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RESPONSE OF NATURAL, MODIFIED AND ARTIFICIAL SANDY BEACHES TO SEA-LEVEL RISE

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ABSTRACT. Sandy beaches occur in a wide variety of environmental settings and as components of a diverse range of coastal system types. These variations among beaches lead to significant differences in their mesoscale (multi-decadal, km length scale) behaviour, including their response to sea-level rise. In addition to this natural variability, the degree to which the sandy beach system has been or will be modified by humans is a major influence on how it responds to sea-level change. From a spectrum of beach types based on the degree of human modification, three situations (Natural, Modified and Artificial beaches) are considered in order to demonstrate the role of humans as geomorphic agents as sandy beaches respond to rising sea level. The potential trajectories of change are assessed, and future scenarios are presented and discussed. Natural beaches are most likely to survive sea-level rise, while the fate of artificial beaches depends almost entirely on the politics and economics of what lies immediately landward. In all categories of beach, human decision-making is the most important determinant of sandy beach response to sea-level rise.

Respuesta de las playas de arena naturales, modificadas y artificiales a la elevación del nivel del mar

RESUMEN. Las playas de arena se encuentran en una amplia variedad de entornos ambientales y como componentes de una amplia gama de tipos de sistemas costeros. Estas variaciones entre playas implican diferencias significativas en su comportamiento a mesoescala (escala de longitud de multi-década a kilómetros), incluyendo su respuesta al aumento del nivel del mar. Además de esta variabilidad natural, el grado en el que el sistema de playa de arena ha sido o será modificado por los seres humanos es importante en la respuesta al cambio del nivel del mar. A partir de un espectro de tipos de playa, basado en el grado de modificación humana, se consideran tres situaciones (playas naturales, modificadas y artificiales) para demostrar el papel de los humanos como agentes geomórficos a medida que las playas de arena responden al aumento del nivel del mar. Se evalúan las posibles trayectorias de cambio y se presentan y discuten escenarios futuros. Las playas naturales tienen más probabilidades de sobrevivir al aumento del nivel del mar, mientras que el destino de las playas artificiales depende casi por completo de la política y la economía. En todas las categorías de playa, la toma de decisiones humana es el determinante más importante en la respuesta de la playa de arena al aumento del nivel del mar.

Key words: Sandy beach, sea-level rise, human impact.

Palabras clave: Playas de arena, elevación del nivel del mar, impacto antrópico.

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1. Introduction

Sandy beaches take a wide variety of geomorphic forms and exhibit various morphological behaviours according to their environmental setting (Carter, 1989; Woodroffe, 2002; Davis and FitzGerald, 2009). Empirical data show that their instantaneous and seasonal variation in morphology reflects the interaction between sediment texture and the associated wave and tidal regime (Jackson and Short, 2020) but at longer-terms (decades to centuries) and larger spatial scales (> 1 km alongshore distance) beach behaviour is strongly influenced by aspects of the geological framework and geomorphological system in which they occur (Cooper and Pilkey, 2004; Anthony, 2013; Cooper *et al.,* 2018). These include the volume of sediment and rate of sediment supply, as well as the surrounding geological framework that may comprise erodible or unerodable materials in various configurations (headlands, Commonly, for example, distinction is made between uninterrupted linear sandy beaches, on which longshore transport is a dominant process (e.g. Abadie *et al.,* 2006; Laïbi *et al.,* 2014; Balouin *et al.,* 2005), and embayed beaches in which cross-shore transport is dominant (Bowman *et al.,* 2009; Pinto *et al.,* 2009; Loureiro *et al.,* 2012). Beaches are often part of a wider sedimentary system involving exchanges of material and energy between beach, dune, lagoon, mainland, tidal inlet sand bodies, shoreface, alongshore environments etc. and their behaviour is strongly determined by the nature of the sedimentary system of which they form a part. At a smaller spatial scale, beaches and parts of beaches have also been classified in terms of their profile and plan morphology into a spectrum of beach states (Jackson and Short 2021).

