrastructure from flooding and erosion<sup>6</sup> (Fig. 1) . Additionally,  
41 these nourishments may be used to increase habitat for beach (foraging) species<sup>7-9</sup>, repair storm  
42 damage<sup>10</sup>, and dispose of dredged sediments, such as those from navigation channels. Projects  
43 can be implemented with the intent to grow or hold a shoreline in place, or as part of a  
44 managed retreat plan<sup>11</sup> that aims to slow erosion to allow for landward redevelopment<sup>11</sup>. Sand  
45 can be placed directly at the site of the identified local need (**Fig. 1a**), or updrift as part of a  
46 larger regional approach that utilizes natural transport pathways to address sand needs along  
47 the coast<sup>12,13</sup>.

48  
49 Nourishment can be preferred over hard structural engineering, such as jetties, seawalls, groynes  
50 and breakwaters, as it is less disruptive of natural sediment pathways<sup>14</sup>. Seawalls, for example,  
51 typically reduce sand supplies from cliff-bluff-failures and can drown the beach when  
52 constructed on shorelines experiencing decadal landward migration<sup>15,16</sup>. Jetties, groynes and  
53 breakwaters alter current-driven sand transport within the coastal cell, leaving adjacent beaches  
54 starved of sand<sup>17</sup>. Sometimes hard structures are combined with nourishments (**Fig. 1b,c**) with  
55 the intention to slow sand transport away from the original placement region and/or  
56 surrounding area<sup>10,18-20</sup>.

57

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

68

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

85 stimulate wind-blown dune growth that can provide ecological habitat as well as flood and  
86 groundwater protection (**Fig. 1d**).

87

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

95

## 96 **[H1] Beach sand nourishment**

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

106

107 Here, we focus on nourishments that add sand (non-cohesive sediments in the size range  
108 0.062 – 2 mm) to open, ocean-exposed beaches where the majority of the sand volume is placed  
109 above the mean water line. The sand can be positioned on the upper beach including dunes  
110 and/or near the waterline, and can (partly) extend onto the underwater beach (**Fig. 1**). After  
111 placement, the sand is sometimes tilled to attain desired beach surface properties. Over time,  
112 waves, currents and wind move the added sand away from the original placement site, so

113 repetitive nourishments, typically placed every few years, are often planned to maintain sand  
114 volumes on the beach over longer periods of time. Occasionally, hard engineering structures are  
115 constructed to enclose nourishment sand on the lateral or offshore side<sup>10,19,20</sup> (**Fig. 1b**), or are  
116 erected nearby in the littoral cell to partially trap nourishment sand in adjacent regions (**Fig. 1c**).  
117 Sandy beach nourishments are widely practiced globally<sup>13,14,18,21,37-42</sup> and observed lifetimes  
118 range from individual storms (days) to decades<sup>14,43-45</sup>. In this section, we discuss the  
119 redistribution of sand, followed by the monitoring and modeling of sand dynamics.

120

## 121 **[H2] Sand redistribution**

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

131

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

142

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

153

154 As the placement region erodes, additional morphological features such as spits, scarps, and  
155 crowns can form (**Fig. 2c-e**). Scarps, near-vertical abrupt height variations on the beach profile,  
156 can be created by storm waves that erode, but do not overtop, the nourishment crest<sup>58</sup> (**Fig.**  
157 **2d,e**). Similar to dunes, beach scarps are removed during storms when water levels overtop the  
158 crest<sup>59</sup>. Scarp heights can reach ~2m creating a hazard for beachgoers and impeding turtle  
159 nesting<sup>60</sup>. At flat-topped nourishments constructed with sand that is coarser than the native  
160 sand, scarps can evolve into crowns as waves deposit sand on the seaward side of the platform  
161 (**Fig. 2f**). The local elevation maximum of the crowns can cause water to pool in the backbeach<sup>53</sup>.  
162 In the longshore direction, spit-like features can form along the seaward ends of a nourishment  
163 pad (**Fig. 2a,c**) due to large sand transport gradients induced by coastline angles at the up and  
164 down-coast edges<sup>43</sup>. Tapered edges are often designed to minimize spit development when  
165 sand retention in the original placement area is desired, although spit development has been  
166 observed on nourishments with tapered edges<sup>53</sup>. In contrast, spit development was intentionally  
167 stimulated as part of the 'Sand Engine' mega-nourishment design to create a sheltered lagoon  
168 and habitat for juvenile flatfish and invertebrates<sup>26</sup> (**Fig. 1e**).

169

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

188

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

198



## 199 [H2] Monitoring sand redistribution at beach nourishments

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

217  
218 Techniques to monitor nourishment sand redistribution are evolving<sup>69</sup>—all-terrain-vehicles  
219 equipped with survey-grade Global Navigation Satellite Systems, real-time kinematic  
220 corrections, and inertial measurement units largely replaced traditional rod and level surveys at  
221 the turn of the last century<sup>70</sup>. These technologies drastically increased spatial resolution and  
222 span while maintaining <10 cm horizontal and vertical accuracy<sup>52,53</sup>. Above-water mapping  
223 technologies often are combined with sonar on boats and personal watercraft for measurements  
224 of the underwater beach. As bubbles and suspended sediment can sometimes obscure the  
225 sonar signal in the shallow water surf-zone, dollies pushed to wading depths or large  
226 amphibious vehicles are used to help ensure continuous measurements across the  
227 profile<sup>52,53,68,71</sup>.

228

229 In the past decade, remote sensing imaging systems have further expanded data collection  
230 capabilities. These can be mounted on fixed (towers, rooftops)<sup>72</sup> or mobile platforms (drones,  
231 airplanes, satellites)<sup>69</sup>. Monocular (single viewing angle) imagery using optical cameras<sup>1,72-74</sup> or  
232 cloud penetrating radar<sup>75</sup> are used to detect the horizontal location of the land-water  
233 intersection of the nourishment and adjacent beaches. These systems can provide long time  
234 series at remote locations with small operational costs, although, owing to uncertainties  
235 (especially such as those in estimating water levels<sup>76</sup>), this method works best when shoreline  
236 migration is large (many 10's of meters for satellite systems<sup>74</sup>). Newer remote imaging  
237 technologies that measure the 3-D beach surface provide more accuracy than monocular  
238 imagery, which relies on the detection of the land-water intersection. For example,  
239 photogrammetric methods (such as structure from motion) reconstruct a 3-D surface from  
240 multiple photographs with different viewing angles<sup>77-79</sup>. Laser scanning<sup>67</sup> (lidar) is generally the  
241 most expensive and accurate remote sensing technique<sup>80,81</sup>, and can provide full wave-form  
242 information useful for resolving different surface layers (such as vegetation on a dune<sup>82</sup>). These  
243 3-D datasets, including true color information of the surface, open new opportunities to identify  
244 beach characteristics (such as distinguishing between native and nourishment sand<sup>83</sup> and cobble  
245 coverage<sup>84</sup>).

246

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

254

255 We envision that as the spaceborne photogrammetry and laser altimetry records grow, they will  
256 be especially transformative for our field. Satellites are providing time-continuous global

257 coverage of sand levels with accuracy on the order of cm's<sup>77,79,80</sup>, which will help map sand  
258 redistribution, expand our understanding of geomorphological processes and enhance our  
259 ability to develop or calibrate numerical models.

260

261

## 262 **[H1] Modeling beach nourishments**

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

277

278 Sand redistribution models range from simple to complex. In their simplest form, coastline  
279 models estimate the shoreline position by schematizing the along-coast sand redistribution as a  
280 diffusion (shoreline smoothing) process where the shoreline orientation relative to the incident  
281 wave conditions governs the alongshore transports over time<sup>94</sup>. When calibrated, these  
282 computationally fast models can provide information on beach change of the largest of scales  
283 (years, kms)<sup>95</sup>. Hybrid models can improve upon coastline model physics by accounting for the  
284 effect of realistic complex bathymetry (such as nearshore canyons or rocky platforms) on wave  
285 propagation. To represent multiple specific details of the nourishment beyond the shape of the

286 coastline (like variations in planform shape), and to provide information needed for ecological  
287 and recreational assessments (including sediment sorting, shells, and spit formation) more  
288 complex models are needed based on the upscaling of processes (process-based modelling)<sup>e.g.</sup>  
289 <sup>96,97</sup>.

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

298  
299 Planform process-based models have a domain that extends both alongshore and cross-shore,  
300 but have limited resolution in the water column<sup>92,101</sup>. Recent planform model computations are  
301 apt at reproducing the multi-year evolution (both erosion and accretive sand volumes) of a  
302 mega beach nourishment<sup>47,92</sup> (**Fig. 2g-n**). However, these models have yet to be rigorously  
303 tested in the peer-reviewed literature on beach nourishments of a more typical size. The latest  
304 process-based numerical models have the ability to differentiate between sediment of different  
305 grain sizes at a project site. For example, these models can be used to examine nourishments  
306 with different grain sizes than the surrounding (native) sand and may be able to reproduce the  
307 coarsening of the sand as fines are transported out of the area<sup>102</sup>. Sufficient high-quality  
308 sediment composition data is needed to further develop and test these grain size specific  
309 transports.

310  
311 Uncertainties in model forecasts arise both from the forcing (such as wave, wind, water level  
312 conditions) and model limitations. For instance, at the well monitored Sand Engine mega-  
313 nourishment, model parameter uncertainty was found to be comparable to the uncertainty in  
314 future wave forcing conditions (wind, waves, currents) for a 2.5 year calibrated coastline position  
315 model that forecasted an additional 2.5 years<sup>103</sup>. For 50- to 100-year predictions of shoreline

316 location on erodible coastlines, the model framework for how the beach responds to sea level  
317 rise dictates the uncertainty in the modeling outcome more than any other factor. In other  
318 words, model choice outweighs the climate change scenario, sea level rise, sand supply, vertical  
319 ground motions and wave-driven shoreline response<sup>98</sup> in determining the output.  
320 Computational power has increased such that if model skill was improved, probabilistic  
321 approaches with a large number of (ensemble) forcing conditions could help coastal planners  
322 navigate nourishment decisions in the face of uncertain sea level rise, and changing wave and  
323 weather conditions<sup>104</sup>. In the meantime, models are only reliable when they have been site-  
324 specifically calibrated and validated, and when the forecasted conditions are similar to those  
325 that were used in calibration and validation<sup>47</sup>. As sufficient calibration data is often lacking,  
326 nourishment designs are still done in a pragmatic manner, relying on both numerical model  
327 output and expert judgment.