Sandy beaches are widespread and important environments as far as humans are concerned. They deliver a range of ecosystem services inasmuch as they support foodwebs, act as buffers against storms, and perhaps most importantly in the Mediterranean and other warm water locations, they are associated with high levels of economic activity via their high recreation and tourism value (Jacob *et al.,* 2021). Consequently, their response to near-future sea-level rise is an important societal issue.

Aside from the natural variability in sandy beach form, sandy beaches also exist in a range of states according to the degree to which they have been modified by human activities (Cooper and Alonso, 2006; Palazón *et al.,* 2016; Cooper and Jackson, 2020) (Fig. 1). Some remain in essentially natural conditions in which sediment supply to and within the beach sedimentary system has not been altered. These are becoming increasingly rare as the global population increase and increased wealth has increased the pressures to which beaches are subjected, but they are often associated with sparely populated, remote and inaccessible locations.

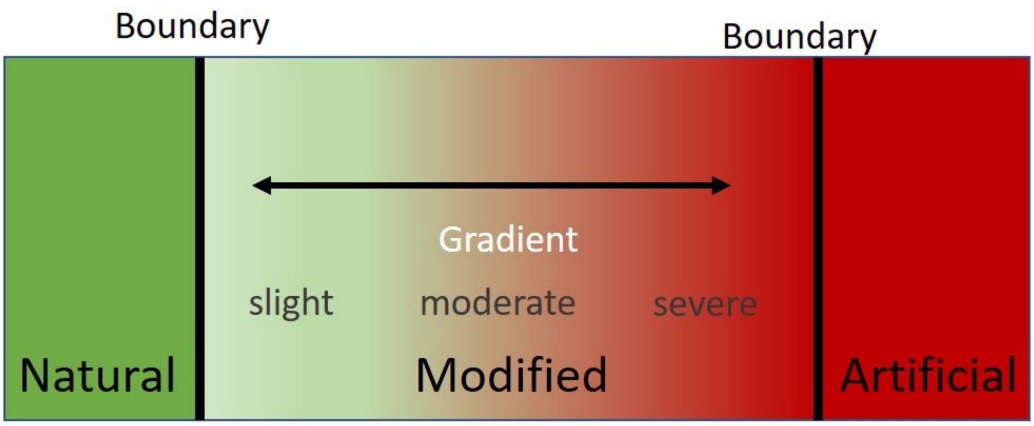

Figure 1. Conceptualisation of the degree to which human activity modifies sandy beaches. Totally natural and artificial states are separated by clear boundaries or thresholds whereas modified beaches exist on a gradient ranging from minor to major modifications of the natural dynamics and/or boundary conditions.

Many other beaches have been modified by human activity to varying degrees and this modification in turn can affect their medium-term behaviour. Ephemeral human impacts related to, for example, driving on a beach, high-density summer tourism use or the effects of a pollution incident, tend to be short-lived and have little lasting impact. More long-lasting and/or widespread impacts are reflected in the medium-term behaviour of beaches (e.g. del Rio Rodriguez *et al.,* 2015; Garel *et al.,* 2015). These human impacts include reduction in beach sediment volume through sand mining (e.g. Alonso *et al.,* 2002; Costas and Alejo, 2007); reduction of external supply (Malvárez, 2012) increases in volume or changes in texture due to sediment input, often via beach nourishment (e.g. Anfuso *et al.,* 2001), changes in boundary conditions through emplacement of coastal engineering structures (e.g. Malvárez, 2012; del Rio *et al.,* 2015) and direct construction on the beach or dune surface (Roig-Munar *et al.,* 2006) to name but a few. These interventions damage the beach and cause changes that occasionally cause further interventions or beach destruction (Pilkey and Cooper, 2014).

Artificial beaches are those that were created or are maintained entirely through ongoing human intervention (Malvárez *et al.,* 2021). They can arise through progressive human alteration of natural beaches to the point that the natural aspects are lost.

The best examples are artificially nourished beaches whose existence relies on continued input of sand by human means. Other artificial beaches are created where previously no beach existed. When accommodation space is available in the geological framework, the addition of sand can lead to development of an artificial beach that may or may not require ongoing human intervention to maintain it.

Ongoing and near-future sea-level rise is often cited as a threat to sandy beaches (e.g. Vousdoukas *et al.,* 2020), but rather than being a ubiquitous threat, the ability of beaches to survive sea-level rise is related partly to the natural geological setting and to human interventions (Cooper *et al.,* 2020). Currently, the rate of sea-level rise is accelerating (Dagendorf *et al.,* 2019) and future sea levels have been estimated for various emissions scenarios (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool). There is much uncertainty regarding future sea-level projections, related mainly to the poorly understood rate of ice sheet decay (Golledge, 2020), however, IPCC AR6 scenarios suggest a rise of between 0.6 and 0.75 m by 2100 relative to a 1995-2014 baseline at sites around the Spanish coast.

Just as beaches have previously been categorized from a coastal management perspective according to their degree of urbanization (Natural, Semi-Urbanized and Urbanized; Palazón *et al.,* 2016), in this paper, three categories of sandy beach are presented (Natural, Modified and Artificial) in terms of the degree to which they have been modified by humans. The likely response of each category of beach to near-future sea-level rise is then considered. The boundaries between the categories are gradational and reflect the progressive and incremental impact of human actions on beaches. The perspective of the paper, based on geomorphological observations and geological principles, is that natural (or lightly impacted) beaches can evolve and persist within the changing boundary conditions imposed by sea-level rise, whereas human intervention, driven by a desire to protect coastal property and human interests through shoreline stabilization, hampers the ability of beaches to adapt. Human responses to beach changes that threaten or are perceived to threaten human interests often involve interventions to stabilize the beach (Cooper and Pilkey 2012). These interventions transform natural beaches into modified beaches and these interventions may proceed to the stage that the beach is transformed into an artificial system whose continued existence depends on beach nourishment (Fig. 2). It is likely that sea-level rise-related changes will be perceived in the same way and further human interventions on natural beaches are likely to occur. In efforts to stabilize the shoreline. The presence of infrastructure landward of a natural beach is the most likely driver of such interventions and in very few cases has the alternative strategy (remove or modify the infrastructure) been adopted (Creach *et al.,* 2020).