328  
329 A promising development in morphodynamic modelling of nourishments is the inclusion of  
330 additional spatial domains and disciplines, such as groundwater<sup>104</sup> and vegetation<sup>105</sup> models. For  
331 example, connecting wave transport models with wind transport models has been important in  
332 long term predictions, as it accounts for transport of sediment towards the dunes and aeolian  
333 infilling of nourishment waterbodies<sup>91</sup> (**Fig. 2n**). However, given the difficulty in modeling  
334 sediment transport, numerical models of nourishment response will likely continue to be highly  
335 parameterized with incomplete physics for some time. Therefore, research comparing the  
336 performance of more complex models to simple models is needed to assess when the  
337 added complexity and computational demands are warranted<sup>106</sup>, and observations will continue  
338 to be essential for model testing.

339  
340

### 341 **[H1] Groundwater impacts**

342 Changes to aquifers below beaches and dunes are increasingly considered as part of coastal  
343 zone management practices as these impact flooding and fresh water quantities. For example,  
344 storms can cause groundwater salinization<sup>107-111</sup>—especially concerning for low-lying islands

345 with limited freshwater supplies such as the barrier islands along subsiding coasts<sup>112</sup> and Pacific  
346 atolls<sup>113-114</sup>—and contribute to coastal flooding<sup>115</sup>. For example, a sea level rise model  
347 assessment for urban Honolulu, Hawaii (USA) at the end of the century, found that including  
348 groundwater processes doubles the size of the flood-prone area compared to when considering  
349 marine inundation alone<sup>116,117</sup>.

350

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

366

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

373

## 374 [H1] Ecological Impacts

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

387

388 Detrimental impacts of nourishment<sup>149-151</sup> largely concern the loss of ecological features during  
389 nourishment construction. Most of these reductions are in the number of species and  
390 individuals, often for invertebrates buried in the sand, but also for birds and fishes. The  
391 mechanisms are varied (**Fig. 4c-f**), but processes commonly identified during construction  
392 include burial and suffocation under a sand layer that exceeds the capacity to burrow  
393 upwards<sup>152,153</sup> and mechanical crushing by heavy machinery, functionally similar to the crushing  
394 effects by off-road vehicles driven over beach invertebrates buried in the sand<sup>154-157</sup>.

395 Increased water turbidity from nourishment operations that bring fine material into suspension  
396 and the suspended silt can clog the delicate feeding structures of filter-feeding invertebrates  
397 (such as clams)<sup>143</sup>; more turbid surf-zone waters can also limit prey detection and thereby impair  
398 feeding by fish<sup>142</sup> (**Fig. 4e**). These impacts can extend beyond the immediate spatial footprint to  
399 affect adjacent systems (including reefs and seagrass meadows) several kilometers away through  
400 turbidity plumes<sup>158</sup>.

401

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

408  
409 Hard structures used in combination with nourishments can additionally impact ecosystems. For  
410 example groynes can trap higher volumes of wrack (such as algae and seagrasses) on the updrift  
411 side, while reducing accumulations downdrift<sup>167</sup>. Wave-sheltering provided by breakwaters can  
412 shift communities from consumer- to producer-dominated systems<sup>168</sup>. Furthermore, hard  
413 structures can create barriers to the transport of mobile animals living on the ocean floor and to  
414 the dispersal of propagules<sup>167</sup>.

415  
416 From an ecological perspective, the best nourishment would be the nourishment that does  
417 minimal harm to the pre-nourishment habitat, restores ecological values lost due to previous  
418 human activities and, depending on the local views on ecology, creates new habitats<sup>169</sup>.  
419 Information gaps remain that limit our ability to design more environmentally benign strategies,  
420 or create habitat opportunities with engineering works. Primarily, the trajectories of recovery  
421 and the thresholds of habitat change that species and assemblages can biologically  
422 accommodate are unknown. Put another way, what is the biological 'dose-response curve' of  
423 beach engineering works? Ecological impacts are often measured by comparing (unimpacted)  
424 control regions with impact areas. Understanding the large scale, long-term (natural) variation in  
425 species (species richness, biomass, and abundance) and habitat (such as water quality and  
426 turbidity) is vital for contextualizing nourishment impacts. Reported recovery times vary widely,  
427 from weeks<sup>152</sup> to several years<sup>144,165</sup>. There is little consensus on impact and recovery, mainly  
428 because almost all ecological studies are much too short (generally months), limiting our ability  
429 to make robust inferences about impacts and recovery<sup>164</sup>.

430



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

448

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

456

457 **[H1] Broader impacts**

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

461

## 462 [H2] Sand mining

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

479

480 The pressure on sand as a resource is reflected in nourishment costs, which are primarily  
481 governed by the distance between the borrow (extraction) location and the nourishment  
482 (placement) location, as well as the nourishment execution method and sand volume<sup>177-179</sup>. In  
483 some projects where borrow areas are close, such as the shallow nearshore seabed and/or  
484 nearby inlets or harbors that are dredged frequently, the cost of sand can be lower than 5 US\$  
485 per m<sup>3</sup> (Textbox 1). At locations with limited sand resources of a suitable size (such as Florida,  
486 USA or Singapore), long travel distances may raise the price of sand to 200 US\$ per m<sup>3</sup>, making  
487 sand trading a part of international disputes<sup>175,180</sup>. Global nourishment costs might reach

488 hundreds of billions in US\$ per year before the end of the century<sup>181</sup>. Government regulations  
489 and contract type (such as Construct only or Design & Construct) can also drastically influence  
490 sand pricing<sup>182</sup>. For example, the reported Dutch nourishment sand prices are often based on  
491 construction costs only, without having to acquire permits or purchase the sand. In contrast,  
492 engineering and environmental assessments required to obtain a permit for sand extraction in  
493 California can cost hundreds of thousands to millions of US\$, such that total nourishment costs  
494 can be raised by ~40%<sup>183</sup>.

495

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

505

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

516

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

525

## 526 **[H2] Recreational impacts**

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

545

546 **[H2] Social and Economic impacts**

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

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

572 Given limited sand resources, difficult decisions will arise about which beach will be saved by  
573 frequent nourishments<sup>180</sup>. With property values being higher behind wider beaches (or else

574 being equal)<sup>199</sup>, investments to restore and widen beaches can presumably be higher in more  
575 affluent beach communities<sup>181</sup>. Therefore, upholding principles of social justice in democratic  
576 systems calls for equitable regulated approaches to decision-making in beach restoration<sup>208,209</sup>.  
577 These approaches should use valuation methods that are inclusive of non-local beach users,  
578 who in many cases cannot afford to live near the coast. If beach nourishments are installed using  
579 (in part) public funds, inclusion can be implemented in the design, for example by requiring  
580 public access every half mile after the construction of a beach nourishment<sup>210</sup>.  
581 Furthermore, it is possible that some beaches might be able to migrate landward with sea level  
582 rise, but would drown when backed by hard structures. Interesting questions are thus posed  
583 about whether to prioritize making way for the migrating beach (often a public asset), or  
584 protecting existing (often private) coastal infrastructure in place. Nourishment could be useful  
585 for either purpose<sup>211</sup>, although more research is needed to assess effectiveness and feasibility.  
586 Communities might choose to restore different local beaches for different purposes, and  
587 designs could be optimized accordingly, for instance a nourishment for surfing at one location,  
588 with another for sunbathing elsewhere.

589

### 590 **[H1] Integrating perspectives**

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

603 combined with site specific calibration and validation, can offer useful guidance throughout the  
604 decision making process.

605

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

618

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

631

632 **[H1] Future directions**

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

645

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

655

656 We identify three broad needs in coastal nourishment science: a better quantitative  
657 understanding of sediment transport processes, particularly the fluxes of sediment in the cross-  
658 shore direction between dunes and deep water; threshold levels for ecological impacts, in other  
659 words, the magnitude of habitat change above which we regularly observe significant ecological  
660 harm attributable to engineering works; and the groundwater response to changing beach



661 profiles, including expansion of freshwater resources and impacts on inland flooding, sediment  
662 transport (by exfiltration, for example), and growth of vegetation (which can stabilize dunes and  
663 other features<sup>124</sup>). Moreover, natural, engineered and sea level rise scenarios must be  
664 intercompared to inform management decisions, where observations are critical to assess  
665 models. Paleoclimate records and observations of beaches experiencing unusually large relative  
666 sea level rise could provide insight as to how projected sea level rise is to affect different  
667 beaches in the future, and should be further integrated with modelled projections of coastal  
668 response

669

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

680

#### 681 **Affiliations**

682 M.A. de Schipper (Delft University of Technology, Delft, The Netherlands)

683 B.C. Ludka (Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA,  
684 United States)

685 B. Raubenheimer (Woods Hole Oceanographic Institution, Woods Hole, MA, United States)

686 A.P. Luijendijk (Deltares, Delft University of Technology, Delft, the Netherlands)

687 T. A. Schlacher (USC – University of the Sunshine Coast, Australia)

688

689

690

691 **References**

- 692 1. Luijendijk, A. *et al.* The State of the World's Beaches. *Sci. Rep.* **8**, 1–11 (2018).
- 693 2. Merkens, J. L., Reimann, L., Hinkel, J. & Vafeidis, A. T. Gridded population projections for  
694 the coastal zone under the Shared Socioeconomic Pathways. *Glob. Planet. Change* **145**,  
695 57–66 (2016).
- 696 3. Ranasinghe, R., Callaghan, D. & Stive, M. J. F. Estimating coastal recession due to sea level  
697 rise: Beyond the Bruun rule. *Clim. Change* **110**, 561–574 (2012).
- 698 4. Voudoukas, M. I. *et al.* Sandy coastlines under threat of erosion. *Nat. Clim. Chang.* **10**,  
699 260–263 (2020).
- 700 5. Nicholls, R. J. Planning for the impacts of sea level rise. *Oceanography* **24**, 144–157 (2011).
- 701 6. Dean, R. G. *Beach Nourishment: theory and Practice.* (World Scientific Publishing  
702 Company, 2003).
- 703 7. Montague, C. L. Nesting Beaches Ecological Engineering of Inlets in Southeastern Florida :  
704 Design Criteria for Sea Turtle Nesting Beaches. 267–276 (1993).
- 705 8. Li, S. *et al.* A comparison of coastal habitat restoration projects in China and the United  
706 States. *Sci. Rep.* **9**, 1–10 (2019).
- 707 9. van der Meulen, F., van der Valk, B., Vertegaal, K. & van Eerden, M. 'Building with nature'  
708 at the Dutch dune coast: compensation target management in Spanjaards Duin at EU and  
709 regional policy levels. *J. Coast. Conserv.* **19**, 707–714 (2015).
- 710 10. Leonard, L., Clayton, T. D., Dixon, K. & Pilkey, O. H. U.S. beach replenishment experience: a  
711 comparison of the Atlantic, Pacific and Gulf coasts. *J. Coast. Res.* 127–140 (1989).
- 712 11. Hino, M., Field, C. B. & Mach, K. J. Managed retreat as a response to natural hazard risk.