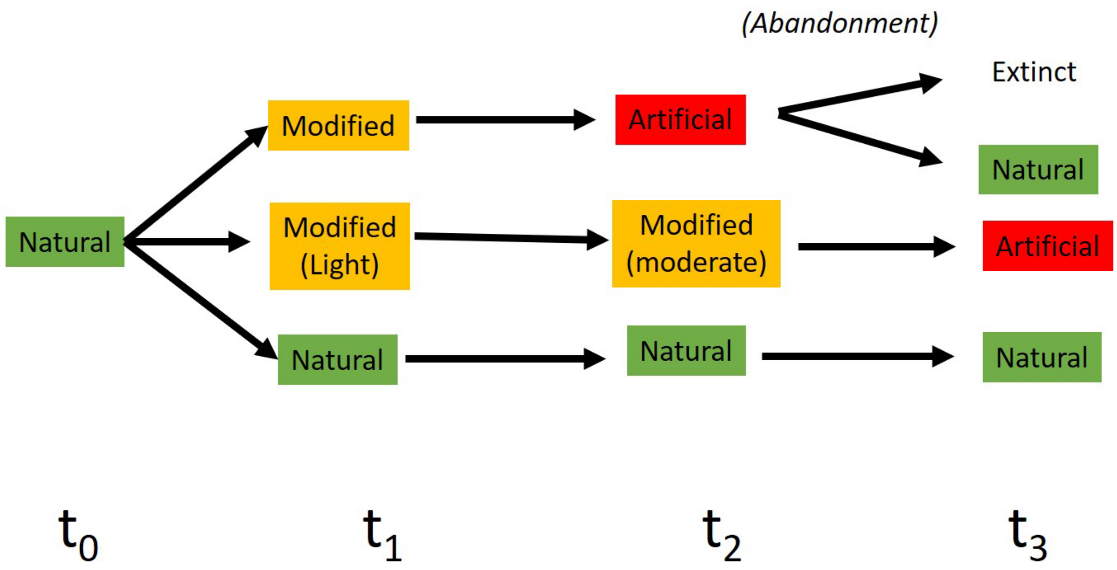

Figure 2. Trajectories of change for natural beaches as sea-level rise continues (t_0 to t_3 denotes time). Natural beaches can remain in a natural state or be modified by human activity to greater or lesser extents. Over time, the degree of modification usually increases until artificial beaches are created.

2. Natural sandy beaches and sea-level rise

Sandy beaches that are in a natural state are free to change morphology in response to external forcing within the confines of the surrounding geology. These changes take place at various timescales and are often difficult to recognise and interpret because of inadequate data (Woodroffe, 2002). Temporal morphological changes on beaches are complex and occur as a result of seasonal or longer-term variations in hydrodynamics or sediment supply (Anfuso *et al.,* 2016) and episodic events such as storms (Loureiro *et al.,* 2009) after which recovery can last for years or even decades (Orford *et al.,* 1999). Beach behaviour can also be decoupled from hydrodynamic forcing and is then characterised by "emergent behaviour" (Hird *et al.,* 2021). There are also feedbacks between beach morphology and dynamics (Sénéchal *et al.,* 2009, Anthony, 2012). Sandy beaches, being composed of uncohesive sediment are, however, able to adjust their morphology as a result.

Beach response to sea-level rise is difficult to detect in the face of the multiplicity of temporal morphological changes attributable to other sources. In broad terms, sea-level rise causes changes in the surrounding geological framework and the plane on which hydrodynamic forces operate. The precise nature of a beach's response to sea-level rise depends to a very great extent on local geological factors (initial morphology, surrounding geological framework and sediment supply; Cooper e*t al.,* 2018) and the rate (not just amount) of sea-level rise (Green *et al.,* 2014) and no generic approach can predict the extent of beach response and future shoreline position (Cooper and Pilkey, 2004). Local factors of a geological nature must be quantified if the future behaviour of a sandy beach is to be envisaged. Among these, the existing morphology and sediment volume, plus the presence or absence of uncohesive, erodible sediment either landward or seaward of a beach are among the most important elements in its future behaviour.

Nonetheless, free from human interference, most natural beaches are likely to adjust and therefore survive sea-level rise by migrating landward as part of an evolving coastal sedimentary system (Cooper *et al.,* 2020). The preservation of littoral deposits on the continental shelves of the world (e.g. Green *et al.,* 2014), testify to the ability of beaches to survive sea-level rise and to adjust to major changes in sea level. The coastal morphology may change according to the geological framework over which transgression takes place, but, free of human interference, a coastal system will be sustained in dynamic equilibrium with the ambient conditions dictated by geological framework, sediment supply and coastal dynamics. Although natural coastal systems will survive, these evolving systems may involve changes in coastal character, including local extinction of beaches in areas of steep topography (e.g. Peterson *et al.,* 2021) and coastal progradation in areas of abundant sediment supply (e.g. Goy *et al.,* 2003).

3. Human-modified sandy beaches and sea-level rise

Sandy beaches can be modified in many ways through human activity. Some of these cause alteration of the beach boundary conditions (e.g. by construction of engineered structures), changes in sediment volume (e.g. reduction by sand mining or augmentation by beach nourishment), or modification of patterns of sediment movement and storage (e.g. by groyne construction or creation of artificial dunes). These interventions are often (but not always) emplaced to adapt the beach to human requirements by stabilizing or altering its position to protect developments to landward. As sea-level rises, it is likely that existing installations on such shorelines will be maintained as long as adequate financial and technological resources are available. The critical issue is that on shorelines adjacent to fixed human infrastructure and property, landward migration of the shoreline is generally perceived primarily as a threat, rather than a natural process. Consequently, the landward migration in response to sea-level rise characteristic of natural beaches, is likely to be resisted (Malvárez *et al.,* 2021). One manifestation of this situation is the presence of seawalls on the landward side of many beaches. As in the case of beaches backed by steep topography, the lack of accommodation space created by seawalls will lead to beach narrowing and ultimately beach extinction.