- 713 *Nat. Clim. Chang.* **7**, 364–370 (2017).
- 714 12. Castelle, B., Turner, I. L., Bertin, X. & Tomlinson, R. Beach nourishments at Coolangatta Bay  
715 over the period 1987–2005: Impacts and lessons. *Coast. Eng.* **56**, 940–950 (2009).
- 716 13. Cooke, B. C., Jones, A. R., Goodwin, I. D. & Bishop, M. J. Nourishment practices on  
717 Australian sandy beaches: A review. *J. Environ. Manage.* **113**, 319–327 (2012).
- 718 14. Hanson, H. *et al.* Beach nourishment projects, practices, and objectives - A European  
719 overview. *Coast. Eng.* **47**, 81–111 (2002).
- 720 15. Young, A. P. *et al.* Coarse Sediment Yields from Seacliff Erosion in the Oceanside Littoral  
721 Cell. *J. Coast. Res.* **263**, 580–585 (2010).
- 722 16. Fletcher, C. H., Richmond, B. M. & Mullane, R. A. Beach loss along armored shorelines on  
723 Oahu, Hawaiian Islands. *J. Coast. Res.* **13**, 209–215 (1997).
- 724 17. Bruun, P. The development of downdrift erosion. *J. Coast. Res.* (1995).
- 725 18. Luo, S., Liu, Y., Jin, R., Zhang, J. & Wei, W. A guide to coastal management: Benefits and  
726 lessons learned of beach nourishment practices in China over the past two decades.  
727 *Ocean Coast. Manag.* **134**, 207–215 (2016).
- 728 19. Lanza, S. & Randazzo, G. Tourist-beach protection in north-eastern Sicily (Italy). *J. Coast.*  
729 *Conserv.* **17**, 49–57 (2013).
- 730 20. Gomez-Pina, G., Munoz-Perez, J. & Enriquez, J. A critical review of beach restoration  
731 projects in the northern coast of Cadiz (Spain) after thirteen years. in *ICCE* (2006).  
732 doi:10.1142/9789812709554.
- 733 21. Valverde, H. R., Trembanis, A. C. & Pilkey, O. H. Summary of Beach Nourishment Episodes  
734 on the U.S. East. *J. Coast. Res.* **15**, 1100–1118 (1999).
- 735 22. Flick, R. E. The Myth and Reality of Southern California Beaches. *Shore & Beach* (1993).

- 736 23. Liu, Z., Cui, B. & He, Q. Shifting paradigms in coastal restoration: Six decades' lessons from  
737 China. *Sci. Total Environ.* **566–567**, 205–214 (2016).
- 738 24. Hamm, L. *et al.* A summary of European experience with shore nourishment. *Coast. Eng.*  
739 **47**, 237–264 (2002).
- 740 25. Jiménez, J. A., Gracia, V., Valdemoro, H. I., Mendoza, E. T. & Sánchez-Arcilla, A. Managing  
741 erosion-induced problems in NW Mediterranean urban beaches. *Ocean Coast. Manag.* **54**,  
742 907–918 (2011).
- 743 26. Stive, M. J. F. F. *et al.* A New Alternative to Saving Our Beaches from Sea-Level Rise: The  
744 Sand Engine. *J. Coast. Res.* **29**, 999–1008 (2013).
- 745 27. Banno, M., Takewaka, S. & Kuriyama, Y. MULTIDECADAL SHORELINE EVOLUTION DUE TO  
746 LARGE-SCALE BEACH NOURISHMENT —JAPANESE SAND ENGINE?—. in *Coastal*  
747 *dynamics 2017* vol. 29 842 (2017).
- 748 28. Liu, G. *et al.* A method to nourished beach stability assessment: The case of China. *Ocean*  
749 *Coast. Manag.* **177**, 166–178 (2019).
- 750 29. van Oudenhoven, A. P. E. *et al.* 'Mind the Gap' between ecosystem services classification  
751 and strategic decision making. *Ecosyst. Serv.* **33**, 77–88 (2018).
- 752 30. Morris, R. L. *et al.* Design Options, Implementation Issues and Evaluating Success of  
753 Ecologically Engineered Shorelines Rebecca. *Oceanogr. Mar. Biol.* **57**, (2019).
- 754 31. de Vriend, H. J., van Koningsveld, M., Aarninkhof, S. G. J., de Vries, M. B. & Baptist, M. J.  
755 Sustainable hydraulic engineering through building with nature. *J. Hydro-Environment*  
756 *Res.* **9**, 159–171 (2015).
- 757 32. Bridges, T. *et al.* *Engineering With Nature*. (Environmental Laboratory (U.S.) Engineering  
758 With Nature Program (U.S.) Engineer Research and Development Center (U.S.), 2018).
- 759 33. Powell, E. J., Tyrrell, M. C., Milliken, A., Tirpak, J. M. & Staudinger, M. D. A review of coastal

- 760 management approaches to support the integration of ecological and human community  
761 planning for climate change. *J. Coast. Conserv.* **23**, 1–18 (2019).
- 762 34. McFarland, S., Whitcombe, L. & Collins, M. Recent shingle beach renourishment schemes  
763 in the UK: Some preliminary observations. *Ocean Coast. Manag.* **25**, 143–149 (1994).
- 764 35. Shu, F. *et al.* Morphodynamics of an Artificial Cobble Beach in Tianquan Bay, Xiamen,  
765 China. *J. Ocean Univ. China* **18**, 868–882 (2019).
- 766 36. Baptist, M. J. *et al.* Beneficial use of dredged sediment to enhance salt marsh  
767 development by applying a 'Mud Motor'. *Ecol. Eng.* **127**, 312–323 (2019).
- 768 37. Clayton, T. D. Beach Replenishment Activities on U.S. Continental Pacific Coast. *J. Coast.*  
769 *Res.* **7**, 1195–1210 (1991).
- 770 38. Haddad, T. C. & Pilkey, O. H. Summary of the New England Beach Nourishment  
771 Experience (1935-1996). *J. Coast. Res.* **14**, 1395–1404 (1998).
- 772 39. Trembanis, A. C. & Pilkey, O. H. Summary of Beach Nourishment along the U.S. Gulf of  
773 Mexico Shoreline. *J. Coast. Res.* **14**, 407–417 (1998).
- 774 40. Palalane, J., Larson, M., Hanson, H. & Juízo, D. Coastal Erosion in Mozambique: Governing  
775 Processes and Remedial Measures. *J. Coast. Res.* **32**, 700 (2015).
- 776 41. Cai, F., Dean, R. G. & Liu, J. Beach nourishment in China: Status and prospects. *Proc. Coast.*  
777 *Eng. Conf.* (2010) doi:10.9753/icce.v32.management.31.
- 778 42. Lee, W. D., Kim, I. H., Yoon, J. S., Cho, W. C. & Hur, D. S. Analysis of Beach Deformation  
779 according to Nourishing Sand in Haeundae Beach, Korea. *J. Coast. Res.* **75**, 1372–1376  
780 (2016).
- 781 43. Elko, N. A. & Wang, P. Immediate profile and planform evolution of a beach nourishment  
782 project with hurricane influences. *Coast. Eng.* **54**, 49–66 (2007).

- 783 44. Yates, M. L., Guza, R. T., O'Reilly, W. C. & Seymour, R. J. Seasonal persistence of a small  
784 southern California beach fill. *Coast. Eng.* **56**, 559–564 (2009).
- 785 45. Seymour, R., Guza, R. T., O'Reilly, W. & Elgar, S. Rapid erosion of a small southern  
786 California beach fill. *Coast. Eng.* **52**, 151–158 (2005).
- 787 46. Dean, R. G. Equilibrium beach profiles: characteristics and applications. *J. Coast. Res.* **7**, 53–  
788 84 (1991).
- 789 47. Luijendijk, A. P. *et al.* The initial morphological response of the Sand Engine: A process-  
790 based modelling study. *Coast. Eng.* **119**, 1–14 (2017).
- 791 48. Smith, A. W. S. Discussion of: Pilkey, O. H., 1990. A time to look back at beach  
792 replenishment (editorial), *Journal of Coastal Research*, 6(1), iii-vii. And, Leonard, L.; Clayton,  
793 T., and Pilkey, O.H., 1990. An analysis of replenished beach design parameters on U.S. east  
794 c. *J. Coast. Res.* **6**, 1041–1045 (1990).
- 795 49. Dean, R. G. & Campbell, T. J. Beach Nourishment BT - Springer Handbook of Ocean  
796 Engineering. in (eds. Dhanak, M. R. & Xiros, N. I.) 635–652 (Springer International  
797 Publishing, 2016). doi:10.1007/978-3-319-16649-0\_29.
- 798 50. Hoonhout, B. & de Vries, S. Aeolian sediment supply at a mega nourishment. *Coast. Eng.*  
799 **123**, 11–20 (2017).
- 800 51. Jackson, N. L. & Nordstrom, K. F. Aeolian sediment transport and landforms in managed  
801 coastal systems: A review. *Aeolian Res.* **3**, 181–196 (2011).
- 802 52. de Schipper, M. A. *et al.* Initial spreading of a mega feeder nourishment: Observations of  
803 the Sand Engine pilot project. *Coast. Eng.* **111**, 23–38 (2016).
- 804 53. Ludka, B. C., Guza, R. T. & O'Reilly, W. C. Nourishment evolution and impacts at four  
805 southern California beaches: A sand volume analysis. *Coast. Eng.* **136**, 96–105 (2018).
- 806 54. Ludka, B. C., Gallien, T. W., Crosby, S. C. & Guza, R. T. Mid-El Niño erosion at nourished

- 807 and un nourished Southern California beaches. *Geophys. Res. Lett.* **43**, 4510–4516 (2016).
- 808 55. de Schipper, M. A. Alongshore variability of nourished and natural beaches. *PhD Thesis*,  
809 *Delft University of Technology, faculty of Civil Engineering and Geosciences* (2014).
- 810 56. Radermacher, M., de Schipper, M. A., Swinkels, C., MacMahan, J. H. & Reniers, A. J. H. M.  
811 Tidal flow separation at protruding beach nourishments. *J. Geophys. Res. Ocean.* **122**,  
812 (2017).
- 813 57. Huisman, B. J. A., de Schipper, M. A. & Ruessink, B. G. Sediment sorting at the Sand Motor  
814 at storm and annual time scales. *Mar. Geol.* **381**, (2016).
- 815 58. van Bemmelen, C. W. T., de Schipper, M. A., Darnall, J. & Aarninkhof, S. G. J. Beach scarp  
816 dynamics at nourished beaches. *Coast. Eng.* 103725 (2020)  
817 doi:<https://doi.org/10.1016/j.coastaleng.2020.103725>.
- 818 59. de Alegria-Arzaburu, A. R., Mariño-Tapia, I., Silva, R. & Pedrozo-Acuña, A. Post-  
819 nourishment beach scarp morphodynamics. *J. Coast. Res.* **65**, 576–581 (2013).
- 820 60. Crain, D. A., Bolten, A. B. & Bjorndal, K. A. EFFECTS OF BEACH NOURISHMENT ON SEA-  
821 TURTLES - REVIEW AND RESEARCH INITIATIVES. *Restor. Ecol.* **3**, 95–104 (1995).
- 822 61. Ranasinghe, R. & Turner, I. L. Shoreline response to submerged structures: A review.  
823 *Coast. Eng.* **53**, 65–79 (2006).
- 824 62. Moreno, L. *et al.* An Engineering Method For The Preliminary Functional Design Of  
825 Perched Beaches. Theoretical Approach. *J. Coast. Res.* **85**, 1261–1265 (2018).
- 826 63. Muñoz-Perez, J. J., Gallop, S. L. & Moreno, L. J. A comparison of beach nourishment  
827 methodology and performance at two fringing reef beaches in Waikiki (Hawaii, USA) and  
828 Cadiz (SW Spain). *J. Mar. Sci. Eng.* **8**, (2020).
- 829 64. Verhagen, H. J. Analysis of beach nourishment schemes. *J. Coast. Res.* **12**, 179–185 (1996).

- 830 65. Pilkey, O. H. The Fox Guarding the Hen House. *J. Coast. Res.* **11**, 1–3 (1995).
- 831 66. Guo, J. *et al.* Monitoring and evaluation of sand nourishments on an embayed beach  
832 exposed to frequent storms in eastern China. *Ocean Coast. Manag.* **195**, 105284 (2020).
- 833 67. Cooper, N. J., Leggett, D. J. & Lowe, J. P. Beach-profile measurement, theory and analysis:  
834 Practical guidance and applied case studies. *J. Chart. Inst. Water Environ. Manag.* **14**, 79–  
835 88 (2000).
- 836 68. Ludka, B. C. *et al.* Sixteen years of bathymetry and waves at San Diego beaches. *Sci. data*  
837 **6**, 161 (2019).
- 838 69. Splinter, K. D., Harley, M. D. & Turner, I. L. Remote sensing is changing our view of the  
839 coast: Insights from 40 years of monitoring at Narrabeen-Collaroy, Australia. *Remote*  
840 *Sens.* **10**, (2018).
- 841 70. Browder, A. E. & Dean, R. G. Monitoring and comparison to predictive models of the  
842 Perdido Key beach nourishment project, Florida, USA. *Coast. Eng.* **39**, 173–191 (2000).
- 843 71. Lee, G. hong, Nicholls, R. J. & Birkemeier, W. A. Storm-driven variability of the beach-  
844 nearshore profile at Duck, North Carolina, USA, 1981-1991. *Mar. Geol.* **148**, 163–177  
845 (1998).
- 846 72. Holman, R. A. & Stanley, J. The history and technical capabilities of Argus. *Coast. Eng.* **54**,  
847 477–491 (2007).
- 848 73. Elko, N. A., Holman, R. A. & Gelfenbaum, G. Quantifying the Rapid Evolution of a  
849 Nourishment Project with Video Imagery. *J. Coast. Res.* **214**, 633–645 (2005).
- 850 74. Vos, K., Harley, M. D., Splinter, K. D., Simmons, J. A. & Turner, I. L. Sub-annual to multi-  
851 decadal shoreline variability from publicly available satellite imagery. *Coast. Eng.* **150**,  
852 160–174 (2019).
- 853 75. Vandebroek, E. *et al.* Semi-automated monitoring of a mega-scale beach nourishment



- 854 using high-resolution terraSAR-X satellite data. *Remote Sens.* **9**, (2017).
- 855 76. Silva, P. G. da, Coco, G., Garnier, R. & Klein, A. H. F. On the prediction of runup, setup and  
856 swash on beaches. *Earth-Science Rev.* (2020) doi:10.1016/j.molliq.2019.111554.
- 857 77. Almeida, L. P. *et al.* Deriving high spatial-resolution coastal topography from sub-meter  
858 satellite stereo imagery. *Remote Sens.* **11**, (2019).
- 859 78. Wiggins, M., Scott, T., Masselink, G., Russell, P. & McCarroll, R. J. Coastal embayment  
860 rotation: Response to extreme events and climate control, using full embayment surveys.  
861 *Geomorphology* **327**, 385–403 (2019).
- 862 79. Shean, D. E. *et al.* An automated, open-source pipeline for mass production of digital  
863 elevation models (DEMs) from very-high-resolution commercial stereo satellite imagery.  
864 *ISPRS J. Photogramm. Remote Sens.* **116**, 101–117 (2016).
- 865 80. Magruder, L. *et al.* New Earth orbiter provides a sharper look at a changing planet. *Eos*  
866 (*Washington, DC*). (2019) doi:https://doi.org/10.1029/2019EO133233.
- 867 81. Phillips, M. S., Blenkinsopp, C. E., Splinter, K. D., Harley, M. D. & Turner, I. L. Modes of Berm  
868 and Beachface Recovery Following Storm Reset: Observations Using a Continuously  
869 Scanning Lidar. *J. Geophys. Res. Earth Surf.* **124**, 720–736 (2019).
- 870 82. Launeau, P. *et al.* Full-waveform LiDAR pixel analysis for low-growing vegetation mapping  
871 of coastal foredunes in Western France. *Remote Sens.* **10**, (2018).
- 872 83. Deronde, B., Houthuys, R., Henriët, J. P. & Van Lancker, V. Monitoring of the sediment  
873 dynamics along a sandy shoreline by means of airborne hyperspectral remote sensing  
874 and LIDAR: A case study in Belgium. *Earth Surf. Process. Landforms* **33**, 280–294 (2008).
- 875 84. Matsumoto, H. & Young, A. P. Automated cobble mapping of a mixed sand-cobble beach  
876 using a mobile LiDAR system. *Remote Sens.* **10**, (2018).
- 877 85. Casella, E. *et al.* Mapping coral reefs using consumer-grade drones and structure from

- 878 motion photogrammetry techniques. *Coral Reefs* **36**, 269–275 (2017).
- 879 86. Peeri, S., Gardner, J. V., Ward, L. G. & Morrison, J. R. The seafloor: A key factor in lidar  
880 bottom detection. *IEEE Trans. Geosci. Remote Sens.* **49**, 1150–1157 (2011).
- 881 87. Brodie, K. L. *et al.* Evaluation of video-based linear depth inversion performance and  
882 applications using altimeters and hydrographic surveys in a wide range of environmental  
883 conditions. *Coast. Eng.* **136**, 147–160 (2018).
- 884 88. Gawehn, M. *et al.* The application of a radar-based depth inversion method to monitor  
885 near-shore nourishments on an open sandy coast and an ebb-tidal delta. *Coast. Eng.* **159**,  
886 103716 (2020).
- 887 89. Hoefel, F. & Elgar, S. Wave-induced sediment transport and onshore sandbar migration.  
888 *Science (80-. )*. **299**, 1885–1887 (2003).
- 889 90. Elko, N. *et al.* The future of nearshore processes research. *Shore and Beach* **83**, 13–38  
890 (2015).
- 891 91. Luijendijk, A. P., de Vries, S., van het Hooft, T. & de Schipper, M. A. Predicting dune  
892 growth at the Sand Engine by coupling the Delft3D Flexible Mesh and Aeolis models. in  
893 *Coastal Sediments 2019* 1319–1326 (WORLD SCIENTIFIC, 2019).  
894 doi:doi:10.1142/9789811204487\_0115.
- 895 92. Luijendijk, A. P., de Schipper, M. A. & Ranasinghe, R. Morphodynamic acceleration  
896 techniques for multi-timescale predictions of complex sandy interventions. *J. Mar. Sci. Eng.*  
897 **7**, (2019).
- 898 93. Huisman, B. J. A., Walstra, D. J. R., Radermacher, M., de Schipper, M. A. & Ruessink, B. G.  
899 Observations and modelling of shoreface nourishment behaviour. *Journal of Marine*  
900 *Science and Engineering* vol. 7 (2019).
- 901 94. Weathers, H. D. & Voulgaris, G. Evaluation of Beach Nourishment Evolution Models Using

- 902 Data from Two South Carolina, USA Beaches: Folly Beach and Hunting Island. *J. Coast. Res.*  
903 84–98 (2013) doi:10.2112/SI.
- 904 95. Tonnon, P. K., Huisman, B. J. A., Stam, G. N. & van Rijn, L. C. Numerical modelling of  
905 erosion rates, life span and maintenance volumes of mega nourishments. *Coast. Eng.* **131**,  
906 51–69 (2018).
- 907 96. Lesser, G. R., Roelvink, J. A., van Kester, J. A. T. M. & Stelling, G. S. Development and  
908 validation of a three-dimensional morphological model. *Coast. Eng.* **51**, 883–915 (2004).
- 909 97. Zyserman, J. A. & Johnson, H. K. Modelling morphological processes in the vicinity of  
910 shore-parallel breakwaters. *Coast. Eng.* **45**, 261–284 (2002).
- 911 98. Walstra, D. J. R., Reniers, A. J. H. M., Ranasinghe, R., Roelvink, J. A. & Ruessink, B. G. On bar  
912 growth and decay during interannual net offshore migration. *Coast. Eng.* **60**, 190–200  
913 (2012).
- 914 99. Barnard, P. L. *et al.* Development of the Coastal Storm Modeling System (CoSMoS) for  
915 predicting the impact of storms on high-energy, active-margin coasts. *Nat. Hazards* **74**,  
916 1095–1125 (2014).
- 917 100. Kalligeris, N., Smit, P. B., Ludka, B. C., Guza, R. T. & Gallien, T. W. Calibration and  
918 assessment of process-based numerical models for beach profile evolution in southern  
919 California. *Coast. Eng.* **158**, 103650 (2020).
- 920 101. Roelvink, D. *et al.* Modelling storm impacts on beaches, dunes and barrier islands. *Coast.*  
921 *Eng.* **56**, 1133–1152 (2009).
- 922 102. Huisman, B. J. A., Ruessink, B. G., de Schipper, M. A., Luijendijk, A. P. & Stive, M. J. F.  
923 Modelling of bed sediment composition changes at the lower shoreface of the Sand  
924 Motor. *Coast. Eng.* **132**, 33–49 (2018).
- 925 103. Kroon, A., de Schipper, M. A., van Gelder, P. & Aarninkhof, S. G. J. Ranking uncertainty:

- 926 wave climate variability versus model uncertainty in probabilistic assessment of coastline  
927 change. *J. Coast. Eng.* (2020).
- 928 104. Le Cozannet, G. *et al.* Quantifying uncertainties of sandy shoreline change projections as  
929 sea level rises. *Sci. Rep.* **9**, 1–11 (2019).
- 930 105. Baas, A. Simulating dune landscapes in vegetated environments. *Scenario* **6**, 1–22 (1997).
- 931 106. Ranasinghe, R. On the need for a new generation of coastal change models for the 21st  
932 century. *Sci. Rep.* **10**, 2010 (2020).
- 933 107. Anderson, W. P. & Lauer, R. M. The role of overwash in the evolution of mixing zone  
934 morphology within barrier islands. *Hydrogeol. J.* **16**, 1483–1495 (2008).
- 935 108. Terry, J. P. & Falkland, A. C. Responses of atoll freshwater lenses to storm-surge overwash  
936 in the Northern Cook Islands. *Hydrogeol. J.* **18**, 749–759 (2010).
- 937 109. Ataie-Ashtiani, B., Werner, A. D., Simmons, C. T., Morgan, L. K. & Lu, C. How important is  
938 the impact of land-surface inundation on seawater intrusion caused by sea-level rise?  
939 *Hydrogeol. J.* **21**, 1673–1677 (2013).
- 940 110. Morgan, L. K. & Werner, A. D. Seawater intrusion vulnerability indicators for freshwater  
941 lenses in strip islands. *J. Hydrol.* **508**, 322–327 (2014).
- 942 111. Ketabchi, H., Mahmoodzadeh, D., Ataie-Ashtiani, B. & Simmons, C. T. Sea-level rise  
943 impacts on seawater intrusion in coastal aquifers: Review and integration. *J. Hydrol.* **535**,  
944 235–255 (2016).
- 945 112. Chang, S. W., Nemec, K., Kalin, L. & Clement, T. P. Impacts of Climate Change and  
946 Urbanization on Groundwater Resources in a Barrier Island. *J. Environ. Eng.* **142**, D4016001  
947 (2016).
- 948 113. White, I. & Falkland, T. Management of freshwater lenses on small Pacific islands.  
949 *Hydrogeol. J.* **18**, 227–246 (2010).

- 950 114. Oberle, F. K. J., Swarzenski, P. W. & Storlazzi, C. D. Atoll groundwater movement and its  
951 response to climatic and sea-level fluctuations. *Water (Switzerland)* **9**, 1–18 (2017).
- 952 115. Befus, K. M., Barnard, P. L., Hoover, D. J., Finzi-Hart, J. A. & Voss, C. I. Increasing threat of  
953 coastal groundwater hazards from sea-level rise. *Nat. Clim. Chang.* (2020)  
954 doi:10.1038/s41558-020-0874-1.
- 955 116. Rotzoll, K. & Fletcher, C. H. Assessment of groundwater inundation as a consequence of  
956 sea-level rise. *Nat. Clim. Chang.* **3**, 477–481 (2013).
- 957 117. Habel, S., Fletcher, C. H., Anderson, T. R. & Thompson, P. R. Sea-Level Rise Induced Multi-  
958 Mechanism Flooding and Contribution to Urban Infrastructure Failure. *Sci. Rep.* **10**, 1–12  
959 (2020).
- 960 118. Huizer, S., Oude Essink, G. H. P. & Bierkens, M. F. P. Fresh groundwater resources in a  
961 large sand replenishment. *Hydrol. Earth Syst. Sci. Discuss.* 1–32 (2016) doi:10.5194/hess-  
962 2016-5.
- 963 119. Huizer, S., Radermacher, M., de Vries, S., Oude Essink, G. H. P. & Bierkens, M. F. P. Impact  
964 of coastal forcing and groundwater recharge on the growth of a fresh groundwater lens  
965 in a mega-scale beach nourishment. *Hydrol. Earth Syst. Sci.* **22**, 1065–1080 (2018).
- 966 120. Robinson, C., Xin, P., Li, L. & Barry, D. A. Groundwater flow and salt transport in a  
967 subterranean estuary driven by intensified wave conditions. *Water Resour. Res.* **50**, 165–  
968 181 (2014).
- 969 121. Li, L., Cartwright, N., Nielsen, P. & Lockington, D. Response of coastal groundwater table  
970 to offshore storms. *China Ocean Eng.* **18**, 423–431 (2004).
- 971 122. Trglavcnik, V., Morrow, D., Weber, K. P., Li, L. & Robinson, C. E. Analysis of Tide and  
972 Offshore Storm-Induced Water Table Fluctuations for Structural Characterization of a  
973 Coastal Island Aquifer. *Water Resour. Res.* **54**, 2749–2767 (2018).

- 974 123. Housego, R. *et al.* BARRIER ISLAND GROUNDWATER. *ICCE* (2018).
- 975 124. Silva, F. G., Wijnberg, K. M., de Groot, A. V. & Hulscher, S. J. M. H. The influence of  
976 groundwater depth on coastal dune development at sand flats close to inlets. *Ocean Dyn.*  
977 **68**, 885–897 (2018).
- 978 125. Horn, D. P. Beach groundwater dynamics. *Geomorphology* **48**, 121–146 (2002).
- 979 126. Evans, T. B. & Wilson, A. M. Groundwater transport and the freshwater-saltwater interface  
980 below sandy beaches. *J. Hydrol.* **538**, 563–573 (2016).
- 981 127. Román-Sierra, J., Muñoz-Perez, J. J. & Navarro-Pons, M. Beach nourishment effects on  
982 sand porosity variability. *Coast. Eng.* **83**, 221–232 (2014).
- 983 128. Soares, A. G., McLachlan, A. & Schlacher, T. A. Disturbance effects of stranded kelp on  
984 populations of the sandy beach bivalve *Donax serra* (Roding). *J. Exp. Mar. Bio. Ecol.* **205**,  
985 165–186 (1996).
- 986 129. Schlacher, T. A. *et al.* Sandy beach ecosystems: Key features, sampling issues,  
987 management challenges and climate change impacts. *Mar. Ecol.* **29**, 70–90 (2008).
- 988 130. Schlacher, T. A. & Thompson, L. Environmental control of community organisation on  
989 ocean-exposed sandy beaches. *Mar. Freshw. Res.* **64**, 119–129 (2013).
- 990 131. Schlacher, T. A. & Thompson, L. Spatial structure on ocean-exposed sandy beaches:  
991 Faunal zonation metrics and their variability. *Mar. Ecol. Prog. Ser.* **478**, 43–55 (2013).
- 992 132. Schoeman, D. S., Schlacher, T. A. & Defeo, O. Climate-change impacts on sandy-beach  
993 biota: Crossing a line in the sand. *Glob. Chang. Biol.* **20**, 2383–2392 (2014).
- 994 133. Rafael Barboza, F. & Defeo, O. Global diversity patterns in sandy beach macrofauna: A  
995 biogeographic analysis. *Sci. Rep.* **5**, (2015).
- 996 134. Maslo, B. *et al.* Selecting umbrella species for conservation: A test of habitat models and

- 997 niche overlap for beach-nesting birds. *Biol. Conserv.* **203**, 233–242 (2016).
- 998 135. Maslo, B. *et al.* Regional drivers of clutch loss reveal important trade-offs for beach-  
999 nesting birds. *PeerJ* **2016**, (2016).
- 1000 136. Schlacher, T. *et al.* The Early Shorebird Will Catch Fewer Invertebrates on Trampled Sandy  
1001 Beaches. *PLoS One* **11**, e0161905 (2016).
- 1002 137. Olds, A. D. *et al.* The ecology of fish in the surf zones of ocean beaches: A global review.  
1003 *Fish Fish.* **19**, 78–89 (2018).
- 1004 138. Rae, C., Hyndes, G. A. & Schlacher, T. A. Trophic ecology of ghost crabs with diverse  
1005 tastes: Unwilling vegetarians. *Estuar. Coast. Shelf Sci.* **224**, 272–280 (2019).
- 1006 139. Schlacher, T. A. *et al.* Key Ecological Function Peaks at the Land–Ocean Transition Zone  
1007 When Vertebrate Scavengers Concentrate on Ocean Beaches. *Ecosystems* (2019)  
1008 doi:10.1007/s10021-019-00445-y.
- 1009 140. Brown, A. Behavioural plasticity as a key factor in the survival and evolution of the  
1010 macrofauna on exposed sandy beaches. *Rev. Chil. Hist. Nat.* **69**, 469–474 (1996).
- 1011 141. Dugan, J. E. *et al.* Give beach ecosystems their day in the sun. *Science (80-. )*. **329**, 1146  
1012 (2010).
- 1013 142. Manning, L. M., Peterson, C. H. & Fegley, S. R. Degradation of surf-fish foraging habitat  
1014 driven by persistent sedimentological modifications caused by beach nourishment. *Bull.*  
1015 *Mar. Sci.* **89**, 83–106 (2013).
- 1016 143. Manning, L. M., Peterson, C. H. & Bishop, M. J. Dominant macrobenthic populations  
1017 experience sustained impacts from annual disposal of fine sediments on sandy beaches.  
1018 *Mar. Ecol. Prog. Ser.* **508**, 1–15 (2014).
- 1019 144. Peterson, C. H., Bishop, M. J., D’Anna, L. M. & Johnson, G. A. Multi-year persistence of  
1020 beach habitat degradation from nourishment using coarse shelly sediments. *Sci. Total*

- 1021            *Environ.* **487**, 481–492 (2014).
- 1022    145. Schlacher, T. A. *et al.* Golden opportunities: A horizon scan to expand sandy beach  
1023            ecology. *Estuar. Coast. Shelf Sci.* **157**, 1–6 (2015).
- 1024    146. Barbier EB *et al.* The value of estuarine and coastal ecosystem services. *Ecol. Monogr.*  
1025            **81(2)**, 169–193 (2011).
- 1026    147. Defeo, O. *et al.* Threats to sandy beach ecosystems: A review. *Estuar. Coast. Shelf Sci.* **81**,  
1027            1–12 (2009).
- 1028    148. Schlacher, T. A. *et al.* Sandy beaches at the brink. *Divers. Distrib.* **13**, 556–560 (2007).
- 1029    149. Speybroeck, J. *et al.* Beach nourishment: An ecologically sound coastal defence  
1030            alternative? A review. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **16**, 419–435 (2006).
- 1031    150. Wooldridge, T., Henter, H. J. & Kohn, J. R. Effects of beach replenishment on intertidal  
1032            invertebrates: A 15-month, eight beach study. *Estuar. Coast. Shelf Sci.* **175**, 24–33 (2016).
- 1033    151. Schooler, N. K., Dugan, J. E. & Hubbard, D. M. No lines in the sand: Impacts of intense  
1034            mechanized maintenance regimes on sandy beach ecosystems span the intertidal zone on  
1035            urban coasts. *Ecol. Indic.* **106**, 105457 (2019).
- 1036    152. Jones, A. R., Murray, A., Lasiak, T. A. & Marsh, R. E. The effects of beach nourishment on  
1037            the sandy-beach amphipod *Exoediceros fossor*: Impact and recovery in Botany Bay, New  
1038            South Wales, Australia. *Mar. Ecol.* **29**, 28–36 (2008).
- 1039    153. Schlacher, T. A., Noriega, R., Jones, A. & Dye, T. The effects of beach nourishment on  
1040            benthic invertebrates in eastern Australia: Impacts and variable recovery. *Sci. Total*  
1041            *Environ.* **435–436**, 411–417 (2012).
- 1042    154. Schlacher, T. A. & Thompson, L. M. C. Exposure of fauna to off-road vehicle (ORV) traffic  
1043            on sandy beaches. *Coast. Manag.* **35**, 567–583 (2007).