In response to sea-level rise, early "adaptation" strategies are likely to involve the emplacement of more defences in a kind of "domino effect" as the impacts of earlier interventions are addressed by still more human modification. This is well illustrated on coasts where groyne fields extend alongshore in response to the longshore impact of the initial groynes. Early "adaptation" can also involve raising or strengthening of sea defences (especially seawalls, but also artificial dunes) and is often followed by beach nourishment. The temporal evolution of this sequence of stabilization approaches is well-illustrated on the Costa del Sol (Malvárez, 2012).

These kinds of intervention incur increasing costs over time as more sand or higher walls are required to hold stabilized shorelines in place as sea levels rise (Cooper and Lemckert, 2012). These responses amount to resisting (rather than adapting to) the natural change driven by sea-level rise (Cooper and Pile, 2014), and at meaningful timescales such responses can be regarded as maladaptation (Magnan *et al.,* 2016). Efforts to hold the shoreline and sustain beaches in the face of sea-level rise by beach nourishment have increased in extent and volume of nourishment and the volumes of sand involved in recent years (de Schipper *et al.,* 2021). This practice leads to beaches crossing a threshold and becoming artificial beaches that cannot survive without continued human intervention.

As sea-level rises and the extent of currently stabilized shoreline is recognised, the financial and technical resources necessary to maintain all such beaches may not be available (Pilkey and Cooper, 2014b). In circumstances where resources do not permit continued maintenance of human structures it is possible that modified sandy beaches could then revert to a more natural state (Fig. 3). In a few localities worldwide, the decision has already been made to permit beaches to migrate in spite of the presence of adjacent human structures and property (Berry *et al.,* 2013; Siders, 2019). In such locations as structures are removed or allowed to decay, the natural beach dynamics may be restored and the beach could therefore survive sea level rise.

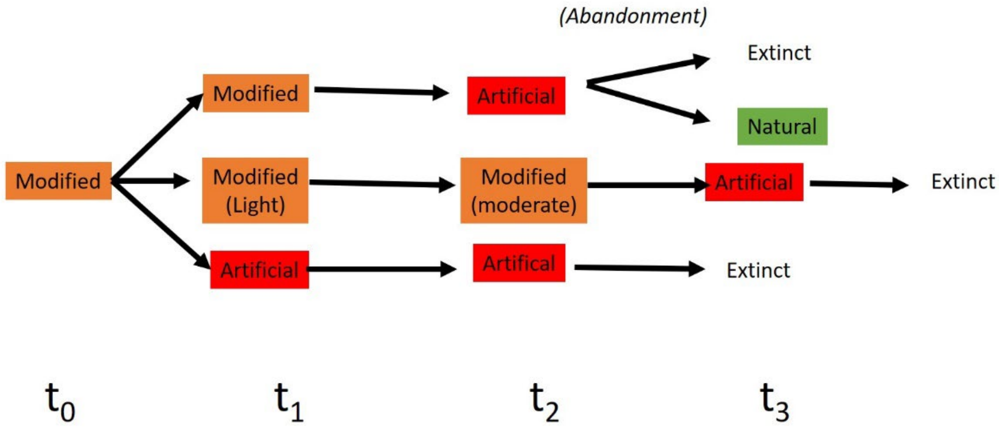

Figure 3. Trajectories of change for modified beaches as sea-level rise continues (t_0 to t_3 denotes time). The degree of modification usually increases, leading to transformation into artificial beaches.