- 1044 155. Schlacher, T. A., Thompson, L. M. C. & Walker, S. J. Mortalities caused by off-road vehicles  
1045 (ORVs) to a key member of sandy beach assemblages, the surf clam *Donax deltoides*.  
1046 *Hydrobiologia* **610**, 345–350 (2008).
- 1047 156. Sheppard, N., Pitt, K. A. & Schlacher, T. A. Sub-lethal effects of off-road vehicles (ORVs) on  
1048 surf clams on sandy beaches. *J. Exp. Mar. Bio. Ecol.* **380**, 113–118 (2009).
- 1049 157. Thompson, L. & Schlacher, T. Beach recreation impacts benthic invertebrates on ocean-  
1050 exposed sandy shores. *Biol. Conserv.* **147**, 123–132 (2011).
- 1051 158. Manzanera, M., Alcoverro, T., Jiménez, J. A. & Romero, J. The large penumbra: Long-  
1052 distance effects of artificial beach nourishment on *Posidonia oceanica* meadows. *Mar.*  
1053 *Pollut. Bull.* **86**, 129–137 (2014).
- 1054 159. Convertino, M. *et al.* Anthropogenic renourishment feedback on shorebirds: A  
1055 multispecies Bayesian perspective. *Ecol. Eng.* (2011) doi:10.1016/j.ecoleng.2011.02.019.
- 1056 160. Martin, K. L. M. & Adams, L. C. Effects of repeated sand replenishment projects on runs of  
1057 a beach-spawning fish, the California grunion. *J. Mar. Sci. Eng.* **8**, (2020).
- 1058 161. Van Tomme, J., Vanden Eede, S., Speybroeck, J., Degraer, S. & Vincx, M. Macrofaunal  
1059 sediment selectivity considerations for beach nourishment programmes. *Mar. Environ.*  
1060 *Res.* **84**, 10–16 (2013).
- 1061 162. Peterson, C. H., Hickerson, D. H. M. & Johnson, G. G. Short-term consequences of  
1062 nourishment and bulldozing on the dominant large invertebrates of a sandy beach. *J.*  
1063 *Coast. Res.* **16**, 368–378 (2000).
- 1064 163. Viola, S. M., Hubbard, D. M., Dugan, J. E. & Schooler, N. K. Burrowing inhibition by fine  
1065 textured beach fill: Implications for recovery of beach ecosystems. *Estuar. Coast. Shelf Sci.*  
1066 **150**, 142–148 (2014).
- 1067 164. Peterson, C. H. & Bishop, M. J. Assessing the Environmental Impacts of Beach

- 1068 Nourishment. *Bioscience* **55**, 887 (2005).
- 1069 165. Peterson, C. H., Bishop, M. J., Johnson, G. A., D'Anna, L. M. & Manning, L. M. Exploiting  
1070 beach filling as an unaffordable experiment: Benthic intertidal impacts propagating  
1071 upwards to shorebirds. *J. Exp. Mar. Bio. Ecol.* **338**, 205–221 (2006).
- 1072 166. Botton, M. L. *et al.* Effects of a Beach Nourishment Project in Jamaica Bay, New York, on  
1073 Horseshoe Crab (*Limulus polyphemus*) Spawning Activity and Egg Deposition. *Estuaries  
1074 and Coasts* **41**, 974–987 (2018).
- 1075 167. Dugan, J. E., Airoidi, L., Chapman, M. G., Walker, S. J. & Schlacher, T. Estuarine and Coastal  
1076 Structures: Environmental Effects, A Focus on Shore and Nearshore Structures. *Treatise  
1077 Estuar. Coast. Sci.* **8**, 17–41 (2012).
- 1078 168. Martins, G. M., Amaral, A. F., Wallenstein, F. M. & Neto, A. I. Influence of a breakwater on  
1079 nearby rocky intertidal community structure. *Mar. Environ. Res.* **67**, 237–245 (2009).
- 1080 169. van Egmond, E. M. *et al.* A mega-nourishment creates novel habitat for intertidal  
1081 macroinvertebrates by enhancing habitat relief of the sandy beach. *Estuar. Coast. Shelf Sci.*  
1082 **207**, 232–241 (2018).
- 1083 170. Brock, K. A., Reece, J. S. & Ehrhart, L. M. The effects of artificial beach nourishment on  
1084 marine turtles: Differences between loggerhead and green turtles. *Restor. Ecol.* (2009)  
1085 doi:10.1111/j.1526-100X.2007.00337.x.
- 1086 171. Lithgow, D. *et al.* Linking restoration ecology with coastal dune restoration.  
1087 *Geomorphology* **199**, 214–224 (2013).
- 1088 172. Pranzini, E. *et al.* Sand colour at Cuba and its influence on beach nourishment and  
1089 management. *Ocean Coast. Manag.* **126**, 51–60 (2016).
- 1090 173. Greene, K. Beach nourishment: A Review of the Biological and Physical impacts. ASMFC  
1091 Habitat Management Series # 7. *Atl. States Mar. Fish. Comm.* 1–174 (2002).

- 1092 174. Bendixen, M., Best, J., Hackney, C. & Iversen, L. L. Time is running out for sand. *Nature*  
1093 **571**, 29–31 (2019).
- 1094 175. Peduzzi, P. Sand, rarer than one thinks. Article reproduced from United Nations  
1095 Environment Programme (UNEP) Global Environmental Alert Service (GEAS). *Environ. Dev.*  
1096 **11**, 208–218 (2014).
- 1097 176. Haasnoot, M. *et al.* Adaptation to uncertain sea-level rise; how uncertainty in Antarctic  
1098 mass-loss impacts the coastal adaptation strategy of the Netherlands. *Environ. Res. Lett.*  
1099 **15**, (2020).
- 1100 177. Vidal, R. & van Oord, G. Environmental Impacts in Beach Nourishment: a Comparison of  
1101 Options. *Terra Aqua* 14–20 (2010).
- 1102 178. Van Der Bilt, V. . Assessing emission performance of dredging projects. (2019).
- 1103 179. Hoagland, P., Jin, D. & Kite-Powell, H. L. The Costs of Beach Replenishment along the U.S.  
1104 Atlantic Coast. *J. Coast. Res.* **278**, 199–204 (2012).
- 1105 180. Parkinson, R. W. & Ogurcak, D. E. Beach nourishment is not a sustainable strategy to  
1106 mitigate climate change. *Estuar. Coast. Shelf Sci.* **212**, 203–209 (2018).
- 1107 181. Hinkel, J. *et al.* A global analysis of erosion of sandy beaches and sea-level rise: An  
1108 application of DIVA. *Glob. Planet. Change* **111**, 150–158 (2013).
- 1109 182. CEDA. EFFECTIVE CONTRACT-TYPE SELECTION IN THE DREDGING INDUSTRY. A Guidance  
1110 Paper. Available <http://www.dredging.org/media/ceda/org/documents/> Resour. 17 (2019).
- 1111 183. SANDAG & NICHOL, M. &. FEASIBILITY STUDY SAN DIEGO REGIONAL BEACH SAND  
1112 REPLENISHMENT PROJECT SAN DIEGO , CALIFORNIA. (2007).
- 1113 184. Bendixen, M., Iversen, L. L. & Overeem, I. Greenland: Build an economy on sand. *Science*  
1114 (80- ). **358**, 879 (2017).

- 1115 185. Boyd, S. E., Limpenny, D. S., Rees, H. L. & Cooper, K. M. The effects of marine sand and  
1116 gravel extraction on the macrobenthos at a commercial dredging site (results 6 years  
1117 post-dredging). *ICES J. Mar. Sci.* **62**, 145–162 (2005).
- 1118 186. de Jong, M. F. *et al.* Impact on demersal fish of a large-scale and deep sand extraction site  
1119 with ecosystem-based landscaped sandbars. *Estuar. Coast. Shelf Sci.* **146**, 83–94 (2014).
- 1120 187. Jiao, S., Chen, X. & Du, Q. Carbon emission of dredged marine sediment. in *2011*  
1121 *International Conference on Electronics, Communications and Control, ICECC 2011 -*  
1122 *Proceedings* 3604–3607 (2011). doi:10.1109/ICECC.2011.6068037.
- 1123 188. Goncalves Castro, M. B., Mestemaker, B. T. W. & Van Den Heuvel, H. Towards Zero  
1124 Emission Work Vessels: The Case of a Dredging Vessel. in *International Conference on*  
1125 *Modelling and Optimisation of Ship Energy Systems* (2019).
- 1126 189. Pendleton, L., Mohn, C., Vaughn, R. K., King, P. & Zoulas, J. G. SIZE MATTERS: THE  
1127 ECONOMIC VALUE OF BEACH EROSION AND NOURISHMENT IN SOUTHERN  
1128 CALIFORNIA. *Contemp. Econ. Policy* **30**, 223–237 (2012).
- 1129 190. Todd, D. J. & Bowa, K. Development of Beach Health Index for the Gold Coast, Australia. *J.*  
1130 *Coast. Res.* **75**, 710–714 (2016).
- 1131 191. Muller, M. W. Beach replenishment and surf-zone injuries along the coast of Delmarva,  
1132 USA. *Ocean Coast. Manag.* **151**, 127–133 (2018).
- 1133 192. De Zeeuw, R. C., De Schipper, M. A., Roelvink, D., De Vries, S. & Stive, M. J. F. Impact of  
1134 nourishments on nearshore currents and swimmer safety on the Dutch coast. in  
1135 *Proceedings of the Coastal Engineering Conference* (2012).
- 1136 193. de Schipper, M. A. ., De Vries, S., Ranasinghe, R., Reniers, A. & Stive, M. J. F. Alongshore  
1137 topographic variability at a nourished beach. *Coast. Dyn. 2013 7th Int. Conf. Coast. Dyn.*  
1138 *Arcachon, Fr. 24-28 June 2013* 6–11 (2013) doi:10.1093/annonc/mdy259/5055604.

- 1139 194. Fletemeyer, J., Hearin, J., Haus, B. & Sullivan, A. The Impact of Sand Nourishment on Beach  
1140 Safety. *J. Coast. Res.* **341**, 1–5 (2018).
- 1141 195. Dally, W. R. & Osiecki, D. A. Evaluating the Impact of Beach Nourishment on Surfing: Surf  
1142 City, Long Beach Island, New Jersey, U.S.A. *J. Coast. Res.* **344**, 793–805 (2018).
- 1143 196. Corne, N. P. The implications of coastal protection and development on surfing. *J. Coast.*  
1144 *Res.* **25**, 427–434 (2009).
- 1145 197. Albada, E., Goshow, C. & Dompe, P. EFFECT OF BEACH NOURISHMENT ON SURFING –  
1146 OBSERVATIONS FROM THE ST. JOHNS COUNTY SHORE PROTECTION PROJECT. 1–22.
- 1147 198. Miller, J. K., Mahon, A. M. & Herrington, T. O. Assesment of alternative beachfill placement  
1148 on surfing resources. *Proc. Coast. Eng. Conf.* 1–15 (2010).
- 1149 199. Gopalakrishnan, S., Smith, M. D., Slott, J. M. & Murray, A. B. The value of disappearing  
1150 beaches: A hedonic pricing model with endogenous beach width. *J. Environ. Econ.*  
1151 *Manage.* **61**, 297–310 (2011).
- 1152 200. Lazarus, E. D., McNamara, D. E., Smith, M. D., Gopalakrishnan, S. & Murray, A. B. Emergent  
1153 behavior in a coupled economic and coastline model for beach nourishment. *Nonlinear*  
1154 *Process. Geophys.* **18**, 989–999 (2011).
- 1155 201. Brad Murray, A., Gopalakrishnan, S., McNamara, D. E. & Smith, M. D. Progress in coupling  
1156 models of human and coastal landscape change. *Comput. Geosci.* **53**, 30–38 (2013).
- 1157 202. Lazarus, E. D., Ellis, M. A., Brad Murray, A. & Hall, D. M. An evolving research agenda for  
1158 human-coastal systems. *Geomorphology* **256**, 81–90 (2016).
- 1159 203. USACE. New Directions in Water Resources Planning for the U.S. Army Corps of Engineers.  
1160 *Natl. Acad. Press Appendix D*, (1999).
- 1161 204. Parsons, G. R., Massey, D. M. & Tomasi, T. Familiar and favorite sites in a random utility  
1162 model of beach recreation. *Mar. Resour. Econ.* **14**, 299–315 (1999).

- 1163 205. Costa, M. F. & Kahn, J. R. BOA VIAGEM EROSION PREVENTION AND BEACH  
1164 NOURISHMENT PROJECT. *IX Congr. da Assoc. Bras. Estud. do Quaternário*. (2003).
- 1165 206. Nordstrom, K. F., Pranzini, E., Jackson, N. L. & Coli, M. The marble beaches of Tuscany.  
1166 *Geogr. Rev.* **98**, 280–300 (2008).
- 1167 207. Asensio-Montesinos, F. *et al.* The origin of sand and its colour on the south-eastern coast  
1168 of Spain: Implications for erosion management. *Water (Switzerland)* **12**, (2020).
- 1169 208. Gopalakrishnan, S., McNamara, D., Smith, M. D. & Murray, A. B. Decentralized  
1170 Management Hinders Coastal Climate Adaptation: The Spatial-dynamics of Beach  
1171 Nourishment. *Environ. Resour. Econ.* **67**, 761–787 (2017).
- 1172 209. Martinich, J., Neumann, J., Ludwig, L. & Jantarasami, L. Risks of sea level rise to  
1173 disadvantaged communities in the United States. *Mitig. Adapt. Strateg. Glob. Chang.* **18**,  
1174 169–185 (2013).
- 1175 210. Whitehead, J. C., Dumas, C. F., Herstine, J., Hill, J. & Buerger, B. Valuing Beach Access and  
1176 Width with Revealed and Stated Preference Data. *Mar. Resour. Econ.* (2006)  
1177 doi:<https://doi.org/10.1086/mre.23.2.42629607>.
- 1178 211. Masselink, G., Russell, P., Rennie, A., Brooks, S. & Spencer, T. Impacts of climate change on  
1179 coastal geomorphology and coastal erosion relevant to the coastal and marine  
1180 environment around the UK. *MCCIP Sci. Rev.* 158– 189. (2020)  
1181 doi:[10.14465/2020.arc08.cgm](https://doi.org/10.14465/2020.arc08.cgm).
- 1182 212. Dean, R. G. & Yoo, C. H. Beach-nourishment performance predictions. *J. Waterw. Port,  
1183 Coast. Ocean Eng.* **118**, 567–586 (1992).
- 1184 213. Pan, Y. *et al.* Performance Evaluation of a Beach Nourishment Project at West Beach in  
1185 Beidaihe, China. *J. Coast. Res.* **27**, 769 (2011).
- 1186 214. Raybould, M. & Mules, T. A cost-benefit study of protection of the northern beaches of

- 1187 Australia's Gold Coast. *Tour. Econ.* **5**, 121–139 (1999).
- 1188 215. Shin, B. S. & Kim, K. H. Basic study on the estimating the value of sand beach using  
1189 amenitiesreplace. *Proc. 7th Int. Conf. Asian Pacific Coasts, APAC 2013* 69–74 (2020).
- 1190 216. Martino, S. & Amos, C. L. Valuation of the ecosystem services of beach nourishment in  
1191 decision-making: The case study of Tarquinia Lido, Italy. *Ocean Coast. Manag.* **111**, 82–91  
1192 (2015).
- 1193 217. Murcia, C. *et al.* A critique of the 'novel ecosystem' concept. *Trends Ecol. Evol.* **29**, 548–553  
1194 (2014).
- 1195 218. Temmerman, S. *et al.* Ecosystem-based coastal defence in the face of global change.  
1196 *Nature* **504**, 79–83 (2013).
- 1197 219. Hinkel, J. *et al.* The ability of societies to adapt to twenty-first-century sea-level rise. *Nat.*  
1198 *Clim. Chang.* **8**, 570–578 (2018).
- 1199 220. Hauer, M. E. Migration induced by sea-level rise could reshape the US population  
1200 landscape. *Nat. Clim. Chang.* **7**, 321–325 (2017).
- 1201 221. Hauer, M. E. *et al.* Sea-level rise and human migration. *Nat. Rev. Earth Environ.* **1**, 28–39  
1202 (2020).
- 1203 222. Oppenheimer. Chapter 4: Sea Level Rise and Implications for Low Lying Islands, Coasts  
1204 and Communities Coordinating. *IPCC* **355**, 126–129 (2019).
- 1205 223. Griffith, A. D., Coburn, A. S., Peek, K. M. & Young, R. S. Hurricane Sandy: Did Beach  
1206 Nourishment Save New Jersey? *Learn. from Impacts Superstorm Sandy* 57–68 (2015)  
1207 doi:10.1016/B978-0-12-801520-9.00005-5.
- 1208 224. Griggs, G. & Kinsman, N. Beach widths, cliff slopes, and artificial nourishment along the  
1209 California Coast. *Shore* **84**, 1–12 (2016).

- 1210 225. Gontz, A. M., Moss, P. T. & Wagenknecht, E. K. Stratigraphic architecture of a regressive  
1211 strand plain, flinders beach, north Stradbroke Island, Queensland, Australia. *J. Coast. Res.*  
1212 **30**, 575–585 (2014).
- 1213 226. Bingham, E. L. *et al.* Functional plasticity in vertebrate scavenger assemblages in the  
1214 presence of introduced competitors. *Oecologia* **188**, 583–593 (2018).
- 1215 227. Jackson, A., Hill, P. & McGrath, J. A history of the implementation and evolution of sand  
1216 nourishment methods on the Gold Coast, Australia. *Coasts Ports 2013* 418–423 (2013).
- 1217 228. Turner, I. L. *et al.* Predicted and observed coastline changes at the Gold Coast artificial  
1218 reef. in *Coastal Engineering 2000* 1836–1847 (2001).
- 1219 229. de Boer, W. *et al.* Understanding coastal erosion processes at the Korean east coast. *Proc.*  
1220 *Coast. Dyn. 2017* 1336–1347 (2017).
- 1221 230. Chang, J. I. & Yoon, S. The economic benefit of coastal erosion control in Korea. *J. Coast.*  
1222 *Res.* **1**, 1317–1321 (2016).
- 1223 231. Kim, K.-H., Yoo, H.-S. & Kobayashi, N. Mitigation of Beach Erosion after Coastal Road  
1224 Construction. *J. Coast. Res.* **27**, 645–651 (2011).
- 1225 232. Ok, H. Y., Ho, Y. S. & Suh, H. L. Seasonal zonation patterns of benthic amphipods in a  
1226 sandy shore surf zone of Korea. *J. Crustac. Biol.* **22**, 459–466 (2002).
- 1227 233. Kabat, P. *et al.* Dutch coasts in transition. *Nat. Geosci.* **2**, 450–452 (2009).
- 1228 234. Janssen, G. M., Leewis, L. & Marx, S. Mitigation of the ecological effects of nourishment on  
1229 sandy shores , a case study. *Sandy beaches Coast. Zo. Manag. – Proc. Fifth Int. Symp. Sandy*  
1230 *Beaches* 121–123 (2011).
- 1231 235. Leewis, L., van Bodegom, P. M., Rozema, J. & Janssen, G. M. Does beach nourishment have  
1232 long-term effects on intertidal macroinvertebrate species abundance? *Estuar. Coast. Shelf*  
1233 *Sci.* **113**, 172–181 (2012).