4. Artificial sandy beaches and sea-level rise

Artificial sandy beaches arise mainly through continued efforts at stabilization that ultimately involve repeated phases of beach nourishment. Often this situation arises after the failure of several types of engineered structure to maintain the beach position. On the Costa del Sol, for example, a succession of hard structures of varying design were emplaced before beach nourishment was adopted as the shoreline stabilization method (Malvárez, 2012). On such beaches, ultimately, the beach is maintained against erosion only by ongoing nourishment and long-term plans are developed to maintain the shoreline. The entire mainland shoreline of the Netherlands is one such example, but large areas of the eastern United States (Armstrong and Lazarus, 2019) and individual beaches around the Mediterranean are now in this category. The Netherlands "dynamic preservation" strategy (Borsje *et al.,* 2017), for example, aims to maintain the 1991 shoreline in the face of rising sea level. Perversely, the strategy has been labelled by its proponents as "working with nature", whereas it is actually resisting the forces of nature that would otherwise cause the shoreline to shift landwards. Some authors have recognised that the approach is not sustainable in the long term (Parkinson and Ogurcak, 2018).

Some artificial beaches, however, have been constructed where no beach previously existed. Examples include Sentosa Island, Singapore (Lai *et al.,* 2015), the engineered shorelines of Dubai (Spurrier, 2008) and many sites in the Canary Islands (Alonso *et al.,* 2019) including the Playa de Las Teresitas in Tenerife (Pranzini *et al.,* 2010).

On artificially nourished beaches the management strategy is to maintain the beach position and in the face of sea-level rise this can only happen through more frequent additions of larger volumes of sand to enable the beach to keep pace with rising sea-level over time. Because the beach system also includes the submerged surf zone and shoreface, this can be a much larger volume of sand than is visible on the intertidal beach (Cooper and Lemckert, 2012). On beach systems that comprise part of a longshore drift system, those adjacent beaches also need to stabilized, thus spreading the need for nourishment alongshore (Armstrong and Lazarus, 2019).

Several factors combine to threaten future beach nourishment practice on a continental or global scale (de Schipper *et al.*, 2021). One important constraint is the availability and cost of sand. Sand is in high demand for construction and as supplies are depleted the costs increase and new sources must be found. A second factor is the increasing volume of sand required for beach stabilization as sea levels rise. In addition, infrastructure behind nourished beaches will be at ever lower elevation compared to future sea-level and the need for additional back-beach defences is therefore likely to increase. Ultimately, stabilization by nourishment could lead to artificial beaches that are much higher in elevation than the adjacent coastal infrastructure.

The fate of artificial sandy beaches lies entirely in the hands of human decisions regarding beach maintenance. If resources permit, the beaches can be maintained against sea-level rise (Fig. 4), although in the case of nourishment becoming unfeasible, seawalls are the last resort to protect landward developments. Sea wall construction would lead to the extinction of beaches as there is no opportunity to migrate (Pilkey and Cooper, 2014a). If political and economic conditions mean that seawalls are not constructed and infrastructure is abandoned or relocated, the possibility exists for re-establishment of natural sedimentary systems (Fig. 4). A Neolithic example has been documented from the coast of Israel (Galili *et al.,* 2019) where, after abandonment of a 7000 year-old seawall, a natural coastal system with a sandy beach was re-established landward of the former sea defence.

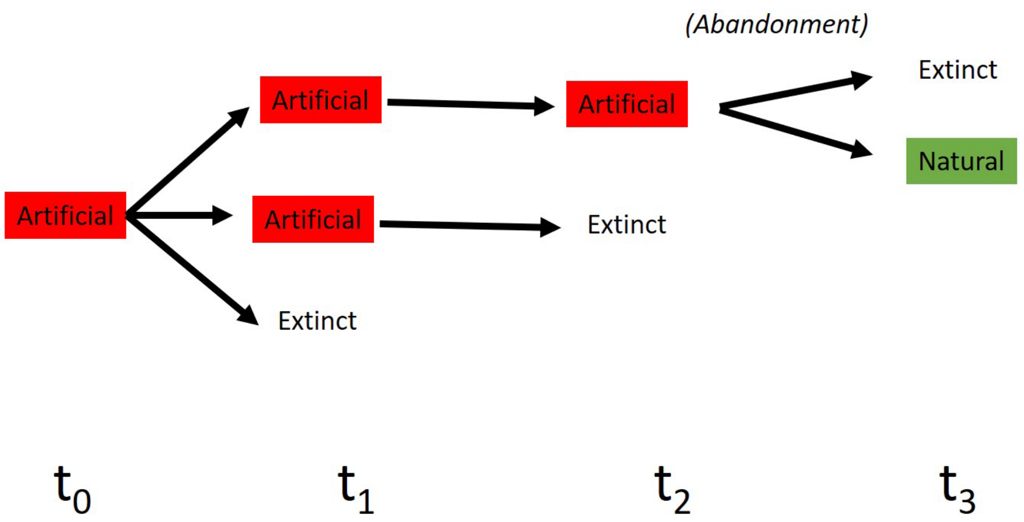

Figure 4. Trajectories of change for artificial beaches as sea-level rise continues (t_0 to t_3 denotes time). At some point controlled by the rate of sea-level rise and socio-political conditions, maintenance of artificial beaches may become unfeasible and the beach is then destroyed. At that point, natural conditions might be re-established, causing a reversion to a natural state, or the shoreline might be stabilized without the presence of a beach.

5. Discussion

The prospect of a general landward migration of beaches as a result of sea-level rise is only partly appreciated by decision-makers and beach nourishment has been widely regarded as an “easy solution”. This has created the misperception that beach loss can be avoided or easily rectified. To date, beach nourishment has been effective in stabilizing some sandy shorelines to the extent that the background rate of beach recession has been masked (Armstrong and Lazarus, 2019) but as volumes of sand for nourishment increase, and the extent of nourished beaches increases, the costs and logistics will put pressure on nourishment as a stabilization technique (Pilkey and Cooper, 2014b).

Sea level rise does not pose a threat to most natural beaches. Beaches have survived many metres of sea-level rise during the Holocene and overstepping of sandy shorelines appears to be associated with much higher rates of sea-level rise than are envisaged for the near future. Widespread overstepping has been noted during glacial meltwater pulses when rates of sea-level rise reached 20-30 mm per year (Green *et al.,* 2014; Cooper *et al.,* 2016), an order of magnitude greater than envisaged in current IPCC projections (IPCC, 2021). Natural beaches can therefore be generally expected to migrate and adjust their morphology as sea levels rise. A risk is posed to natural beaches, however, if there is development in close proximity that might create pressure for future shoreline stabilization. Such shorelines were classified as “at risk” by Cooper and Jackson (2019).

On highly developed back-beach areas, such as those with high-rise commercial and residential development, defence of property is likely to be maintained by continued nourishment to stabilize the shoreline and maintain the artificial beach. On less developed areas, the cost of nourishment may become prohibitive, at which stage seawalls are likely to be emplaced to protect property and the beach will be eroded due to a lack of accommodation space. On the least developed shorelines a cessation of nourishment without alternative hard defences could lead to the re-establishment of natural beach conditions. If beach nourishment stops, then such beaches are likely to narrow and disappear as sea-level rise.

Consistent with current views on global dynamics in the Anthropocene (e.g. Zalasiewicz *et al.,* 2008) on all beaches, whether natural, modified or artificial, decisions made by humans are the single most important determinant of their future status and trajectory of change. This highlights the importance of adaptation planning for beach preservation. The adoption of policies that prioritise the preservation of beaches (long-lasting, natural features) over buildings (ephemeral artificial structures) is an urgent priority because at present, human interventions continue to damage beaches in order to protect property. These conditions stimulate ongoing property development in back-beach areas and increase the future threats to the survival of beaches. Adoption of alternative strategies is politically difficult but in the current climate emergency, increased attention on the importance of natural ecosystems might create conditions in which beach survival is prioritised. Some authors (e.g. Anderson *et al.,* 2020) consider retreat of beachfront communities (and infrastructure) to be unavoidable in the future engineered responses to shoreline stabilization become less feasible both technically and economically.

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