1234 236. Stronkhorst, J., Huisman, B., Giardino, A., Santinelli, G. & Santos, F. D. Sand nourishment  
1235 strategies to mitigate coastal erosion and sea level rise at the coasts of Holland (The  
1236 Netherlands) and Aveiro (Portugal) in the 21st century. *Ocean Coast. Manag.* (2018)  
1237 doi:10.1016/j.ocecoaman.2017.11.017.

## 1238 **Acknowledgments**

1239 M.S. acknowledges financial support from NWO Domain Applied and Engineering Sciences  
1240 under project code 15058. B. L. acknowledges financial support from United States Army Corps  
1241 of Engineers (USACE), California Department of Parks and Recreation, Natural Resources Division  
1242 Oceanography Program, and the Copley Foundation. B.R. acknowledges financial support from  
1243 U.S. National Science Foundation, USACE and the WHOI investment in Science Fund. A.L. is  
1244 supported by the Deltares Strategic Research Programme 'Coastal and Offshore Engineering'.  
1245 Rob Grenzeback, Lucian Parry and Brian Woodward (Scripps Institution of Oceanography) are  
1246 thanked for providing feedback on the latest survey techniques. Sumi Selvaraj and Carey Batha  
1247 (California Coastal Commission) are thanked for helpful discussions about coastal management  
1248 and social justice. Seok-Bong Lee is thanked for providing information on South Korean  
1249 nourishments.

## 1250 **Author contributions**

1251 MA de Schipper and BC Ludka conceived the project. All co-authors contributed to the writing  
1252 and editing of the manuscript. MA de Schipper and BC Ludka gave special attention to the  
1253 Introduction, Sand redistribution, Broader Impacts, Integrating Perspectives and Future  
1254 Directions. B Raubenheimer gave special attention to Groundwater Impacts and Integrating  
1255 Perspectives. AP Luijendijk gave special attention to the Sand Redistribution, TA Schlacher gave  
1256 special attention to Ecological Impacts, Integrating Perspectives and Future Directions. MA de  
1257 Schipper compiled edits of the text and finalized them in collaboration with the editor.

## 1258 **Competing interests**

1259 The authors declare no competing interests.

1260 **Peer review information**

1261 Nature Reviews Earth & Environment thanks [Referee#1 name], [Referee#2 name] and the other,  
1262 anonymous, reviewer(s) for their contribution to the peer review of this work.

1263 **Publisher's note**

1264 Springer Nature remains neutral with regard to jurisdictional claims in published maps and  
1265 institutional affiliations.

1266

1267 **Figure legends**

1268 **Fig 1. Beach nourishment projects.** Nourishment sand bodies and additional hard structures indicated in black  
1269 dashed and red lines respectively. a| Beach nourishment placement in progress, San Diego (USA). b| Beach  
1270 nourishment with groyne field, Coney Island (New York, USA). c| Perched beach nourishment with groyne field and  
1271 submerged sill, Pellestrina (Italy). d| Beach and dune nourishment with lagoon, Hondsbossche (Netherlands). e| 'Sand  
1272 Engine Mega Nourishment' intended to feed adjacent beaches with constructed lake and lagoon for additional types  
1273 of recreational and ecological habitats, Kijkduin (Netherlands). [\[PR: CHECK AND ADD IMAGE PERMISSIONS\]](#)

1274

1275 **Fig 2. Evolution of sandy beach nourishments.** Morphological evolution of a sandy beach nourishment in planform  
1276 (bird's eye view) and profile (side-view). a| As the nourishment pad retreats, sand is redistributed laterally, with possible  
1277 spit development along the edges. b| In the original placement region, erosion of the pad coincides with a general  
1278 decrease of the profile slope. c| At adjacent coastal sections, nourishment sand delivered by spit features creates an  
1279 elevated bump on the profile. d| Erosion of the nourishment near the water line can result in the creation of scarps. e|  
1280 Scarps can be removed when high waves overwash the scarp crest. f| Crowns can form when overtopping waves bring  
1281 sediment on top of the nourishment pad. Advances in morphodynamic model predictions illustrated for the 'Sand  
1282 Engine' nourishment, with the columns representing the initial (2011), one year (2012) and 5-year bed levels (2016). g|  
1283 Observed bed levels in 2011. h| Observed bed levels in 2012. i| Observed bed levels in 2016. j| Model input. k| The  
1284 uncalibrated 1 year ocean-forced (waves & currents) model prediction. l| 18 month calibrated, ocean-forced, extended  
1285 5 year prediction<sup>92</sup>. m| 1 year calibrated, ocean-forced model output<sup>47</sup>. n| 18 month calibrated extended 5 year  
1286 prediction including ocean-forcing and wind-blown sand transport on the above-water beach<sup>91</sup>. Thick black lines in g-  
1287 n note the mean sea level.

1288

1289 **Figure 3. Groundwater processes related to nourishments.** Fresh rainwater is trapped in the ground (surface aquifer)  
1290 above saline water that infiltrates from the ocean. a| Beach nourishments expand the region that traps water, including

1291 precipitation, potentially expanding freshwater resources. b| During large ocean surge and wave events, the beach and  
1292 dune absorbs seawater, creating a groundwater bulge that increases in magnitude with storm period. c| Following a  
1293 storm, the groundwater under the dune exfiltrates onto the beach, potentially enhancing erosion or reducing onshore  
1294 blowing sand that could rebuild the dune. In addition, the groundwater bulge moves inland, potentially causing flooding  
1295 in low-lying areas.

1296

1297 **Figure 4. Potential ecological changes during and following beach nourishment.** a| Ocean beaches without  
1298 significant human stressors are ecosystems rich in species and individuals. b| Human activities at developed (eroding)  
1299 seashores often result in a reduction in beach fauna. c| Beach nourishment can cause a range of changes to beach  
1300 habitats and their fauna. These impacts can arise through direct mechanical impact. d| Excess coarse material, such as  
1301 shell hash, can make it difficult for predators to detect prey and to extract prey from the seafloor. e| High concentrations  
1302 of silts and clays in suspension can suffocate infauna, by clogging their gills. f| Because invertebrates living in the sand  
1303 have very specific requirements, changes to granulometry are often inimical to beach fauna, including lower recruitment  
1304 by larvae from the ocean. Note, the panels are conceptual sketches only, with organisms and human activities not to  
1305 scale.

1306

1307 **Figure 5. Integration of impacts into nourishment design.** a| Main design parameters impacting coastal zone  
1308 functions. b| Flowchart for designing and evaluating beach nourishments. Nourishment strategy examples (not  
1309 comprehensive) show the diversity in designs and their relation to design choices. Actual designs could combine several  
1310 elements to reflect the nourishment project goals.

1311

1312 [b1] Regional nourishment strategies

---

1313 [bH1] United States, San Diego County, Southern California

1314 The Southern California coastal zone contains large cliffed sections, intersected with river and  
1315 estuarine valleys. Wide beaches in this region are primarily the result of large opportunistic  
1316 nourishments between the 1940s and 1980s<sup>22</sup>. More recently smaller nourishments (order of  
1317 magnitude  $200,000 \text{ m}^3$ )<sup>45,53</sup> are typically placed to protect coastal infrastructure and bolster  
1318 tourism, impacting beach-spawning fish<sup>160</sup>, shore birds<sup>147</sup> and invertebrates<sup>150</sup>. Sands are  
1319 obtained from a mix of harbor dredge material<sup>160</sup> and offshore pits<sup>150</sup> with costs of 12-25 US\$  
1320 per  $\text{m}^3$  (Ref<sup>224</sup>). These projects are financed by state and federal funds, with smaller contributions  
1321 from the local cities.

1322 [bH1] Australia, SE-Queensland

1323 The southernmost part of the Queensland coastline contains large, low-lying sandy islands  
1324 backed by lagoons and inlet systems<sup>225</sup>. These beach systems host amongst others  
1325 invertebrates, fish and larger scavengers<sup>153,226</sup>. Tourist beaches on this coastline have been  
1326 nourished since the 1970s<sup>227</sup>. Surfing conditions are engineered by an artificial reef in the  
1327 nearshore zone<sup>228</sup>. Local and state government have invested in a continual program that adds  
1328 sand from a nearby estuarine inlet to popular tourist beaches. The majority of the sand is  
1329 dredged from nearby estuaries and inlets and a small percentage of the sands (15%) are  
1330 obtained from offshore sources<sup>227</sup>. Costs are ~ 5 US\$ per m<sup>3</sup> (Ref<sup>214</sup>). Sand supply is also  
1331 enhanced by an estuarine bypass system, a continuous beach nourishment system that  
1332 redistributes sand from the updrift beach through a pipeline to several outlets on beaches  
1333 down-current of the estuarine inlet<sup>12</sup>.

1334 [bH1] South Korea, East Coast

1335 The South Korean east coast is a rocky coastline with embayed sandy beaches<sup>229</sup> subjected to  
1336 multiple severe storm and typhoon events per year<sup>230</sup>, and some parts suffer from structural  
1337 erosion. Urban areas along the east coast of South Korea typically consist of coastal  
1338 infrastructure fronted by a narrow beach, increasing the demand for coastal protection and  
1339 space for recreation using frequent beach nourishments<sup>42,230,231</sup>. Even in these developed  
1340 regions, the beach ecosystem hosts a range of species, including various burrowing and tube-  
1341 dwelling amphipods<sup>232</sup>. Sand is mined from nearby rivers and estuaries or from offshore areas at  
1342 distance of the beach<sup>42</sup>. Costs are 35-45 US\$ per m<sup>3</sup>.

1343 [bH1] The Netherlands.

1344 The majority of the Netherlands is situated below mean sea level and is densely populated. A  
1345 narrow beach and dune ridge are the primary defense against flooding<sup>233</sup>. High potential for  
1346 inundation damages have led to frequent nourishment interventions that are backed by federal  
1347 funding and with long-term nationwide planning. Annually, 10-15 million m<sup>3</sup> of sand is used in  
1348 nourishment projects along the sandy shoreline<sup>26</sup>. Nourished sand is placed on the beach but

1349 also in shallow waters (4-6 m water depth) with the intent that it will either act as a breakwater  
1350 sandbar or feed sand onshore. These nourishments are found to affect macroinvertebrates,  
1351 bivalves and migrating birds (amongst others)<sup>234,235</sup>. These sands are mined 5 km offshore in  
1352 shallow waters (~20 m water depth) from a wide continental shelf. Costs are ~ 5 US\$ per m<sup>3</sup>  
1353 (Ref<sup>236</sup>). Federal planning allows for experimenting with new nourishment designs, such as  
1354 concentrated mega nourishments.

1355 [\[PR: CHECK AND ADD IMAGE PERMISSIONS\]](#)

---

1356